ICAP2❂22

The 27th International Conference on Atomic Physics

JULY 17-22, 2022 • TORONTO, CANADA

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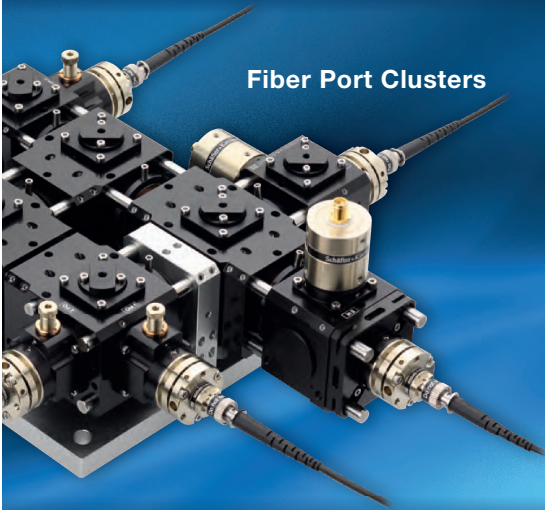
Book of Abstracts

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Schedule at-a-glance

	Sunday July 17th	Monday July 18th	Tuesday July 19th	Wednesday July 20th	Thursday July 21st	Friday July 22nd
7:30-8:00		Registration / Info Desk Open				
8:00 - 8:40			Registration / Info Desk Open	Registration / Info Desk Open	Registration / Info Desk Open	Registration / Info Desk Open
8:45-10:25		Francesca Ferlaino	**ECR Prize Talk** Ana Asenjo-García	**HOT TOPIC** Patrick Cheinet	Monika Aidelsburger	**HOT TOPIC** Tracy Northup
		Giacomo Roati	Kyungwon An	**HOT TOPIC** Manuel Endres	Leticia Tarruell	**HOT TOPIC** Loic Anderegg
		Isabelle Bouchoule	Julien Laurat	**HOT TOPIC** Adam Kaufman	Zhen-Sheng Yuan	**HOT TOPIC** Debayan Mitra
10:30-11:00		**Coffee Break**				
11:05-12:20		Klaus Mølmer	**HOT TOPIC** Julian Schmitt	**HOT TOPIC** Saida Guellati-Khelifa	Mike Tarbutt	Markus Greiner
		Jonathan Home	**HOT TOPIC** Chris Vale	**HOT TOPIC** Shimon Kolkowitz	**HOT TOPIC** Zoe Z. Yan	Jonathan Simon
12:20-13:55		**Lunch break**		**ICAP x TRIUMF** Crossover Session Room 25 321 Bloor St W 12:45-13:45		**Closing Remarks & Farewell Reception**
13:55-15:10	Registration / Info Desk Open, RCM, 14:00-19:00	Monika Schleier-Smith	Tom Killian	John Bollinger	David Leibrandt	Lab Tours at the University of Toronto 60 St. George Street 14:30-16:30
		James Thompson	Tilman Pfau	Olga Smirnova	Eric Hessels	
15:10-15:40		**Break**				
15:45-17:00		Ekkehard Peik	Jun Ye	Helen Margolis	Norman Yao	
		Eric Cornell	Wolfgang Ketterle	Hidetoshi Katori	Vladan Vuletic	
17:00-18:30		**Poster Session I**	**Poster Session II**	**Poster Session III**	**Poster Session IV**	
18:30-19:00		**End of Day**				

Lab Tours at the University of Toronto 60 St. George Street 14:30-16:30

Welcome Reception Exhibitor Hall, RCM 17:00-19:00

If there is a discrepancy between this printed schedule and the online schedule, the online schedule should be taken as correct.

Purple and green columns represent the opening hours of the Registration/Info Desk and Exhibition Hall, respectively. For example, on Monday July 18th the Registration/Info Desk and Exhibition Hall are open between 7:30 and 17:30.

Program

SUNDAY JULY 17th

14:00 - 19:00   Registration/Info Desk Open

14:30 - 16:30   **Lab Tours at the University of Toronto**   Department of Physics, 60 St. George Street

17:00 - 19:00   Exhibition Hall Open

MONDAY JULY 18th

07:30 - 17:30   Registration/Info Desk Open

07:30 - 17:30   Exhibition Hall Open

08:40 - 10:30   **Plenary Session I - Quantum Fluid Dynamics**   Chair: Ludwig Mathey, U Hamburg (Germany)

New paradigms with dipolar quantum gases: Vortices, two-dimensional supersolidity, and angular responses

Francesca Ferlaino, Innsbruck (Austria)

A quantum vortex collider

Giacomo Roati, LENS (Italy)

Generalized hydrodynamics in 1D Bose gases

Isabelle Bouchoule, Institut d'Optique (France)

10:30 - 11:00   Coffee Break

11:05 - 12:20   **Plenary Session II - Qubits**   Chair: Rainer Blatt, U Innsbruck (Austria)

Interactions with pulses of quantum radiation

Klaus Mølmer, Copenhagen (Denmark)

Stabilisation of a logical grid-state qubit by laser cooling

Jonathan Home, ETHZ (Switzerland)

12:20 - 13:55   Lunch Break

13:55 - 15:10   **Plenary Session III - Cavity QED**   Chair: Duncan O'Dell, McMaster U (Canada)

Atoms Interlinked by Light: Programming Interactions and Probing Entanglement

Monika Schleier-Smith, Stanford (US)

Entanglement-Enhanced Matter-Wave Interferometry in a High-Finesse Cavity

James Thompson, JILA (US)

15:10 - 15:40   Break

Program Con't

15:45 - 17:00   **Plenary Session IV - Precision Measurement I**   Chair: Protik Majumder, Williams College (USA)

Atomic and nuclear clocks for testing fundamental physics

Ekkehard Peik, PTB (Germany)

An improved measurement of the electron's electric dipole moment

Eric Cornell, JILA (US)

17:00 - 18:30   **Poster Session I**   Hart House, University of Toronto

TUESDAY JULY 19th

08:00 - 17:30   Registration/Info Desk Open

08:00 - 17:30   Exhibition Hall Open

08:40 - 10:30   **Plenary Session V - Quantum Optics**   Chair: Michal Bajcsy, IQC Waterloo (Canada)

IUPAP C15 (AMO) 2022 ECR Prize talk: Many-body quantum optics in atomic arrays   `PRIZE TALK`

Ana Asenjo-García, Columbia University (US)

Superradiance, Superabsorption and a Photonic Quantum Engine

Kyungwon An, Seoul National U (Korea)

Quantum optics with cold atoms trapped along nanowaveguides

Julien Laurat, LKB Paris (France)

10:30 - 11:00   Coffee Break

11:05 - 12:20   **Plenary Session VI - Fermi Gasses**   Chair: Randy Hulet, Rice (USA)

Compressibility and the equation of state of an optical quantum gas in a box   `HOT TOPIC`

Julian Schmitt, Bonn (Germany)

Higgs mode in a unitary Fermi gas   `HOT TOPIC`

Chris Vale, Swinburne (Australia)

12:20 - 13:55   Lunch Break

13:55 - 15:10   **Plenary Session VII - New Directions**   Chair: Wonho Jhe, Seoul (Korea)

Laser-driven and Magnetized Ultracold Neutral Plasmas

Tom Killian, Rice (US)

Quantum Optics based on dipolar interactions between hot atoms

Tilman Pfau, Stuttgart (Germany)

15:10 - 15:40   Break

15:45 - 17:00   **Plenary Session VIII - Quantum Simulation**   Chair: Alan Jamison, IQC Waterloo (Canada)

A tunable spin Hamiltonian of dipolar molecules

Jun Ye, JILA / NIST Boulder (US)

Spin dynamics of ultracold atoms in optical lattices

Wolfgang Ketterle, MIT (US)

17:00 - 18:30   **Poster Session II**   Hart House, University of Toronto

WEDNESDAY JULY 20th

08:00 - 17:30   Registration/Info Desk Open

08:00 - 17:30   Exhibition Hall Open

08:40 - 10:30   **Plenary Session IX - Alkaline Earth Atoms**   Chair: Gabriele Ferrari, U Trento (Italy)

Coherent Light Shift on Alkaline-Earth Rydberg Atoms   `HOT TOPIC`

Patrick Cheinet, Aimee-Coton (France)

Probing Quantum Many-Body Dynamics with Tweezer Arrays   `HOT TOPIC`

Manuel Endres, Caltech (US)

Quantum science with microscopically-controlled arrays of two-electron atoms   `HOT TOPIC`

Adam Kaufman, JILA (US)

10:30 - 11:00   Coffee Break

11:05 - 12:20   **Plenary Session X - Precision Measurement II**   Chair: Gordon Drake, U Windsor (Canada)

Accurate determination of the fine-structure constant using atom interferometry   `HOT TOPIC`

Saïda Guellati-Khelifa, LKB Paris (France)

A precision laboratory test of the gravitational redshift at the sub-cm scale   `HOT TOPIC`

Shimon Kolkowitz, U Wisconsin (US)

12:20 - 13:55   Lunch Break

Program Con't

12:45 - 13:45 **ICAP X TRIUMF Crossover Session** Room 25 in Woodsworth College Residences, 321 Bloor St W

Live streamed session showcasing achievements and opportunities for atomic and molecular physics pursued by the TRIUMF community. The Woodsworth College Residence building is less than 5 minutes' walk from the main ICAP venue, Koerner Hall.

Speakers:
Gerald Gwinner (UManitoba)
Takamasa Momose (UBC)
Ronald Garcia Ruiz (MIT)

13:55 - 15:10 **Plenary Session XI - Non-equilibrium Dynamics** Chair: Maciej Lewenstein, ICFO (Spain)

Ultrafast chirality: twisting light to twist electrons

Olga Smirnova, MBI Berlin (Germany)

Non-equilibrium dynamics and sensing with large trapped-ion crystals

John Bollinger, NIST Boulder (US)

15:10 - 15:40 Break

15:45 - 17:00 **Plenary Session XII - Optical Clocks** Chair: Piet Schmidt, PTB (Germany)

Optical atomic clocks – what challenges remain on the roadmap towards a redefinition of the SI second?

Helen Margolis, NPL (UK)

Making optical lattice clocks compact and useful for real-world applications

Hidetoshi Katori, Tokyo (Japan)

17:00 - 18:30 **Poster Session III** Hart House, University of Toronto

THURSDAY JULY 21st

08:00 - 17:30 Registration/Info Desk Open

08:00 - 17:30 Exhibition Hall Open

08:40 - 10:30 **Plenary Session XIII - Quantum Simulation of Gauge Theories**
Chair: Lindsay LeBlanc, U Alberta (Canada)

Towards quantum simulation of U(1) LGTs with alkaline-earth-like atoms

Monika Aidelsburger, LMU Munich (Germany)

Engineering a topological gauge theory in an optically dressed Bose-Einstein condensate

Leticia Tarruell, ICFO (Spain)

Simulating a Lattice Gauge Theory with Ultracold Atoms

Zhen-Sheng Yuan, USTC (China)

10:30 - 11:00   Coffee Break

11:05 - 12:20   **Plenary Session XIV - Molecules**   Chair: Robin Coté, U Connecticut (USA)

Testing fundamental physics using laser cooled molecules

Mike Tarbutt, Imperial College (UK)

Quantum gas microscopy of polar molecules   HOT TOPIC

Zoe Z. Yan, Princeton (US)

12:20 - 13:55   Lunch Break

13:55 - 15:10   **Plenary Session XV - Precision Measurement III**   Chair: Zong Chao Yan, UNB (Canada)

Four-second optical coherence between different atomic species, and the search for new physics with atomic clocks

David Leibrandt, NIST Boulder (US)

The proton size, the fine-structure constant, and the electron electric dipole moment

Eric Hessels, York University (Canada)

15:10 - 15:40   Break

15:45 - 17:00   **Plenary Session XVI - Metrology**   Chair: Aephraim Steinberg, U Toronto (Canada)

A Landau Theory for Spin Squeezing

Norman Yao, Berkeley (US)

Time-Reversal-Based Quantum Metrology beyond the Standard Quantum Limit

Vladan Vuletic, MIT (US)

17:00 - 18:30   **Poster Session IV**   Hart House, University of Toronto

FRIDAY JULY 22nd

08:00 - 14:00   Registration/Info Desk Open

Program Con't

08:40 - 10:30 **Plenary Session XVII - Cooling Beyond Atoms** Chair: Amar Vutha, U Toronto (Canada)

Cooling nanoparticles in ion traps: a route to the quantum regime HOT TOPIC

Tracy Northup, Innsbruck (Austria)

Laser-cooled Molecules, from Controlled Collisions to Qbits HOT TOPIC

Loic Anderegg, Harvard (US)

Laser Cooling of Complex Polyatomic Molecules HOT TOPIC

Debayan Mitra, Columbia University (US)

10:30 - 11:00 Coffee Break

11:05 - 12:20 **Plenary Session XVIII - New Directions** Chair: Joseph Thywissen, U Toronto (Canada)

Quantum simulation of Fermi-Hubbard dynamics and bosonic Laughlin states

Markus Greiner, Harvard (US)

Cavity QED: from Many-body Physics to Transduction

Jonathan Simon, Stanford (US)

12:30 - 14:00 Closing Remarks & Farewell Reception

14:30 - 16:30 **Lab Tours at the University of Toronto** Department of Physics, 60 St. George Street

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ALPhANOV aims to boost innovation through collaboration between research and industry. It offers multiple modes of action which enable it to act all along the value chain: collaborative projects, feasibility studies, access to shared technical facilities, dedicated resources for companies and laboratories, technical support of entrepreneurship.

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Dear Colleagues and Friends,

It is with great pleasure that we welcome you to our beautiful city of Toronto and the Royal Conservatory of Music for the 27th edition of the International Conference on Atomic Physics, ICAP 2022.

First, we would like to thank all of you for your participation at the conference, and your willingness to travel despite the ongoing presence of COVID-19. The present meeting was originally scheduled for 2020, but has been postponed due to COVID-19 until 2022. We are aware that many of you have had difficulties in obtaining funding, visas, travel tickets, and many have travelled a long way to reach us. Thank you!

In the current edition of the ICAP we are proud to have an outstanding scientific program, reporting the main developments in the field in the last four years in the form of 33 invited talks, a selection of 8 hot topic presentations with recent relevant advances and the presentation of the IUPAP Young Scientist Prize. In addition, the conference will host four poster sessions where all the attendees will be able to present their recent research. Exceptional this year are over 70 virtual participants with 48 online-only abstracts of recent work. This, together with a limited social program with opening and closing receptions excursions and the well-known attractions of the city of Toronto, will certainly make your participation at the conference an unforgettable one. All this has been possible thanks to your participation, to our sponsors' support and to our helpers generous service. We do hope that you enjoy your attendance at the ICAP 2022!

Michal Bajcsy (Waterloo), ICAP27 Co-chair
Gordon Drake (Windsor), ICAP27 Co-chair
Joseph Thywissen (Toronto), ICAP27 Chair

Volunteers

We are especially grateful to the following people for their many hours of work in editing and revising this book of abstracts, and contributing in other ways to the success of the conference. Without their help, this book, graphic design, lab tours, and many other aspects of the planning process would not have been possible.

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Finally, we wish to thank the University of Toronto for its complete financial backing of the conference, and especially Physics Chairs Kimberly Strong and Michael Luke for their encouragement and moral support.

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Contents

Structure and properties of atoms, ions, and molecules 352

Invited talk / Mo-1:   *Quantum fluid dynamics*   ID400

New paradigms with dipolar quantum gases: Vortices, two-dimensional supersolidity, and angular responses

Author: Francesca Ferlaino

Institute for Experimental Physics, Universität Innsbruck, Austria & Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Science

Quantum physics often makes possible conceptual paradoxes that appear ephemeral to our classical intuition. A recent example is the discovery of supersolid states in ultracold dipolar gases. These states combine the properties of superfluidity with those of crystalline order.

This talk traces the fundamental steps for the observation of supersolidity in two dimensions from the perspective of the Innsbruck experiments. We will discuss how a quantum gas of erbium and dysprosium atoms spontaneously breaks its translational symmetry, creating a periodic modulation of its density while globally maintaining quantum phase coherence. We will show how in our experiments it is possible to access this exotic state of matter either by cooling a thermal gas or surprisingly by heating a superfluid. Finally, we will report on the recent observation of quantized vortices in dipolar condensates.

Invited talk / Mo-2:   *Quantum fluid dynamics*   ID401

A quantum vortex collider

Author: Giacomo Roati

CNR-INO and LENS, Florence, Italy

Quantum vortices occur in a wide range of systems, from atomic Bose–Einstein condensates to superfluid helium liquids and superconductors. Their dynamics is associated with the onset of dissipation, which makes the superflow no longer persistent. In this work, we study the fundamental mechanisms of vortex energy dissipation by realising a versatile two-dimensional vortex collider in homogeneous atomic Fermi superfluids across the BEC-BCS crossover. We unveil vortex-sound interactions by observing the conversion of the energy of vortex swirling flow into sound energy during vortex collisions. We visualise vortices annihilating into sound waves, i.e., the ultimate outcome of small-scale vortex collisions, and we find indications of the essential role played by vortex-core-bound fermionic excitations in strongly-correlated fermion superfluids. Our programmable platform opens the route to exploring new pathways for quantum turbulence decay, vortex by vortex.

Invited talk / Mo-3:   *Quantum fluid dynamics*   ID402

Generalized hydrodynamics in 1D Bose gases

Author: Isabelle Bouchoule

CNRS, Laboratoire Charles Fabry Institut d'Optique 2, avenue Augustin Fresnel 91127 Palaiseau Cedex FRANCE

Hydrodynamics describes long wavelength dynamics, which occurs on time scales long enough so that one can assume local relaxation of the gas. In a chaotic system, the gas is then locally described as a gas at thermal equilibrium, parametrized by three quantities, the local temperature, the local density and the local velocity. The dynamics is then captured by three equations describing the time evolution of these spatially dependent quantities. In an integrable system, the notion of relaxation is still meaningful, the relaxed state being however no longer described by only three numbers but by an infinite number of quantities, or equivalently by a function. The one-dimensional Bose gas with contact interactions is an integrable system and its relaxed state is described by the rapidities distribution. One then derives generalized hydrodynamics equations which describe the time evolution of the spatially dependent rapidity distribution. In this seminar we will present the experimental tests of the generalized hydrodynamic theory.

Invited talk / Mo-4:   *Qbits*   ID403

Interactions with pulses of quantum radiation

Author: Klaus Molmer

Niels Bohr Institute, University of Copenhagen, Denmark

Photons and phonons communicate interactions between distant material quantum systems, and wave packets of radiation may act as "flying qubits" and transmit quantum states and quantum gate operations in quantum optics and quantum information technologies. A theoretical description of how a wave packet of quantum radiation interacts with a local material quantum system is, hence, crucial and necessary, but no textbook provides a general description of this elementary process!

In the talk, I will show how to cast the problem in a form that permits a (simple) density matrix theory for the excitation of a general quantum system by an incident quantum pulse of radiation. This theory differs significantly from the treatment of interactions between, e.g., an atom and a single optical mode in cavity QED. In particular, our theory acknowledges the multi-mode character of the final state of the field and it permits evaluation of the quantum state of any outgoing wave packet mode. We present applications of the theory to recent experiments with atomic and superconducting systems that interact with pulses of optical, microwave and acoustic radiation.

Invited talk / Mo-5: *Qbits* ID404

Stabilisation of a logical grid-state qubit by laser cooling

Author: Jonathan Home

Trapped-Ion Quantum Information Institute of Quantum Electronics + Quantum Center ETH Zürich

Quantum computers will require error-correction in order to produce reliable results. At the lowest level, error-correcting codes require the encoding of information in a larger Hilbert space, such that measurements used for correction can avoid corrupting the logical information. An experimentally simple choice for this low-level encoding is to use harmonic oscillators, which have an infinite Hilbert space in a single quantum system. I will describe recent experiments using a single trapped ion in which we have realised quantum error correction on a harmonic oscillator code consisting of superpositions of displaced squeezed states which produce a grid-like periodic phase space array. Error information is periodically transferred to the internal electronic state, which is then repumped, offering an error correction cycle similar to laser cooling. We use this to perform >100 rounds of error correction, extending logical coherence of the encoded qubit by a factor of more than 3.

Invited talk / Mo-6: *Cavity QED* ID405

Atoms Interlinked by Light: Programming Interactions and Probing Entanglement

Author: Monika Schleier-Smith

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The graph of interactions in a quantum many-body system is crucial for governing the flow of information and the structure of correlations. We engineer programmable nonlocal interactions in an array of atomic ensembles within an optical resonator, where photons convey information between distant atomic spins. In our system of spin-1 atoms, the photon-mediated interactions manifest in the formation of correlated atom pairs. We verify the resulting entanglement by observations of spin-nematic squeezing. We furthermore demonstrate versatile tools for controlling the graph of interactions and the structure of multimode entanglement, including (1) programming the spectrum of a drive field and (2) supplementing global cavity-mediated interactions with local addressing. These techniques open opportunities in simulating quantum gravity, exploring quantum optimization paradigms, and generating entangled resource states for sensing and computation.

Invited talk / Mo-7:   *Cavity QED*   ID406

Entanglement-Enhanced Matter-Wave Interferometry in a High-Finesse Cavity

Author: James Thompson

JILA, University of Colorado, Boulder, CO 80309, USA

Entanglement is a fundamental resource that allows quantum sensors to surpass the standard quantum limit set by the quantum collapse of independent atoms. Collective cavity-QED systems have succeeded in generating large amounts of directly observed entanglement involving the internal degrees of freedom of laser-cooled atomic ensembles. Here we demonstrate cavity-QED entanglement of external degrees of freedom to realize a matter-wave interferometer of 700 atoms in which each individual atom falls freely under gravity and simultaneously traverses two paths through space while also entangled with the other atoms [1]. We demonstrate both quantum nondemolition measurements and cavity-mediated spin interactions for generating squeezed momentum states with directly observed metrological gain 3.4 dB and 2.5 dB below the standard quantum limit respectively. An entangled state is successfully injected into a Mach-Zehnder light-pulse interferometer with 1.7 dB of directly observed metrological enhancement. These results open a new path for combining particle delocalization and entanglement for inertial sensors, searches for new physics, particles, and fields, future advanced gravitational wave detectors, and accessing beyond mean-field quantum many-body physics.

[1] Graham P. Greve*, Chengyi Luo*, Baochen Wu, James K. Thompson arXiv2110.14027, to appear in Nature

Invited talk / Mo-8:   *Precision measurement I*   ID407

Atomic and nuclear clocks for testing fundamental physics

Author: Ekkehard Peik

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We use frequency comparisons between highly accurate optical clocks for tests of fundamental principles. In particular, the 171Yb+ optical clock based on an electric octupole (E3) transition between the S-ground-state and the lowest excited F-level with a radiative lifetime of 1.58 years provides a favorable combination of low systematic uncertainty and high sensitivity to potentially new physics. Using this system we have established improved limits for some violations of the Einstein equivalence principle, including the most stringent limits for temporal variations of the fine structure constant and the electron-proton mass ratio. In order to control or suppress the light shift in this optical clock based on a strongly forbidden transition we apply generalized Ramsey schemes and also the excitation of the ion in the dark center of a vortex beam.

I will give an outlook on the development of a 229Th nuclear optical clock that will open new perspectives for fundamental tests in atomic and nuclear physics. We have started experiments on laser spectroscopy of trapped thorium ions at about 150 nm wavelength with the aim to observe resonant laser excitation of the 8.3 eV nuclear transition.

Invited talk / Mo-9:   *Precision measurement I*   ID408

An improved measurement of the electron's electric dipole moment

Author: Eric Cornell

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The observed fact that the hadronic matter in the universe is overwhelmingly composed of matter and not antimatter tells us that there is at least one origin of CP violation that is not accounted for by the standard model of particle physics. It seems likely this as-yet uncharacterized CP-violating physics will give rise to electric dipole moments (EDM) in elementary particles. At JILA we use precision spectroscopy of trapped HfF+ to search for the electron's EDM. We anticipate that by the end of the summer we will have completed a new measurement with unprecedented accuracy. Looking five years out into the future, we think we can do yet another factor of five better in an experiment based around ThF+. We will discuss both the near-term and the longer-term project.

Invited talk / Tu-1:   *Quantum optics*   ID409

Many-body quantum optics in atomic arrays

Author: Ana Asenjo-García

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Atomic arrays are a unique platform for many-body physics, enabling efficient and controllable atom-atom interactions in crystal-like, ordered ensembles. In this talk, I will go beyond Hamiltonian dynamics, and discuss out-of-equilbrium physics of dissipative origin, where interactions are mediated by electromagnetic vacuum fluctuations and photon exchange. In particular, I will focus on the most paradigmatic many-body problem in quantum optics, Dicke superradiance, where a collection of initially-inverted atoms synchronizes as they decay, emitting a short and intense pulse of light. I will show that superradiance is a universal phenomenon in ordered arrays (either of atoms in free space or coupled to one-dimensional photonic channels), and is controlled by the lattice constant and array dimensionality. Our predictions can be tested in state of the art experiments with arrays of neutral atoms, molecules, and solid-state emitters and pave the way towards understanding the role of many-body decay in quantum simulation, metrology, and lasing.

[Prof. Asenjo Garcia is the 2022 laureate of the IUPAP Early Career Scientist Prize In Atomic, Molecular And Optical Physics.] "

Invited talk / Tu-2: *Quantum optics* ID410

Superradiance, Superabsorption and a Photonic Quantum Engine

Author: Kyungwon An

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A superradiant state is a special superposition state of atoms capable of undergoing superradiance immediately without the usual delay involved with Dicke states. We can prepare a superradiant state in a cavity by preparing N atoms in the same superposition state of the ground and excited states. By sending atoms through a nanohole array aperture with a period equal to the atomic transition wavelength, we can impose a common phase to all individual superposition states and localize the atoms exactly at antinodes of a cavity while they traverse the cavity. Surprisingly, these correlated atoms generate superradiance in the cavity even when the mean number of intracavity atoms is much less than unity. It turns out that these time-separated atoms are correlated via the long-lived cavity field so that a single intracavity atom can undergo superradiance as if the preceding atoms outside the cavity were also in the cavity. Another interesting feature of this superradiance is that the emission is amplified like a laser but without exhibiting a threshold. Through second-order-correlation measurements, we observed that the cavity field is coherent even when the mean number of photons is less than unity, in contrast to the thermal light emitted from the usual thresholdless lasers under the same condition.

The superradiant state can also be used to realize the long-sought superabsorption, the opposite of superradiance. It is well known that the bright state responsible for superradiance also has an absorption rate the same as the superradiant emission rate. This notion motivated theorists to suggest various ideas for realizing superabsorption, but none has worked so far. From theoretical considerations, we found that a superradiant state can absorb light instead of emitting light if its phase is chosen properly depending on the phase of the input field. Based on this idea, we have recently realized superabsorption by reversing the superradiance process in time. The maximum number of photons absorbed was proportional to the square of the number of atoms, proving the cooperative nature of superabsorption. In addition, the superradiant state can be used to realize a superradiant photonic quantum engine. Here, the atoms entering the cavity are our fuel and their nonzero excited state population can be associated with an effective temperature by the Boltzmann factor. Our engine operates between a thermal state and a superradiant state of reservoir at the same reservoir temperature. Photons emitted by superradiance exert radiation pressure to the cavity mirrors to perform a work. The observed efficiency of the engine was 98%. Our quantum engine can serve as a testbed for quantum thermodynamics in nanoscale systems.

Invited talk / Tu-3: *Quantum optics* ID411

Quantum optics with cold atoms trapped along nanowaveguides

Author: Julien Laurat

Laboratoire Kastler Brossel, Sorbonne Université, Paris, France

Considerable efforts have been recently devoted to combining ultracold atoms and nanophotonic devices to obtain not only better scalability and figures of merit than in free-space implementations, but also new paradigms for atom-photon interactions. Dielectric waveguides offer a promising platform for such integration because they enable tight transverse confinement of the propagating light, strong photon-atom coupling in single-pass configurations and potentially long-range atom-atom interactions mediated by the guided photons. In the talk, I will present our efforts in this emerging neutral-atom waveguide-QED field of research. Using nanofiber trapped atoms, we demonstrated the capability to herald, store and read out a single collective excitation that is preferentially coupled to the guided mode. In this nanofiber setting, using a dynamically-controlled Bragg configuration, we also recently pushed the nonlinearity down to the few-photon level. I will then describe our works towards stronger coupling in single pass by using photonic-crystal slow-mode waveguides with engineered dispersion. Localizing and trapping atoms in the proximity is a strong challenge and I will describe how novel structures and optical techniques can be used.

Invited talk / Tu-4: *Fermi gases* ID412

Compressibility and the equation of state of an optical quantum gas in a box

Author: Julian Schmitt

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Quantum gases of atoms, exciton-polaritons, and photons provide a test bed for many-body physics under both in- and out-of-equilibrium settings. Experimental control over their dimensionality, potential energy landscapes, or the coupling to reservoirs offers wide possibilities to explore phases of matter, for example, by probing susceptibilities, as the compressibility. For gases of material particles, such studies of the mechanical response are well established, in fields from classical thermodynamics to cold atomic quantum gases; for optical quantum gases, they have so far remained elusive.

In my talk, I will discuss experimental work demonstrating a measurement of the compressibility of a two-dimensional quantum gas of photons in a box potential, from which we obtain the equation of state for the optical medium. The experiment is carried out in a nanostructured dye-filled optical microcavity. We observe signatures of Bose-Einstein condensation at large phase-space densities in the finite-size system. Upon entering the quantum degenerate regime, the density response to an external force sharply increases, hinting at the peculiar prediction of a highly compressible Bose gas. In other recent work, we have demonstrated a non-Hermitian phase transition of an open photon Bose-Einstein condensate, which is revealed by an exceptional point in the fluctuation dynamics.

Invited talk / Tu-5: *Fermi gases* ID413

Higgs mode in a unitary Fermi gas

Author: Chris Vale

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Rapid quenches of the interactions in a strongly interacting Fermi superfluid can induce oscillations of the order parameter, commonly known as the Higgs amplitude mode. Here, we use Bragg spectroscopy to locally measure the time-resolved response of a Fermi gas following a quench to unitarity, directly revealing the amplitude oscillations. The normalised oscillation frequency, set by twice the pairing gap, remains relatively constant for temperatures below the superfluid transition while the oscillation amplitude displays a strong temperature dependence in good agreement with time-dependent BCS theory. The Higgs excitation decays according to a power law and we measure a damping exponent at unitarity approximately midway between the BCS and BEC limits.

Invited talk / Tu-6:   *New directions I*   ID414

Laser-driven and Magnetized Ultracold Neutral Plasmas

Author: Tom Killian

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Ultracold neutral plasmas (UNPs), created by photoionizing laser-cooled atoms just above threshold, stretch the boundaries of neutral plasma physics towards low energies and strong Coulomb coupling (measured by Γ, the ratio of the average Coulomb interaction energy to kinetic energy). Precise diagnostics and control over plasma conditions make UNPs useful for validating plasma theory and discovering new phenomena. In this talk, I will describe several experiments with UNPs formed by photoionizing an ultracold gas of neutral strontium atoms. Laser cooling of ions in the UNP yields ion temperatures as low as 50 mK and Coulomb coupling parameters as high as $\Gamma=11$. Electrons and Sr+ ions can be magnetized with experimentally accessible fields (~ 100 G). I will describe the use of laser-induced fluorescence to study the expansion of an UNP created in a quadrupole magnetic field and the first evidence of magnetic trapping of a UNP. This opens new possibilities for studying transport phenomena in strongly coupled and strongly magnetized systems.

Invited talk / Tu-7:   *New directions I*   ID415

Quantum Optics based on dipolar interactions between hot atoms

Author: Tilman Pfau

5. Physikalisches Institut, University of Stuttgart, Germany

Electrical dipolar interactions between Rydberg atoms are so strong that even for thermal atomic vapor the Rydberg blockade can be observed via the single photon emission of a blockaded ensemble. Additionally, the light induced dipolar interaction between two level atoms, the so-called Lorentz-Lorenz shift, can be observed in very thin cells as a 2D geometry of interacting dipoles as well as in 1D geometries, which are realized in integrated nano-photonic slot waveguides. The latter leads to a substantial and observable Purcell enhancement of the blue shift at telecom wavelengths due to the dipolar interaction. As an outlook we present the concept of an optical single thermal atom detector based on a freestanding photonic crystal cavity that enhances the atom light coupling to the strong coupling regime.

These examples of thermal atoms acting as a reconfigurable strongly nonlinear medium in integrated nano-photonic circuits show that quantum optical applications on the single photon level are within reach.

Invited talk / Tu-8: *Quantum simulation* ID416

A tunable spin Hamiltonian of dipolar molecules

Author: Jun Ye

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A degenerate Fermi gas of polar molecules [1] sets the stage to explore novel molecular dynamics. An external electric field is used to tune the elastic dipolar interaction by orders of magnitude while suppressing reactive loss. Efficient dipolar evaporation leads to the onset of quantum degeneracy in two-dimensional optical traps [2]. The electric field tuning of the rotational energy also produces sharp collision resonances, giving rise to three orders-of-magnitude modulation of the chemical reaction rate [3].

The precise control of electric field facilitates the preparation and addressing of isolated, individual two-dimensional layers of molecules with a free choice of rotational states. Spin exchange between molecules of neighboring layers occurs through the long-range dipolar interaction, demonstrating quantum-state engineered stereo chemical reaction [5]. Meanwhile, these interacting molecules in 2D are used to realize a fully tunable spin Hamiltonian, with both the Ising and spin exchange interactions precisely controlled via the electric field strength, orientation, and internal spin state. This work establishes an itinerant molecular spin platform to explore phenomena such as spin entanglement and spin transport mediated by the strong and tunable dipolar interaction.

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Invited talk / Tu-9:   *Quantum simulation*   ID417

Spin dynamics of ultracold atoms in optical lattices

Author: Wolfgang Ketterle

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Ultracold atoms offer a unique platform to perform quantum simulations of quantum materials and many-body systems. When atoms with spin are arranged in an optical lattice in form of a Mott insulator, they realize paradigmatic Heisenberg spin models, where only neighboring spins interact. Until very recently, all experimental studies with cold atoms addressed the special case of an isotropic Heisenberg model. Using lithium-7 atoms and Feshbach resonances to tune the interactions, we have created spin ½ Heisenberg models with adjustable anisotropy, including the special XX-model which can be exactly solved by mapping it to noninteracting fermions. Spin transport changes from ballistic to diffusive depending on the anisotropy. Special transverse spin patterns in the form of helices are exact eigenstates of the Heisenberg model and are called phantom states since they carry momentum, but no energy. We have realized these phantom helix states and used them to accurately measure the interaction anisotropy. We find major contributions from virtual molecules and short-range off-site interactions which had not been observed before.

Invited talk / We-1:   *Alkaline earth atoms*   ID418

Coherent Light Shift on Alkaline-Earth Rydberg Atoms

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Atoms presenting two valence electrons have an opportunity for optical manipulation of their Rydberg state thanks to the second (core-)electron transitions. Unfortunately, excitation of this electron then brings enough energy to ionize and auto-ionization usually takes place in less than a nanosecond, thus preventing any useful application. In order to allow such a manipulation, one could use the auto-ionization zeros observed long ago in the core-electron photo-excitation spectrum. They arise from the quantum interference between different ionization paths and can be understood within Multi-channel Quantum Defect Theory.

We will present our quantitative description of both the auto-ionization spectrum and of the induced light-shift when illuminating Yb Rydberg atoms in 6sns singlet states with light close to the Yb+ 6s-6p transition. We demonstrate experimentally for the first time the ability to apply a significant light-shift while keeping auto-ionization negligible. These results give high prospects for coherent state manipulation in quantum computation or quantum simulation platforms based on divalent Rydberg atoms. This effect will contribute in long term coherence of trapped atoms which can then remain trapped in their Rydberg states. It will also allow site addressing with focussed light acting solely on the Rydberg state while leaving the ground state untouched. A proof of principle has been recently demonstrated in Princeton group in a parallel study.

[1] N. H. Tran, R. Kachru, and T. F. Gallagher, Phys. Rev. A 26, 3016 (1982). [2] W. E. Cooke and C. L. Cromer, Phys. Rev. A 32, 2725 (1985). [3] K.-L. Pham, T. F. Gallagher, P. Pillet, S. Lepoutre, and P. Cheinet PRX Quantum 3, 020327 (2022) [4] A. P. Burgers, S. Ma, S. Saskin, J. Wilson, M. A. Alarcón, C. H. Greene, and J. D. Thompson PRX Quantum 3, 020326 (2022)

Invited talk / We-2: *Alkaline earth atoms* ID419

Probing Quantum Many-Body Dynamics with Tweezer Arrays

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Atom-by-atom assembly with optical tweezers enables the generation of defect-free atomic arrays with flexible geometric arrangements. Combined with controlled excitation to Rydberg states, this has become a highly versatile platform for quantum computing, simulation, and metrology. I will review these developments with a focus on two valence electron atoms: The rich level structure of such atoms enables novel cooling, control, and read-out schemes, which we have used in demonstrations of record imaging and two-qubit entanglement fidelities for neutral atoms.

Applying this high-fidelity approach to chaotic many-body dynamics, we recently uncovered the generation of random distributions of pure quantum states over a Hilbert space, emerging from either temporal sampling or partial projective measurements. Such random ensembles play an important role in quantum information science associated with device verification, supremacy tests, and quantification of complexity growth. Our work opens the door to applications of such concepts in an analog quantum simulation and many-body dynamics context; as a concrete example, I will show global fidelity estimation for highly entangled states in our Rydberg atom quantum simulator.

Invited talk / We-3:   *Alkaline earth atoms*   ID420

Quantum science with microscopically-controlled arrays of two-electron atoms

Author: Adam Kaufman

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Quantum science with neutral atoms has seen great advances in the past two decades. Many of these advances follow from the development of new techniques for cooling, trapping, and controlling atomic samples. In this talk, I will describe ongoing work where we have explored a new type of atom - two-electron atoms - for optical tweezer trapping. While their increased complexity leads to challenges, these atoms also offer new scientific opportunities by virtue of their rich internal degrees of freedom. Accordingly, they have impacted multiple areas in quantum science, including quantum information processing, quantum simulation, and quantum metrology. I will report on my group's progress in these areas.

Invited talk / We-4:   *Precision measurement II*   ID421

Accurate determination of the fine-structure constant using atom interferometry

Author: Saida Guellati-Khelifa

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Testing the standard model requires knowledge of the parameters that scale the fundamental inter actions. Among them is the fine-structure constant, α, which characterises the strength of the electromagnetic interaction, and thus plays a crucial role in quantum electrodynamics calculations. Using atom interferometry to measure the quotient $\hbar/m_{\mathrm{Rb}}$ of the reduced Planck's constant and the mass of a rubidium-87 atom, we obtained the most accurate determination of the fine structure constant $\alpha = 1/137.035999206(11)$ with a relative accuracy of 81 parts per trillion (ppt).

Our ultra-stable and robust experimental setup combines a Ramsey-Bordé interferometer based on Raman diffraction, with Bloch oscillations in an accelerated optical lattice. It allows us to achieve a record sensitivity to α of 4×10^{-11} in 48 h integration time. This enabled us to investigate experimentally several systematic effects, notably those related to wave-front distortions.

A test can be performed by comparing the Penning trap measurement of the electron gyromagnetic anomaly a_e to its Standard Model prediction. Using our new value of α, we observe a 1.6σ agreement. This result is the most stringent test of the standard model in the electron sector. However a discrepancy of 5.6σ is observed between our value and the one measured with cesium atoms by the Berkeley group. This discrepancy remains unexplained. Future measurements using a Bose-Einstein condensate and rubidium-85 atoms are in progress to investigate this issue.

This work is also part of an exciting research area beyond atomic physics. One of the objectives is to explain the persistent discrepancy of 4.2σ between the experimental value and the prediction of the standard model for the magnetic moment of the muon, by looking to see if such a discrepancy may be observed for the electron.

Invited talk / We-5:   *Precision measurement II*   ID422

A precision laboratory test of the gravitational redshift at the sub-cm scale

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The remarkable precision of optical atomic clocks offers sensitivity to new and exotic physics through tests of relativity, searches for dark matter, gravitational wave detection, and probes for beyond Standard Model particles. While much of optical clock research has focused on improving absolute accuracy, many searches for new physics can be performed with relative comparisons between two clocks. To this end, we have recently realized a "multiplexed" strontium optical lattice clock consisting of two or more clocks in one vacuum chamber. In comparisons between two spatially separated atom ensembles in the same lattice we observe atom-atom coherence times exceeding 26 seconds using correlated Ramsey spectroscopy and measure fractional frequency shifts at a precision below one part in 10^{19}.

In this talk I will explain the concept and operating principles of our multiplexed optical lattice clock. I will then present recent experimental results in which we performed a novel, blinded, precision test of the gravitational redshift with an array of 5 evenly-spaced atomic ensembles spanning a total height difference of 1 cm. I will present the error budget produced from our systematic evaluation, and the recently unblinded results of the test. I will also discuss how these results can also be viewed as a proof-of-principle demonstration of relativistic geodesy at the sub-cm scale. Finally, I will discuss the outlook for future searches for new physics with our apparatus.

Invited talk / We-6: *Nonequilibrium dynamics I* ID423

Ultrafast chirality: twisting light to twist electrons

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I will describe several new, extremely efficient approaches to chiral discrimination and enantio-sensitive molecular manipulation, which take advantage of ultrafast electronic response [1,2]. One of them is based on the new concept of synthetic chiral light [3,4], which can be used to trigger bright nonlinear optical response in the molecule of a desired handedness while keeping its mirror twin dark in the same frequency range. The other is based on the new concept of geometric magnetism in photoionization of chiral molecules and leads to a new class of enantio-sensitive observables in photoionization [5]. Crucially, the emergence of these new observables is associated with ultrafast excitation of chiral electronic or vibronic currents prior to ionization and can be viewed as their unique signature.

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Invited talk / We-7: *Nonequilibrium dynamics I* ID424

Nonequilibrium dynamics and sensing with large trapped-ion crystals

Author: John Bollinger

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I will describe experimental work measuring nonequilibrium quantum dynamics and sensing with single-plane crystals of up to 200 ions stored in a Penning trap. We engineer long range Ising interactions with a spin-dependent optical dipole force that couples the center-of-mass vibrational mode of the crystal with the collective electronic spin or qubit degrees of freedom of the ions. In a quench experiment the engineered interactions generate nonequilibrium quantum dynamics of the spin degrees of freedom, which we benchmark through measurements of out-of-time-ordered correlation functions (OTOCs) made possible by time reversing the interaction.

In a second experiment I will describe how the previously mentioned spin-motion coupling can be used to generate entangled states of the ions' spin and center-of-mass motional degrees of freedom that are sensitive to weak motional displacements. By entangling the center-of-mass oscillator with the collective spin before the motional displacement is applied and by controlling the coherent dynamics via time-reversal and a many-body echo that disentangles the spin and motion, we map the displacement into a spin rotation, avoid quantum back-action, and cancel thermal noise. We report quantum enhanced sensitivity to displacements of 8.8 dB below the standard quantum limit and 19 dB below thermal noise. The prospects of using this sensitivity to detect weak electric fields from dark matter will be discussed.

Invited talk / We-8: *Optical clocks* ID425

Optical atomic clocks – what challenges remain on the roadmap towards a redefinition of the SI second?

Author: Helen Margolis

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Over recent years, there has been enormous progress in the development of optical atomic clocks based on either atoms trapped in an optical lattice or single trapped ions. These optical clocks have demonstrated unprecedented frequency stability and estimated systematic frequency uncertainty, far surpassing the current generation of caesium microwave primary frequency standards, with the result that a future optical redefinition of the SI second is anticipated. However before this can happen several key challenges remain to be addressed.

First of all, the uncertainty budgets of the optical clocks need to be validated through a programme of international comparisons between systems developed independently by different research groups around the world. Continuity with the current caesium-based definition must also be ensured, by performing absolute frequency measurements with as low an uncertainty as possible. And finally, we need to improve the robustness of optical clocks and automate their operation, enabling them to be operated routinely as secondary representations of the second, regularly contributing to International Atomic Time (TAI) via reporting to the International Bureau of Weights and Measures, and being used to steer the local UTC(k) time scales maintained by national timing laboratories. I will discuss recent progress towards addressing these challenges, in particular drawing on examples of NPL work performed in the European collaborative project Robust Optical Clocks for International Timescales (ROCIT).

Invited talk / We-9: *Optical clocks* ID426

Making optical lattice clocks compact and useful for real-world applications

Author: Hidetoshi Katori

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An "optical lattice clock" benefits from a low quantum-projection noise by simultaneously interrogating many atoms trapped in an optical lattice. The essence of the scheme is an engineered perturbation based on the "magic wavelength" protocol, which has been proven successful up to 10^{-18} uncertainty. About a thousand atoms enable such clocks to achieve 10-18 stability in a few hours of operation. This superb stability is especially beneficial for chronometric leveling, which discriminates a centimeter height difference of the clocks located at distant sites by the gravitational redshift.

We overview the progress of optical lattice clocks and address recent topics to explore real-world applications of the 18-digit-accurate clocks, including 1) compact optical lattice clocks under development in collaboration with industry partners, 2) demonstration of an on-vehicle clock, and 3) our challenge to downsize of the clock as well as to improve the clock stability by "longitudinal Ramsey spectroscopy" that allows continuous interrogation of the clock transition.

Invited talk / Th-1:   *Quantum simulation of gauge theories*   ID427

Towards quantum simulation of U(1) LGTs with alkaline-earth-like atoms

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Well-controlled synthetic quantum systems, such as ultracold atoms in optical lattices, offer intriguing possibilities to study complex many-body problems in regimes that are beyond reach using state-of-the-art classical computations. The basic idea is to construct and use a well-controlled quantum many-body system in order to study its in- and out-of-equilibrium properties. An important future quest concerns the development of novel experimental techniques that allow us to expand the range of models that can be accessed. Simulating lattice gauge theories is a particularly promising direction, which combines a broad range of research areas including high-energy physics and topological quantum computation. One of the main challenges for quantum simulation of lattice gauge theories is to find resource-efficient implementations of the required local symmetries. Despite the recent experimental progress, there is no clear path towards implementations of lattice gauge theories in extended systems beyond one dimension or with non-Abelian symmetries. Here, I report on the development of a new hybrid optical lattice-tweezer platform that combines local state-dependent control of tunnel couplings with the unique properties of fermionic alkaline-earth-like atoms to realize $U(1)$ lattice gauge theories coupled to matter. Moreover, the $SU(N)$ symmetric interactions of fermionic Yb atoms pave the way towards novel schemes for the realization of more complex non-Abelian symmetries. Our scheme relies on correlated tunneling of fermionic atoms in a state-dependent programmable optical lattice. We have performed ab initio calculations of the lattice gauge theory dynamics, identifying suitable parameter regimes. On the experimental side we have performed measurements of the required laser wavelengths, which is the first step towards building the final lattice setup.

Invited talk / Th-2: *Quantum simulation of gauge theories* ID428

Engineering a topological gauge theory in an optically dressed Bose-Einstein condensate

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Topological gauge theories describe the low-energy properties of certain strongly correlated quantum systems through effective weakly interacting models. A prime example is the Chern-Simons theory of fractional quantum Hall states, where anyonic excitations emerge from the coupling between weakly interacting matter particles and a density-dependent gauge field. While in traditional solid-state platforms such gauge theories are only convenient theoretical constructions, engineered quantum systems enable their direct implementation and provide a fertile playground to investigate their phenomenology without the need for strong interactions. In my talk, I will present the quantum simulation of a one-dimensional reduction of the Chern-Simons theory, the chiral BF theory, in a Bose-Einstein condensate. Using the local conservation laws of the theory we eliminate the gauge degrees of freedom in favour of chiral matter interactions, which we engineer by synthesising optically dressed atomic states with momentum-dependent scattering properties. This allows us to reveal the key properties of the chiral BF theory: the formation of chiral solitons and the emergence of an electric field generated by the system itself. Our results expand the scope of quantum simulation to topological gauge theories and pave the way towards implementing analogous gauge theories in higher dimensions.

Invited talk / Th-3: *Quantum simulation of gauge theories* ID429

Simulating a lattice gauge theory with ultracold atoms

Author: Zhen-Sheng Yuan

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Gauge theories implement fundamental laws of physics by local symmetry constraints. For example, quantum electrodynamics and quantum chromodynamics are both based on gauge theories. However, the equations of gauge theories are usually hard to solve, forming exceptional challenges to supercomputer based numerical procedures.

We developed unique techniques of spin-dependent superlattices, microscopic absorption imaging, and number resolved detection. A new method of deep cooling in optical lattice is realized and a defect-free system is achieved for creating 1250 pairs of entangled atoms. Thanks to these advances, we implemented the Schwinger model with a Hubbard model in deep-lattice regime of a 71-site quantum simulator. We observed the interaction and conversion between matter fields and gauge fields and verified Gauss's law. The quantum simulator may be also used to study nonequilibrium lattice gauge systems, false vacuum decay, dynamical transitions related to the topological θ-angle, and thermal signatures of gauge theories under extreme conditions.

Invited talk / Th-4: *Molecules* ID430

Testing fundamental physics using laser cooled molecules

Author: Mike Tarbutt

Centre for Cold Matter, Blackett Laboratory, Imperial College London, Prince Consort Road, London SW7 2AZ, UK

Laser cooling of molecules is advancing rapidly. Magneto-optical traps have been developed for several species of diatomic and triatomic molecules. The molecules have been cooled to temperatures of a few microkelvin and confined in magnetic traps, optical dipole traps, tweezer traps and lattices. Collisions between the molecules, and between laser-cooled atoms and molecules, have been studied, with results suggesting that high phase space densities can be reached through sympathetic or evaporative cooling.

These ultracold molecules can be used to test fundamental physics. I will present progress on two experiments in this direction. In the first, we are developing a clock based on vibrational transitions in CaF molecules confined in a magic wavelength lattice. Pure vibrational transitions have little sensitivity to external perturbations so can make highly accurate clocks. By comparing to an optical atomic clock, we aim to measure variations in the electron-to-proton mass ratio. The molecular lattice clock could also provide improved frequency standards in the infra-red. In the second experiment, we aim to measure the electron's electric dipole moment using ultracold YbF molecules. I will present the construction of this experiment which features a slow-moving beam cooled below 100 µK in an extremely low magnetic noise environment.

Invited talk / Th-5: *Molecules* ID431

Quantum gas microscopy of polar molecules

Author: Zoe Z. Yan

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Ultracold molecules are a promising platform for quantum simulation of spin physics due to their long-range interactions and large set of internal states. To understand the complex many-body states that emerge in these systems in and out of equilibrium, new experimental techniques are needed to probe molecule correlations in the strongly-interacting regime. Here we study the site-resolved dynamics of spin correlations in a gas of ultracold 23Na 87Rb molecules in a 2D optical lattice.

We first form Feshbach molecules in the lattice before transferring them to the ground state via STIRAP with 85% one-way efficiency. We operate at near-magic trapping conditions where we prepare long-lived superpositions of the ground and first excited rotational states. The molecules realize a 2D quantum XY model with long-range interactions. Using a site-resolved Ramsey interferometric technique, we detect oscillations in nearest- and next-nearest-neighbor correlations due to spin interactions. Furthermore, we apply a periodic external microwave field to engineer XXZ spin Hamiltonians with tunable anisotropies. The correlations are measured by dissociating the molecules and detecting the corresponding Rb atoms with single-site resolution using a quantum gas microscope. The techniques presented here open new doors for probing quantum correlations in complex many-body systems of ultracold molecules.

Invited talk / Th-6:   *Precision measurement III*   ID432

Four-second optical coherence between different atomic species, and the search for new physics with atomic clocks

Author: David Leibrandt

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The extreme precision and accuracy of today's optical atomic clocks can be used to look for very small deviations from the predictions of the Standard Model, offering a tool to search for beyond Standard Model (BSM) physics complementary to particle accelerators. These searches are based on measuring the frequency ratio of two transitions that depend differently on interactions with BSM particles or fields. In this talk, I will present frequency ratio measurements between atomic clocks based on Al+, Hg+, Sr, and Yb atoms, and the use of these measurements to constrain the coupling of ultralight scalar dark matter candidates to the Standard Model. The precision of traditional, incoherent frequency ratio measurements and resulting constraints on BSM physics are limited by the coherence time of the lasers used to probe the atomic transitions. We have recently demonstrated a new, coherent frequency ratio measurement technique called differential spectroscopy that removes this limitation and achieved a record for the precision of frequency ratio measurements between different atomic species. I will conclude with a brief discussion of the prospects for optical clocks based on different atomic, molecular, and nuclear transitions with much higher sensitivity to BSM physics in a variety of sectors.

Invited talk /Th-7:   *Precision measurement III*   ID433

The proton size, the fine-structure constant and the electron electric dipole moment

Author: Eric Hessels

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Fundamental physics (including physics beyond the Standard Model) can be tested using table-top precision measurements. The talk will describe measurements of the size of the proton, the fine-structure constant and the electric dipole moment of the electron. Two recently completed measurements will be described. For the first measurement, the n=2 Lamb shift of atomic hydrogen is measured, allowing for a new determination of the charge radius of the proton. This determination is crucial to helping resolve the proton radius puzzle, in which it appeared that the proton radius took on a different value when measured with muons compared to measurements using electrons. The second measurement is of the n=2 triplet P fine structure of atomic helium, and this work is part of a program to obtain a new determination of the fine-structure constant. Both of these measurements use a new measurements technique: Frequency offset separated oscillatory fields. Finally, a new major effort (EDM^3) is starting to measure the electron electric dipole moment using polar molecules embedded into inert-gas solids.

Invited talk /Th-8: *Metrology* ID434

A Landau theory for spin squeezing

Author: Norman Yao

Department of Physics, University of California, Berkeley, California 94720, USA

Quantum metrology makes use of structured entanglement to perform measurements with far greater precision than would be possible with only classically correlated particles. A paradigmatic example of such entanglement is spin squeezing, which is known to be dynamically generated by the celebrated one-axis-twisting model, corresponding to an all-to-all coupled Ising Hamiltonian. Motivated by recent advances in a variety of quantum simulation platforms, there has been tremendous interest in the possibility of generating spin squeezing via Hamiltonians which do not require all-to-all interactions. This interest has centered on a class of power-law interaction models, corresponding to long-ranged generalizations of the so-called XXZ model. We conjecture that optimal spin squeezing in such models is intimately connected to the presence of finite-temperature, easy-plane ferromagnetism, which arises from the spontaneous breaking of a continuous symmetry. In particular, we demonstrate that if the temperature of the initial product state is below the ordering temperature for an XY ferromagnet, then the system will exhibit scalable spin squeezing. I will end by discussing some recent experimental efforts toward realizing spin squeezing in two dimensional ensembles of dipolar interacting spins.

Invited talk / Th-9: *Metrology* ID435

Time-reversal-based quantum metrology beyond the standard quantum limit

Author: Vladan Vuletic

Department of Physics, MIT-Harvard Center for Ultracold Atoms and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

Linear quantum measurements with independent particles are bounded by the Standard Quantum Limit (SQL) that can be overcome by inducing entanglement between the particles. In optical-transition clocks, entanglement can be induced by the collective interaction of the atoms with a cavity mode. We demonstrate cavity-induced, nearly unitary spin squeezing between the nuclear spin states of the electronic ground state of 171Yb. We transfer this entanglement onto the optical-clock transition, and demonstrate 4.4dB of spin squeezing on the clock transition, corresponding to a reduction of the clock averaging time by a factor of 2.8.

However, the metrological gain from entanglement is often limited by the final state readout rather than the state preparation, especially for more complex entangled many-body states with non-Gaussian probability distributions. An alternative is to use a time-reversal protocol to amplify small displacement of the entangled state. We implement such a time-reversal protocol through a controlled sign change in many-body Hamiltonian of atomic spins coupled to an optical cavity. With this approach, we demonstrate quantum measurement with non-Gaussian states with a precision improving in proportion to the particle number (Heisenberg scaling), at fixed distance of 12.6 dB from the ultimate Heisenberg Limit. Using a system of 350 neutral 171Yb atoms, this signal amplification through time-reversed interaction (SATIN) protocol achieves an improvement of 12 dB beyond the SQL in a Ramsey sequence. We also use the time-reversed Hamiltonian to experimentally investigate the relation between quantum information scrambling, out-of-time-order correlators and metrological gain.

Invited talk / Fr-1: *Cooling beyond atoms* ID436

Cooling nanoparticles in ion traps: a route to the quantum regime

Author: Tracy Northup

Research Center Technikerstraße 25/3 (Victor-Franz-Hess-Haus) 6020 Innsbruck, Austria

Recently, nanoparticles levitated in optical traps have been cooled to the motional ground state. This achievement can be seen as a starting point for preparing quantum-mechanical states of a nanoparticle's motion, such as macroscopic superposition states, building on established techniques for quantum control of atoms and molecules. A major hurdle, however, is the decoherence introduced in optical traps via both direct light scattering and particle heating. Here, I will present an alternate approach based on ion traps. We have recently demonstrated a new method for precise position measurement and cooling of (charged) nanoparticles in an ion trap, and I will describe prospects to extend this to all-electrical cooling. Furthermore, we will examine how techniques originally developed for trapped atomic ions, such as sympathetic cooling, can be transferred to the domain of nanoparticles.

Invited talk / Fr-2: *Cooling beyond atoms* ID437

Laser-cooled molecules, from controlled collisions to qbits

Author: Loic Anderegg

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Ultracold molecules have a wide range of potential applications spanning from fundamental physics to quantum simulation and computation. Motivated by potential discoveries in these areas, significant advances in controlling molecules at the single-quantum-state level have occurred over the past years. Progress in direct laser-cooling of molecules has led to the first molecular magneto-optical traps, which have allowed for optical trapping of ultracold molecules. Optical tweezer arrays have permitted both high-fidelity readout as well as quantum control of individual molecules. In this talk, we will discuss laser cooling of molecules into the ultracold regime and the creation of an optical tweezer array of CaF molecules with which we study ultracold collisions. By applying microwave radiation, we directly engineer and tune the interaction potentials between molecules, creating a repulsive shield which suppresses inelastic loss. This generalizable approach provides a route to creating dense, long-lived samples of ultracold molecules by applying evaporative cooling. We will also present data on rotational coherence times in optical tweezer traps, which parametrizes the potential performance of polar-molecule-based quantum simulators or computers. We will discuss progress we are making toward this goal with new larger arrays.

The rich structure of diatomic molecules that leads to powerful scientific avenues is qualitatively increased with polyatomic molecules. In particular, the presence of closely spaced opposite parity levels offers a new frontier in quantum science. We will present results on the laser-cooling and optical trapping of polyatomic CaOH molecules. Recent results on manipulation of states with the aforementioned parity doublet structure will also be presented.

Invited talk / Fr-3: *Cooling beyond atoms* ID438

Laser cooling of complex polyatomic molecules

Author: Debayan Mitra

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Compared to atoms and diatomic molecules, polyatomic molecules (those that contain three or more atoms) offer qualitatively distinct vibrational and rotational motions that are predicted to enable new opportunities in physics, chemistry, and quantum technology. For instance, all polyatomic molecules have long-lived rotational and vibrational states with angular momentum arising from nuclear motion (e.g. in a symmetric top molecule, the existence of nearly degenerate K states). These states offer distinct level structures, including full molecular polarization at low applied electric fields, along with field insensitive states, that form the core of proposals for improved quantum computation and precision measurement experiments. To fully leverage these features often requires ultracold temperatures. However, the structural asymmetries present nontrivial complications to laser cooling. It was previously unclear whether or not laser cooling would be limited to a select group of small (diatomic) species.

Recent theoretical and experimental work has shown that, in fact, many classes of complex molecules can potentially be tamed using rapid photon cycling and laser cooling. In this talk, we will review work aiming to extend direct laser cooling to complex polyatomic molecules, including both symmetric and asymmetric top species. We will describe the direct laser cooling of the symmetric top molecule $CaOCH_3$ using 1D Doppler and Sisyphus methods. We will next discuss theoretical proposals to extend laser cooling to asymmetric top molecules. As a specific example of interesting asymmetric top molecules, we will focus on aromatic rings (phenol and naphthol) adorned with optical cycling centers. We will describe the promise of these species for next-generation experiments and the possible challenges that must be overcome to bring this class of molecules into the ultracold regime. Though early in the evolution of this field, we are witnessing the rapid development of both tools and ideas to control complex molecules that are uniquely suited for next-generation experiments.

Invited talk / Fr-4: *New directions II* ID439

Quantum simulation of Fermi-Hubbard dynamics and bosonic Laughlin states

Author: Markus Greiner

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Quantum simulations with ultracold atoms in optical lattices expand into new regimes with ample room for discovery. I will present work that investigates the intricate interplay between spin and charge in the Fermi-Hubbard model, and that gives evidence for magnetic polarons, whose dynamics may explain emergent properties of quantum materials such as high-temperature superconductivity. We directly observe the formation dynamics and subsequent spreading of individual magnetic polarons, enabling the study of out-of-equilibrium emergent phenomena in the Fermi-Hubbard model, one dopant at a time. In our bosonic work we realize strongly correlated topological states of matter and find evidence for a two-particle fractional quantum Hall state following a bottom-up approach.

Cavity QED: from Many-body Physics to Transduction

Author: Jonathan Simon

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In this talk, I will describe recent developments in the Simon/Schuster collaboration, where we are harnessing cavity quantum electrodynamics for both manybody physics and quantum information. I will begin with an overview of our photonic quantum materials efforts, highlighting the analogy between photons in a lattice of cavities (or family of cavity modes) and electrons in a solids. After a brief summary of the broad range approaches we have explored for harnessing this analogy, I will specialize to our explorations of Hubbard physics in a quantum circuit, where we have demonstrated reservoir engineering approaches to stabilizing incompressible solids, and, more recently, disorder-assisted adiabatic approaches to preparation of compressible fluids. From here, I will change gears, introducing our quantum limited mmwave-to-optical transducer, based upon crossed optical and superconducting mmwave resonators. In this platform we have achieved >50% transduction efficiency with 100's of kHz of bandwidth, and less than one noise photon. Finally, I will conclude with my outlook on places where resonator technology has the potential to revolutionize modern quantum science.

Poster session / Mo-1: *At. mol. & charged-part. collisions* ID33

cold ion-molecule reactions relevant to astrochemistry

Authors: Olivia Krohn[1]; Katherine Catani[2]; Srivathsan Sundar[3]; James Greenberg[4]; Gabriel da Silva[3]; Heather Lewandowski[4]

[1] *JILA/CU Boulder*

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[3] *Department of Chemical Engineering, University of Melbourne*

[4] *JILA/Department of Physics at CU Boulder*

Laboratory measurements of cold ion-molecule collisions help to develop understanding of the dynamics and kinetics of interstellar chemistry. In our linear Paul ion trap, we trap ions at cold temperatures and react them with neutral molecules in an isolated environment. The products and branching ratios of these reactions are measured with high resolution with a time-of-flight mass spectrometer. Recently, we studied two reactions of interstellar importance ($C_2H_2^+$ + CH_3CN, acetonitrile and CCl^+ + C_6H_6, benzene) in this apparatus. Isotopologue substitution and quantum chemical calculations aid in identifying and analyzing the resulting products and branching ratios of these reactions. Both systems are potential pathways for the buildup of cyclic carbocations in the interstellar medium. The CCl^+ + benzene reaction, in particular, demonstrates potential as a participant in the growth of larger aromatics that occurs in the interstellar medium.

Presenter name: Olivia Krohn

Poster session / Mo-2:   *At. mol. & charged-part. collisions*   ID232

Exploring the lithium few-body puzzle with the DITRIS interferometer and with minimal multichannel models

Authors: Yaakov Yudkin[1]; Roy Elbaz[1]; Jose P. D'Incao[2]; Paul S. Julienne[3]; Lev Khaykovich[1]

[1] *Bar-Ilan University*

[2] *JILA, University of Colorado, Boulder*

[3] *JQI, University of Maryland*

In the vicinity of a Feshbach resonance only a handful of length scales, such as the scattering length and the effective range, determine the observed physics. Few-body observables, such as recombination loss maxima and minima, are related to the underlying length scales via universal theories. In particular, the Efimov-van-der-Waals universality relates the position of the first three-body recombination resonance on the negative scattering length side to the van-der-Waals length according to the Feshbach resonance strength. While numerous experiments in several species seem to verify this universality, Lithium was found to defy it.

Here we use coherent few-body spectroscopy (the DITRIS interferometer) to explore the positive scattering length side in Lithium. By creating a superposition of two different loosely bound states, Feshbach dimers and Efimov trimers, we measure the Efimov binding energy relative to that of the dimer. It is applied to the theoretically controversial and experimentally demanding regime, where the first excited trimer supposedly merges with the dimer-atom continuum. Contrary to the universal expectation we discover that it crosses into the continuum and remains a long-lived bound state.

In an attempt to explain this observation, we build minimal models including the dominant multichannel contributions to the long-range physics. In two separate models we add either an additional closed or open channel – both of which are present in Lithium. The failure of these models to replicate the experiment indicates that, in addition to the multichannel character of the interactions, the short-range details of the interaction potential are necessary. This is in stark contrast to the assumption of universality.

Presenter name: Yaakov Yudkin

Poster session / Tu-1: *At. mol. & charged-part. collisions* ID60

Tomography of Feshbach resonance states

Authors: Baruch Margulis[1]; Karl Horn[2]; Daniel Reich[2]; Mariusz Pawlak[3]; Piotr S Zuchowski[3]; Christiane Koch[2]; Ed Narevicius[1]

[1] *Weizmann Institute of Science*

[2] *Freie Universität Berlin*

[3] *Nicolaus Copernicus University*

Quantum phenomena that lead to the formation of long-lived collision complexes, such as scattering resonances play a central role in cold molecular collisions. These resonances are fundamental probes of the fine details of internuclear interactions and serve as a benchmark for current computational methods.

Here we present a joint experimental and theoretical study where we are able to generate and investigate the multi-channel decay of a Feshbach resonance state with quantum state-to-state resolution. Our method is based on the coincidence detection of electron/ion momenta in Penning ionization collisions between metastable noble gas atoms and neutral molecules. Here, in a single measurement, we obtain both the energy and the composition at the continuum of each resonance state. Such a tomography of the Feshbach resonance states provides several tens of quantum numbers per measurement. We show that our results deviate from a purely statistical approach where the probability to decay into each open channel scales as its degeneracy level.

We also present an experimental scheme for control of tomography of the Feshbach states which is based on the initial constraint of total angular momentum at the ionization step of the dynamics. The latter is motivated by our recent observation of a partial wave resonance at the lowest state of relative angular momentum.

Presenter name: Baruch Margulis

Poster session / Tu-2:   *At. mol. & charged-part. collisions*   ID235

Investigating ultracold collisions with ^{23}Na^{39}K ground-state molecules

Authors: Kai Voges[1]; Jakob Stalmann[1]; Philipp Gersema[1]; Mara Meyer zum Alten Borgloh[1]; Leon Karpa[1]; Silke Ospelkaus[1]

[1] *Leibniz University Hannover, Institute of Quantum Optics, Germany*

Ultracold ground-state molecular quantum gases and mixtures yield highly complex and mostly unknown scattering behavior. In molecule-molecule collisions it ranges from the formation of long-lived four-body complexes to subsequent chemical reactions [1], photo-excitation [2] or spontaneous spin relaxation [3]. Atom-molecule collisions can give rise to tunable interactions such as Feshbach resonances [4] and might be used for evaporative cooling of molecules or trimer formation.

Here, we present our investigations of collisions with ultracold bosonic and chemical stable ^{23}Na^{39}K ground-state molecules. In the pure molecular gas we probe photo-induced loss of four-body complexes in chopped optical dipole traps. We find the lower limit of the complex lifetime to be much larger than the lifetime derived from RRKM theory. In mixtures of ^{23}Na^{39}K ground-state molecules with dense ^{39}K atoms in different spin states, we find spin dependent loss rates. For one particular state of the ^{39}K atoms, we observe unexpected suppression of the loss rate of several orders of magnitude below the universal scattering limit.

We also present our approach for the detection of such collisional events and product particles by state-selective ionization and VMI mass spectrometry [5] for our ultracold ^{23}Na^{39}K ground-state molecules.

[1] Science, 2019, 366, 6469, 1111-1115
[2] Phys. Rev. Lett., 2020, 124, 163402
[3] arXiv, 2021, 2110.07501
[4] Science, 2019, 363, 6424, 261-264
[5] Phys. Chem. Chem. Phys., 2020, 22, 4861-4874

Presenter name: Kai Voges

Controlling reactive interactions with ultracold magnetic molecules

Authors: Giacomo Valtolina[1]; Johannes Seifert[1]; Sascha Schaller[1]; Nicole Walter[1]; Gerard Meijer[1]

[1] *Fritz Haber Institute*

We are realizing a new experiment for investigating and controlling ultracold chemical reactions. We plan to use mixtures of magnetic atoms and create molecular gases and atom-molecule mixtures with widely tunable interactions. Combining techniques from quantum optics and physical chemistry, we will develop new methods for shielding chemical reactions and stabilizing bosonic molecular gases.

Presenter name: Giacomo Valtolina

Poster session / We-2:   *At. mol. & charged-part. collisions*   ID359

Towards magnetoassociation of the ultracold open-shell RbSr molecule

Authors: Mateusz Borkowski[1]; Premjith Thekkeppatt[2]; Lukas Reichsöllner[3]; Benjamin Pasquiou[4]; Klaasjan Van Druten[2]; Florian Schreck[2]

[1] *Columbia University,*

[2] *University of Amsterdam*

[3] *Max Planck Institute of Quantum Optics*

[4] *Laboratoire de Physique des Lasers, CNRS*

Ultracold dipolar molecules offer an ideal platform for investigations in the fields of quantum simulation, precision measurement and quantum chemistry. The range of possibilities offered by ultracold molecules could be substantially extended by employing the previously unexplored class of open-shell molecules like RbSr. Thanks to its unpaired valence electron RbSr possesses both a magnetic and an electric dipole moment offering an additional level of control with new exciting possibilities for quantum simulations.

Here we present our novel quantum-engineering approach towards the production of ultracold open-shell RbSr molecules that utilizes an ultra-narrow magnetic Feshbach resonance at 1311 G. Due to its extremely low relative width on the order of 10^{-6}, this is a serious experimental challenge. Our state-of-the-art dual stabilization approach to the control of magnetic fields now enables us to achieve a relative magnetic field stability at the ppm level at fields beyond 1000 G.

As a real-life benchmark of the capabilities of our system, we efficiently produce Rb Feshbach molecules on an ultranarrow 1.3-mG-wide resonance at 911.7 G. This is the first time that Feshbach molecule association is successful for such a narrow relative width and it is a crucial step towards the ultimate goal of magnetoassociating RbSr molecules.

Presenter name: Mateusz Borkowski

Electric-field-controlled dipolar collisions between trapped polyatomic molecules

Authors: Florian Jung[1]; Manuel Koller[1]; Jindaratsamee Phrompao[1]; Martin Zeppenfeld[1]; Isabel M. Rabey[1]; Gerhard Rempe[1]

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Polar symmetric top molecules offer a multitude of interesting research opportunities as their permanent electric dipole moment makes them interact strongly and anisotropically and allows manipulating them already with moderate static electric fields. This, together with their wealth of internal states, permits studies and applications ranging from cold dipolar collisions to quantum information processing and quantum simulation. While their complexity is a blessing from an application perspective, it also renders trapping polyatomic molecules, achieving high densities and understanding as well as controlling collisions a challenging task.

By combining [1] a cryogenic buffer-gas cell with a centrifuge decelerator and an electrostatic trap [2], we can now confine up to 2×10^7 CH_3F molecules at a temperature of ~ 350 mK for several seconds, achieving densities of up to $10^7/cm^3$. Such high densities allow for the observation of collisions between the trapped molecules [3]. An ab-initio theory, taking into account both elastic and inelastic collisional loss channels, shows excellent agreement with our experiment and allows for the identification of dipolar relaxation as the major loss mechanism, accounting for $\sim 95\%$ of the observed losses. We obtain inelastic rate constants below $4 \times 10^{-8} cm^3/s$ and control and suppress the losses by tuning a homogeneous control field covering a large fraction of the volume of the trap. As understanding and suppression of these inelastic losses is imperative to proceed towards higher phase-space densities, our findings are immediately relevant for cold molecular collision studies and are an important step towards the observation of re-thermalisation between polyatomic molecules.

[1] X. Wu *et al.*, Science **358**, 645-648 (2017).
[2] B. G. U. Englert *et al.*, Phys. Rev. Lett. **107**, 263003 (2011).
[3] M. Koller *et al.*, Phys. Rev. Lett. **128**, 203401 (2022).

Presenter name: Florian Jung

Poster session / Th-2:   *At. mol. & charged-part. collisions*   ID383

Interactions and ultracold scattering of Cr with Yb

Authors: Matthew Frye[1]; Piotr Żuchowski[2]; Michał Tomza[1]

[1] *University of Warsaw, Poland*

[2] *Nicolaus Copernicus University in Toruń, Poland*

We investigate the scattering of a high-spin spherical atom Cr (^{7}S) with a closed shell atom Yb (^{1}S). We evaluate the spin-spin interaction arising from the multiple unpaired electrons from the Cr atom perturbed by the Yb atom, and show this provides a substantial coupling. We perform calculations of the magnetic Feshbach resonances this causes, and show are guaranteed to exist at low magnetic fields (below ~ 250 G) with experimentally useful widths, regardless of the scattering length. This system has advantages over other similar systems such as alkali-metal+alkaline-earth systems – where the resonances are extremely narrow – and systems involving nons-state atoms such as Er or Dy – which are extremely hard to make accurate microscopic models of. Applications of this system could include a starting point to form novel high-spin molecules or controlling interactions in a mixed gas of dipolar and nondipolar atoms.

Presenter name: Matthew Frye

Virtual poster / Vir1:   *At. mol. & charged-part. collisions*   ID230

nonBorn-Oppenheimer confined variational calculation of low-energy Ps-H2 scattering

Authors: Wang Du [1]; Meng-Shan Wu[2]; Jun-Yi Zhang[1]; Ying Qian[3]; Kalman Varga[4]; Zong-Chao Yan[5]

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[2] *School of Science, Hainan University, Haikou, China*

[3] *Department of Computer Science and Technology, East China Normal University, Shanghai, China*

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Using the confined variational method, the low-energy S-wave elastic scattering of positronium from molecular hydrogen is studied nonadiabatically at incident energy up to 0.13 eV [1]. Accurate S-wave phase shifts, scattering lengths, and cross sections are calculated and compared with other theoretical and experimental values. Using the modified effective range formula, the S-wave scattering length is determined to be 1.97 Bohr radii that is about 2.5% smaller than that of the confined variational calculation under the fixed nuclear approximation. The consistency of the present cross sections with those from the angular correlation of annihilation radiation experiment indicates that the results of Doppler broadening spectroscopy might be problematic. We also discuss the distortion effects of positronium and molecular hydrogen.

[1] W. Du, M.-S. Wu, J.-Y. Zhang , Y. Qian , K. Varga, and Z.-C. Yan, Phys. Rev. A **105**, 052809 (2022).

Presenter name: Jun-Yi Zhang

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online poster URL:

Virtual poster / Vir2: *At. mol. & charged-part. collisions* ID248

Toward coherent formation of ultracold single molecule arrays

Authors: Xiao-Dong He[1]; Kun-Peng Wang[1]; Cheng Sheng[1]; Jun Zhuang[1]; Ming-Rui Wei[1]; Peng Xu[1]; Min Liu[1]; Jin Wang[1]; Ming-Sheng Zhan[1]

[1] *Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences*

Compared with ultracold atoms, ultracold molecules possess richer internal structure that lend themselves useful for a variety of applications, such as ultracold chemistry, precision measurements, quantum simulation, and quantum computation and so on. A key ingredient in many of above proposed applications is the realization of such a single molecule array, where not only the quantum internal and external degrees of freedom of the individual molecules, but also the molecular interaction, and the numbers and species of molecules can be all controlled over. The relative research has been becoming an important frontier and hot topic in the worldwide [1]. To realize single molecule arrays, one can assemble molecules one by one from their constituent atoms individually trapped in the optical tweezers [2]. In this presentation, we will present the our recently experimental advances [3,4,5,6] towards assembly of single 87Rb85Rb molecules arrays.

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[4]K. P. Wang, J. Zhuang, X. D. He, et al., Chinese Phys. Lett.37,044209 (2020).
[5]X. D. He, K. P. Wang, J. Zhuang, et al., Science 370, 331-335 (2020).
[6]C. Sheng et al., Phys. Rev. Lett. 128, 083202 (2022).

Presenter name: Xiao-Dong He

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online poster URL:

Confined variational calculation of low energy Ps-Li$^+$ scattering

Authors: Deng-xin Zhao[1]; Jun-Yi Zhang[2]

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Interactions of positron and positronium (Ps) with atoms and ions have been extensively studied in recent years, with great attention being paid to the formation of weakly bound states of positronic complexes [1,2], the collision and electron-positron annihilation processes [3]. However, accurate *ab initio* description of these systems is challenging due to the complicated short-range correlations among particles. Utilizing the gradient-based optimization method [4,5] and the stochastic variational method (SVM) [6,7] with 4200 explicit correlated Gaussian (ECG) basis functions, we obtained the nonrelativistic energy -7.53241063 hartree for the ground state of Ps-Li$^+$(^1S), which has improved the previous value -7.53241048 hartree obtained by Bubin et al. [1] with 3000 ECGs. This improvement demonstrated that our program of the gradient-based optimization of ECGs' nonlinear parameters is correct and efficient. Therefore, the low energy Ps-Li$^+$ elastic scattering is studied with the confined variational method (CVM) developed by Mitroy et al. [8,9] and the gradient-based optimization method.

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Presenter name: Deng-xin Zhao

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Poster session / Mo-3:   *Degen. gases, many-body phys. & quant. sim.*   **ID5**

Simultaneous trapping and cooling of sodium and potassium atoms towards quantum degeneracy

Author: Sagar Sutradhar[1]

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We present the design, implementation and characterization of a new dual-species cold atomic mixture of ^{39}K and ^{23}Na with a large number of atoms. The dual species magneto-optical trap (MOT) has more than 10^{10} ^{39}K atoms and 5×10^9 ^{23}Na atoms, which are simultaneously loaded using two independent 2D$^+$MOT with high cold atomic beam flux. The dual cold atomic clouds were further cooled to tens of μK via sub-Doppler cooling and Gray molasses technique. The ^{23}Na and ^{39}K atoms are thereafter transferred into a quadrupole magnetic trap and transported towards the "Science cell" for further experiments. This versatile experimental system provides a favourable starting point for the realization of the quantum degenerate Bose-Bose mixture for quantum simulation with ultracold quantum gases in optical potentials.

Presenter name: Sagar Sutradhar

Synthetic dimensions of trap states in cold atoms

Authors: Aaron Smith[1]; Thomas Easton[2]; Christopher Oliver[2]; Nathan Goldman[3]; Grazia Salerno[4]; Giovanni Barontini[2]; Hannah Price[2]; Vera Guarrera[2]

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I will report on the first realisation of a very long and controllable synthetic dimension of atomic harmonic trap states [1]. To create this, we couple trap states by dynamically modulating the trapping potential of the atomic cloud with patterned light. By controlling the detuning between the frequency of the driving potential and the trapping frequency, we implement a controllable force in the synthetic dimension. This induces Bloch oscillations in which atoms move periodically up and down tens of atomic trap states. We experimentally observe the key characteristics of this behaviour in the real space dynamics of the cloud, and verify our observations with numerical simulations and semiclassical theory. This experiment provides an intuitive approach for the manipulation and control of highly-excited trap states, and sets the stage for the future exploration of topological physics in higher dimensions. I will also report on the realization and characterisation of optical potentials for ultracold atoms using a superluminescent diode [2]. The light emitted by this class of diodes is characterised by high spatial coherence but low temporal coherence. On the one hand, this implies that it follows Gaussian propagation similar to lasers, allowing for high intensities and well-collimated beams. On the other, it significantly reduces those interference effects that lead to severe distortions in imaging.
[1] arXiv:2112.10648
[2] arXiv:2109.05096

Presenter name: Aaron Smith

One- and two-axis squeezing via laser coupling in an atomic Fermi-Hubbard model

Authors: Tanausú Hernández Yanes[1]; Marcin Płodzień[2]; Mažena Mackoit Sinkevičienė[3]; Giedrius Žlabys[3]; Gediminas Juzeliūnas[3]; Emilia Witkowska[1]

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We study the Ramsey-type spectroscopy and the production of spin-squeezed states with ultra-cold atomic fermions described by the Fermi-Hubbard model in the Mott insulating regime. We show activation of two twisting mechanisms by a position-dependent laser coupling between internal degrees of freedom of atoms. A single laser coupling simulates the one-axis twisting model with the axis and direction of squeezing determined by the value of phase defining the atom-laser coupling. As such, adding a second laser beam with an adequately chosen phase paves the way to simulate the two-axis counter-twisting model, allowing reaching the Heisenberg-limited level of squeezing. The scheme can be implemented readily in state-of-the-art optical lattice clocks.
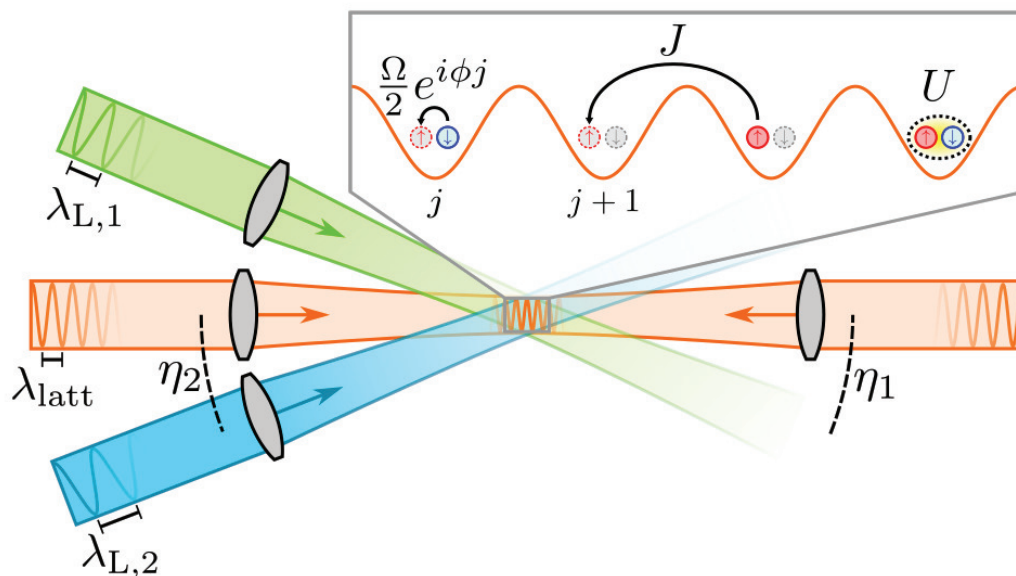
Figure 1: Fermi-Hubbard model (FHM) for atoms in optical lattices or tweezer arrays with nearest-neighbor tunneling rate J, on-site interaction U and additional coupling between atomic internal degrees of freedom with position-dependent strength $\Omega e^{i\phi j}$. The coupling can be realized with one or two off-resonant laser beams.

Presenter name: Hernández Yanes, Tanausú

Emergent atom pump in a nonhermitian system

Authors: Simon Hertlein[1]; Davide Dreon[1]; Alexander Baumgärtner[1]; Xiangliang Li[1]; Tilman Esslinger[1]; Tobias Donner[1]

[1] *ETH Zurich*

The time evolution of a quantum system can be strongly affected by dissipation. Although this mainly implies that the system relaxes to a steady state, in some cases it can make new phases appear and trigger emergent dynamics. In our experiment, we study a Bose-Einstein Condensate dispersively coupled to a high finesse resonator. The cavity is pumped via the atoms, such that the sum of the coupling beam(s) and the intracavity standing wave gives an optical lattice potential. When the dissipation and the coherent timescales are comparable, we find a regime of persistent oscillations where the cavity field does not reach a steady state. In this regime the atoms experience an optical lattice that periodically deforms itself, even without providing an external time dependent drive. Eventually, the dynamic lattice triggers a pumping mechanism. We show complementary measurements of the light field dynamics and of the particle transport, proving the connection between the emergent nonstationarity and the atomic pump.

https://arxiv.org/abs/2112.11502

Presenter name: Simon Hertlein

Poster session / Mo-7: *Degen. gases, many-body phys. & quant. sim.* ID73

From a polaron into a cluster: the fate of an impurity in a Bose-Einstein condensate

Authors: Arthur Christianen[1]; J. Ignacio Cirac[1]; Richard Schmidt[2]

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[2] *Max-Planck-Institute of Quantum Optics and MCQST, Garching, Germany*

Ultracold atomic gases can be used to simulate phenomena from condensed matter physics, such as the formation of polaron quasiparticles. However, at strong coupling a Bose polaron formed by an impurity atom in a Bose Einstein condensate (BEC) displays fascinating behavior quite distinct from the common condensed matter scenario. This is due to the possibility of bound state formation and the Efimov effect, which leads to attractive impurity-mediated interactions between the bosons from the BEC. In particular, the intricate competition between these impurity-mediated interactions and the intrinsic interboson repulsion plays an important role. In our work we fully incorporate both of these processes and compare different variational methods to form a complete theoretical picture of the strong coupling Bose polaron. We find two parameter regimes with qualitatively different behavior. For light impurities and weak repulsion, the impurity-mediated interactions dominate and we find a polaronic instability due to the formation of large Efimov clusters. For strong repulsion or heavier impurities, we find that the formation of large clusters and the polaronic instability are prevented, and that there is a smooth crossover into a small cluster or molecule instead.

Presenter name: Arthur Christianen

From superradiance to subradiance : exploring the many-body Dicke Ladder

Authors: Antoine Glicenstein[1]; Giovanni Ferioli[1]; Antoine Browaeys[1]; Igor Ferrier-Barbut[1]

[1] *Institut d'Optique*

We are interested in the problem of light scattering by a dense ensemble of two-level atoms in a regime close to the Dicke regime, in which many atoms are trapped in a volume whose dimensions are smaller than the wavelength of the atomic transition. When the medium is dense and the frequency of the light is close to that of an atomic transition, the light-induced dipoles interact with each other. These resonant interactions between the dipoles modify the collective response of the ensemble. Here we report a time-resolved study of collective emission in dense ensembles of two-level atoms.

We compare, on the same sample, the build-up of superradiance and subradiance from the ensemble when driven by a strong laser. This allows us to measure the dynamics of the population of superradiant and subradiant states as a function of time. We demonstrate the buildup in time of subradiant states through the superradiant dynamics. This illustrates the dynamics of the many-body density matrix of superradiant ensembles of two-level atoms when departing from the ideal conditions of Dicke superradiance in which symmetry forbids the population of subradiant states.

Presenter name: Antoine Glicenstein

Poster session / Mo-9: *Degen. gases, many-body phys. & quant. sim.* ID91

Emergent spin dynamics in a superradiant quantum gas: from dynamical tunnelling to atomic mode parametric amplifiers

Authors: Rodrigo Rosa-Medina[1]; Fabian Finger [1]; Nicola Reiter[1]; Francesco Ferri[1]; Tobias Donner[1]; Tilman Esslinger[1]

[1] *ETH Zurich*

Dynamic transients are a natural ingredient of out-of-equilibrium quantum systems. One paradigmatic example is Dicke superradiance, describing the collectively enhanced population inversion of an ensemble of two-level atoms coupled to a single mode of the electromagnetic field.

Here, we present a new approach exploiting superradiance to engineer dynamical tunneling in a synthetic lattice geometry. Our experimental implementation is based on a spinor Bose-Einstein condensate (BEC), which is coupled to a single mode of an ultrahigh-finesse optical cavity [1]. Transverse laser fields induce cavity-assisted Raman transitions between discrete momentum modes of two spin levels, which we interpret as photon-assisted tunnelling in a momentum-space lattice. In particular, the tunnelling rate evolves dynamically with the emergent cavity field. By monitoring the cavity leakage, we gain real-time access to the lattice currents and benchmark their collective behaviour [2].

In a series of recent experiments, we engineer an atomic mode parametric amplifier induced by virtual cavity photons. The spinor BEC is initialized in the $|F = 1, m_F = 0\rangle$ Zeeman sublevel (pump mode), and correlated pairs of atoms in $|m_F = 1\rangle$ (signal and idler modes) are created by four-photon processes, which involve scattering of virtual cavity photons in a far-detuned regime. The pair production is highly nonlinear, as evidenced by its scaling with atom number. Moreover, the spin pairs are ejected out of the BEC with opposite relative momenta, in resemblance parametric four-wave mixing. While similar to collisional spin-mixing dynamics [3], the timescales of this process (~10 s) are significantly faster, providing prospects rapid entanglement production in cold atom experiments.

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Presenter name: Rodrigo Rosa-Medina

Poster session / Mo-10:   *Degen. gases, many-body phys. & quant. sim.*   ID103

Spin-charge separation in a 1D Fermi gas with tunable interactions

Authors: Ruwan Senaratne[1]; Danyel Cavazos-Cavazos[1]; Sheng Wang[2]; Feng He[3]; Aashish Kafle[1]; Ya-Ting Chang[1]; Han Pu[1]; Xi-Wen Guan[2]; Randall Hulet[1]

[1] *Rice University*

[2] *Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences*

[3] *SISSA, Trieste*

Ultracold atoms confined in optical lattices are a powerful platform for quantum simulation of complex many-body systems. We confine spin-1/2 atomic fermions (^{6}Li) to one dimension and realize the Yang-Gaudin model, the low-energy behavior of which is expected to be that of a Tomonaga-Luttinger liquid [1]. Such liquids exhibit bosonic collective low-energy excitations and spin-charge separation. Using Bragg spectroscopy and a Feshbach resonance, we directly excite either the spin or charge wave with a tunable repulsive interaction strength. We observe the onset of spin-charge separation as interactions are increased from zero. The spin and charge excitation velocities are equal for the noninteracting case, while the charge-mode velocity increases and the spin-mode velocity decreases with increasing interaction, a hallmark of spin-charge separation. The excitation spectra provide access to the dynamic structure factors of each mode, which are in quantitative agreement with the Tomonaga-Luttinger liquid theory, including nonlinear corrections due to band-curvature and backscattering.

[1] Ruwan Senaratne, Danyel Cavazos-Cavazos, Sheng Wang, Feng He, Aashish Kafle, Ya-Ting Chang, Han Pu, Xi-Wen Guan and Randall G. Hulet, arXiv:2111.11545 [cond-mat.quant-gas]

Presenter name: Ruwan Senaratne

Poster session / Mo-11:   *Degen. gases, many-body phys. & quant. sim.*   ID127

Orbital Feshbach molecules

Authors: Yann Kiefer[1]; Max Hachmann[1]; Andreas Hemmerich[1]

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Spin-polarized samples, spin mixtures and Feshbach molecules of quantum degenerate fermionic atoms are prepared in selected excited Bloch bands of an optical chequerboard square lattice. For the spin-polarized case, extreme band lifetimes above 10 s are observed, reflecting the suppression of collisions by Pauli's exclusion principle. For spin mixtures, lifetimes are reduced by an order of magnitude by two-body collisions between different spin components, but still remarkably large values of about one second are found [1].

Access to a broad Feshbach resonance allows for precise control of the interactions between atoms and molecules. Collision dynamics and binding energies of orbital Fermi gases in the unitary regime and are investigated for the first time. Remarkably long lifetimes of dimers in the second Bloch band on the onset of the unitarity regime are observed. By analyzing momentum spectra and band populations, we can directly observe the orbital character of the optical lattice.

[1] M. Hachmann et al., Phys. Rev. Lett. 127 033201, July 2021

Presenter name: Yann Kiefer

Poster session / Mo-12:   *Degen. gases, many-body phys. & quant. sim.*   ID132

Catalyzation and domain supersolidity in binary dipolar condensates

Author: Luis Ardila[1]

Co-authors: Thomas Bland [2]; Daniel Scheiermann [3]; Russell Bisset [4]; Luis Santos [3]

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Breakthrough experiments have newly explored the fascinating physics of dipolar quantum droplets and supersolids. The recent realization of dipolar mixtures opens further intriguing possibilities. We show that under rather general conditions, the presence of a second component catalyzes droplet nucleation and supersolidity in an otherwise unmodulated condensate. For miscible mixtures, droplet catalyzation results from the effective modification of the relative dipolar strength, and may occur even for a surprisingly small impurity doping. We show that different ground states may occur, including the possibility of two coexisting interacting supersolids [1,2].

In addition, we predict the existence of a binary supersolid state in which the two components form a series of alternating domains, producing an immiscible double supersolid. Remarkably, we find that a dipolar component can even induce supersolidity in a nondipolar component. In stark contrast to single-component supersolids, the number of crystal sites is not strictly limited by the condensate populations, and the density is hence substantially lower. Our results are applicable to a wide range of dipole moment combinations, marking an important step towards long-lived bulk-supersolidity [3].

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[3] Thomas Bland, Elena Poli, Luis A. Peña Ardila, Luis Santos, Francesca Ferlaino, Russell N. Bisset. arXiv:2203.11119 (2022)

Presenter name: Luis A. Peña Ardila

Poster session / Mo-13:   *Degen. gases, many-body phys. & quant. sim.*   ID145

Universal properties of anisotropic dipolar bosons in two dimensions

Authors: Juan Sánchez-Baena[1]; Grigory Astrakharchik[2]; Luis Peña Ardila[3]; Ferran Mazzanti[2]

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[2] *Departament de Física, Campus Nord B4-B5, Universitat Politècnica de Catalunya, E-08034 Barcelona, Spain*

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The energy of ultra-dilute quantum many-body systems is known to be a universal function of the gas parameter $x = na_0^d$, where n is the density, a_0 the s-wave scattering length, and d the dimensionality of the space (d = 1, 2, 3) [1]. The universal regime typically holds only at small x and extends up to values no larger than 0.001 [2,3]. Beyond that point, specific details of the interaction start to be relevant, and different interactions with the same s-wave scattering length lead to different predictions. Dipolar systems are peculiar in this regard since the anisotropy of the interaction makes a_0 depend on the polarization angle α, in such a way that different combinations of n and α value of the gas parameter x [4]. In this work we analyze the scaling properties of a system of polarized dipolar bosons in two dimensions as a function of the density and polarization dependent scattering length, up to very large values of x. We study the energy per particle and main structural properties of the ground state as a function of the density and scattering length at fixed gas parameter. We find that the dipolar interaction shows relevant scaling relations up to unusually large values of x that hold almost to the boundaries in the phase diagram where a transition to a stripe phase takes place. The impact of the anisotropy of the interaction in this context is also analyzed.

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Presenter name: Ferran Mazzanti

Poster session / Mo-14: *Degen. gases, many-body phys. & quant. sim.* ID158

Quantum Rabi dynamics of trapped atoms far in the deep strong coupling regime

Authors: Geram Hunanyan[1]; Johannes Koch[1]; Stefanie Moll[1]; Enrique Rico[2]; Enrique Solano[3]; Martin Weitz[1]

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The coupling of a two-level system with a field mode, whose fully quantized field version is known as the *quantum Rabi model* (QRM), is among the central topics of quantum physics and recent quantum information technologies. When the coupling strength reaches the field mode frequency, the full QRM Hamiltonian comes into play, where excitations can be created out of the vacuum.

We demonstrate a novel approach for the realization of a periodic variant of the quantum Rabi model using two coupled vibrational modes of cold atoms in optical potentials, which has allowed us to reach a Rabi coupling strength of 6.5 times the bosonic field mode frequency, i.e., far in the so called deep strong coupling regime. For the first time, the coupling term dominates over all other energy scales. Field mode creation and annihilation upon e.g., de-excitation of the two-level system here approach equal magnitudes, and we observe the atomic dynamics in this novel experimental regime, revealing a subcycle timescale raise in field mode excitations, in good agreement with theoretical predictions. We have also studied the *collapse and revival* of the initial state in the system. The current experimental status will be presented.

Presenter name: Geram Hunanyan

Poster session / Mo-15:   *Degen. gases, many-body phys. & quant. sim.*   ID173

Parametric excitations in a quantum gas with Bogoliubov-de Gennes method

Authors: Alejandra del Rio Lima[1]; Jorge Amin Seman Harutinian[2]; Rocío Jáuregui Renaud[2]; Freddy Jackson Poveda Cuevas[3]

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[2] *Instituto de Física, Universidad Nacional Autónoma de México*

[3] *Cátedras CONACYT; Instituto de Física, Universidad Nacional Autónoma de México*

Quantum gases of bosons and fermions behave as superfluids, and for parametric excitations, the sample exhibit Faraday Waves, which obey a Mathieu equation. Therefore, to generate them, we need to consider a periodic modulation in a parameter of the system, e.g., the trap frequencies or contact interaction. From the experimental point of view, these excitations are manifested in trapped gas when the density pattern appears. Theoretically, these phenomena have been studied in a variational approximation using mean-field equations. For the case of a Bose-Einstein Condensate, the system is described by the Gross-Pitaevskii equation, and for a Fermi Unitary Gas the Extended Thomas-Fermi model is used. However, we believe that the natural way to study these excitations is using Bogoliubov-de Gennes (BdG) method, where the density modulation generates the excitations (phonons). The usual treatment in this theory is to consider a homogeneous gas. In this context, we present the description of Faraday waves using BdG method. As preliminary results, we consider a homogeneous case with a modulation of the contact interaction.

Presenter name: Alejandra del Río Lima

Poster session / Mo-16: *Degen. gases, many-body phys. & quant. sim.* ID192

Quantum simulation with Rydberg states of lanthanide atoms

Authors: Samuel J. M. White[1]; Hagai Edri[1]; Julián G. Maloberti[2]; Antonio Ortu[3]; Manfred J. Mark[3]; Francesca Ferlaino[3]

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Lanthanide atoms provide a rich platform for a number of ultracold atom experiments due to their variety of available optical transitions, strong anisotropic interactions and the large spin space of their fermionic ground states [1]. Leveraging these properties alongside the large, programmable defect-free arrays of qubits that can be realised using optical tweezer arrays of Rydberg atoms promise to provide exciting systems for quantum simulation. Recent works using ytterbium have already demonstrated an enhanced tweezer loading scheme [2] and indicated that trapping Rydberg states is possible [3].

We present our progress in implementing a quantum simulator utilising Rydberg states of erbium trapped in an optical tweezer array. We have already identified approximately 550 states in the erbium Rydberg series including a possible state from the *ng* series to which excitation is only possible due to the incompletely filled erbium *f*-shell [4]. Within our system the large 7/2 nuclear spin of the fermionic ^{167}Er isotope will allow us to implement computational schemes involving up to 8-level qudit states. Additionally, we expect to find a large range of trappable erbium Rydberg states in our optical tweezers.

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Presenter name: Samuel White

Poster session / Mo-17:   *Degen. gases, many-body phys. & quant. sim.*   ID208

Dynamics following an interaction quench in the BEC-BCS crossover and machine-learning the phase diagram

Authors: Moritz Breyer[1]; Andreas Kell[1]; Daniel Eberz[1]; Martin Link[1]; Michael Köhl[1]

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With a specially designed coil [Rev. Sci. Instrum. **92**, 093202 (2021)], we quench the interaction strength of an ultracold cloud of ^{6}Li atoms instantaneously, i.e. faster than the Fermi time. In the short time dynamics following the quench we observe first indications of an oscillation in the condensate fraction reminiscent of the Higgs-mode.

The observation was facilitated by a deep neural network trained to determine the amount of superfluidity in the cloud from simple time-of-flight images. This quantity is hidden for conventional fitting techniques, especially under real experimental conditions.

We record a high-resolution phase diagram of the BEC-BCS crossover with the neural network and show that such networks are also able to detect the existance of a phase transition without any additional training input.

Presenter name: Moritz Breyer

Poster session / Mo-18: *Degen. gases, many-body phys. & quant. sim.* ID224

Cavity-QED quantum simulator of random spin models

Author: Nick Sauerwein[1]

Co-authors: Francesca Orsi [1]; Philipp Uhrich [2]; Soumik Bandyopadhyay [2]; Francesco Mattiotti [3]; Tigrane Cantat-Moltrecht [1]; Philipp Hauke [2]; Guido Pupillo [3]; Jean-Philippe Brantut [1]

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My poster will present a cavity QED experiment where we use ^{6}Li atoms to perform quantum simulations of random spin models.

The atom-cavity system realizes a spin chain with random transition frequencies coupled to an extended photon mode, with controlled disorder realized by a local light-shift of the excited state of the atoms. We study the competition between the collective many-body physics and the disorder in two regimes: in the near-resonant regime, N spins with random energies are coupled to a bosonic mode [1]. In the dispersive regime, one can adiabatically eliminate the cavity to obtain long-range spin-exchange interactions [2]. The effective Hamiltonian can be rewritten in terms of N spins precessing around an external magnetic field with random inhomogeneities. We measure the magnetic susceptibility of the system as a function of the disorder strength and observe the fragmentation of the collective Dicke excitations into semi-localized grey states.

As an outlook, my poster will discuss possible perspectives on using cavity-mediated interaction in combination with our light-shifting technique for the quantum simulation of holographic matter such as SYK-type models [3].

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Presenter name: Nick Sauerwein

Laser cooling Cd atoms and AlF molecules in the deep UV

Authors: Simon Hofsäss[1]; Maximilian Doppelbauer[1]; Eduardo Padilla[1]; Sebastian Kray[1]; Russell Thomas[1]; Sidney Wright[1]; Gerard Meijer[1]; Stefan Truppe[2]

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We present our recent results on the fast loading of a dense magneto-optical trap (MOT) of Cd atoms from a pulsed cryogenic helium buffer gas beam. We can load more than 10^7 atoms of each Cd isotope in less than 10 ms from a single atomic pulse and reach densities well above 10^{11} cm^{-3} by using the strong transition in the deep ultraviolet near 229 nm. The Cd MOT serves as a starting point for precise isotope shift measurements to search for new physics beyond the Standard Model of particle physics. In addition, Cd is an excellent species to test our MOT apparatus to cool the diatomic, polar and deeply bound molecule AlF using the strong $A^1\Pi \leftrightarrow X^1\Sigma^+$ transition near 227.5 nm. We demonstrate the efficient production of AlF, and the implementation of a simple and fast optical cycling scheme. As a first application, we reduce the transverse temperature of a molecular beam of AlF by using a blue-detuned optical molasses. Finally, we discuss the implementation of a Zeeman slower and a MOT for AlF.

Presenter name: Stefan Truppe

On Demand Formation of Polar Core Vortices in Ferromagnetic Spinor Bose Einstein Condensates

Authors: Zachary Kerr[1]; Guillaume Gauthier[2]; Halina Rubinsztein-Dunlop[2]; Tyler W. Neely[2]; Matthew J. Davis[3]

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Spinor BECs are Bose-Einstein condensates (BECs) where all the spin states $\{m_F = +1, 0, -1\}$ of the atom are accessible [1]. These novel ultracold atomic systems can exhibit both ferromagnetic and antiferromagnetic order and thus offer enhanced opportunities for exploring phenomena beyond those accessible in scalar BECs, such as new classes of topological defects [2]. The polar core vortex (PCV) is one such topological defect occurring in the easy-plane phase of ferromagnetic spinor BECs. A PCV exhibits 2 spin circulation, but with zero mass circulation where the vortex core is populated by unmagnetized atoms in the $m_F = 0$ state. The first experimental observation of a PCV was achieved by Sadler et al [2] in 2006, where the vortex spontaneously formed during a magnetic field quench. Due to the nondeterministic nature of creating PCVs, further experimental study of their properties and dynamics has been limited. Controlled creation of PCVs can enable such studies, including few-body PCV dynamics, PCV turbulence, and the equilibrium dynamics of PCV systems. In this work, we describe our efforts to realize on-demand PCV creation in quasi-2D $Rb^8 7$ spinor BECs with uniform density enabled by digital-micromirror devices (DMD) optical traps [3].

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Presenter name: Zachary Kerr

Poster session / Mo-21:   *Degen. gases, many-body phys. & quant. sim.*   ID296

Many-body quantum necklace states in waveguide QED

Author: Daniel Goncalves-Romeu[1]

Co-authors: Gian-Marcello Andolina [1]; Darrick E. Chang [1]

[1] *Institute of Photonic Sciences (ICFO)*

The field of waveguide QED, where atoms (real or artificial) are coupled to one-dimensional waveguides, has attracted immense theoretical and experimental interest recently. However, despite the huge body of research, our understanding of the many-body regime consisting of many atoms and photons remains limited. This stems partly from the usual challenge of many-body systems – the exponentially large Hilbert space size – and also from the intrinsically open and nonequilibrium nature of waveguide QED systems. Recently, it has been theorized that the dynamics in disordered waveguide QED systems can exhibit a many-body localized phase, where the underlying Hamiltonian becomes diagonalizable in terms of local integrals of motion and the dynamics can be solved in a nonperturbative fashion. Moreover, a dynamical phase transition is predicted between delocalized, many-body localized, and Anderson localized phases as a function of the density of excitations in the system. We hypothesize that the microscopic mechanism responsible for said phase transition is the formation of extended "necklace" states that facilitate transport across the system. These states are formed by the hybridization of localized modes of different resonance frequencies that span the system length, and can facilitate tunneling of photons in combination with interactions in the form of quantum nonlinear frequency mixing. We discuss our ongoing efforts to show that these quantum necklace states dominate quantum transport of photons in disordered waveguide QED, and how they manifest themselves in accessible observables like the transmission spectra, two-photon correlations, and their fluctuations.

Presenter name: Daniel Goncalves Romeu

Poster session / Mo-22:   *Degen. gases, many-body phys. & quant. sim.*   ID307

Dynamics in a spin imbalanced gas of Li6

Authors: Allan Pennings[1]; Paul Dyke[1]; Sascha Hoinka[1]; Ivan Herrera[1]; Chris Vale[1]

[1] *Swinburne University of Technology*

Two-component Fermi gases with imbalanced spin populations feature mismatched Fermi surfaces which can lead to a range of novel behaviours. Here, we produce and study spin-imbalanced Fermi gases following a quench which removes a fraction of the atoms in one spin state, from an initially balanced spin-mixture. We apply this approach to harmonically trapped lithium-6 gases and measure the ensuing dynamics as the atoms approach equilibrium. Furthermore, we present our progress towards studies of the contact parameter in spin-imbalanced Fermi gases using Bragg spectroscopy.

Presenter name: Allan Pennings

Poster session / Mo-23:   *Degen. gases, many-body phys. & quant. sim.*   ID317

Toward the realization of single quantum impurities in a new ultracold ytterbium experiment

Authors: Francesco Scazza[1]; Omar Abdel Karim[2]; Alessandro Muzi Falconi[3]; Stefano Vigneri[3]

[1] *University of Trieste and CNR-INO*

[2] *CNR-INO and University of Napoli*

[3] *University of Trieste*

Ultracold atoms provide a unique playground for exploring many-body phenomena emerging in strongly correlated systems, owing to an exceptional control over Hamiltonians, their long coherence times, and recently established single-atom microscopy techniques. Here, I will report on the ongoing development of a new atom experimental apparatus in Trieste, aiming to control and detect ytterbium atoms at the single-particle level. Ytterbium presents several features which make it ideal to investigate open questions in problems based on quantum impurity systems. Manipulating the external and internal degrees of freedom of individual atoms by optical tweezer microtraps, and exploiting the precise toolbox of two-electron-atom clock spectroscopy, we aim at coherently manipulating individual, localized impurities interacting with a many-particle medium, triggering and observing their dynamics with interferometric techniques. This will allow to shed light on important questions, such as the ultrafast response and the formation of Kondo resonances in Fermi systems, as well as the competition between quantum dephasing and thermal decoherence therein.

Presenter name: Francesco Scazza

Poster session / Mo-24: *Degen. gases, many-body phys. & quant. sim.* ID327

Dilute quantum liquid in a K-Rb Bose mixture

Authors: Leandra Vranjes Markic[1]; Viktor Cikojević[1]; Elena Poli[2]; Francesco Ancilotto[3]; Jordi Boronat[4]

[1] *University of Split, Faculty of Science*

[2] *Institut für Experimentalphysik, Universität Innsbruck,*

[3] *Dipartimento di Física e Astronomia "Galileo Galilei" and CNISM, Universita di Padova*

[4] *2Departament de Física, Universitat Politìcnica de Catalunya*

Recently, the formation of heteronuclear quantum droplets has been observed in an attractive bosonic mixture of ^{41}K and ^{41}Rb. [1], with increased lifetimes with respect to the homonuclear mixture of ^{39}K. In order to enable fruitful comparison with experiments, we have performed a study of the ^{41}K and ^{41}Rb mixture using the diffusion Monte Carlo method and the Density Functional Theory [2].

We have proved that the perturbative Lee-Huang-Yang term for a heterogeneous mixture is valid only near the gas-liquid transition. Based on the equations of state of the bulk mixture, calculated with diffusion Monte Carlo, we present extensions to Lee-Huang-Yang corrected mean-field energy functionals.

Using Density Functional Theory, a systematic comparison between different functionals is performed, focusing on the critical atom number, surface tension, surface width, Tolman length, and compressibility. These results are given as a function of the inter-species interaction strength, within the stability domain of the liquid mixture and for an experimentally relevant range of scattering parameters.

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[2] V. Cikojević, E. Poli, F. Ancilotto, L. Vranješ Markić, J. Boronat, Dilute quantum liquid in a K-Rb Bose mixture, Phys. Rev. A, **104**, 033319 (2021).

Presenter name: Leandra Vranjes Markic

The integration of 2D atomic arrays with photonic crystal waveguides

Author: Jacob Thornfeldt Hansen[1]

Co-authors: Jonas Bundgaard Mathiassen [1]; Anders Simonsen [1]; Jörg Helge Müller [1]; Jean-Baptiste Béguin [1]; Eugene Polzik [1]

[1] *Niels Bohr Institute*

Arrays of neutral atoms offer a promising platform for building controllable and scalable quantum many-body systems. Atoms of the same species have identical transitions and are practically unlimited in supply. Given the maturity of the field of atomic physics, a large toolbox of advanced techniques for cooling and manipulating atoms is available. Atoms in ultra-high vacuum systems are also decoupled from their environment, allowing for long coherence- and lifetimes. However, this strong decoupling poses a challenge for coupling atoms with one another.

We seek to couple atoms via the exchange of optical photons. However, it is generally difficult to achieve strong coupling between atoms and light, propagating in free space, at the single particle level. Moreover, the spontaneous emission of light from an atom into free space is isotropic, further limiting the interaction strength. Based on pioneering work[1,2], our goal is to engineer strong atom-atom interactions mediated by light, in a 2D setting. By trapping atoms near carefully designed photonic crystals, the light emitted by the atoms couples strongly to the crystal.

The light guided by the photonic crystals can be highly confined, allowing for much stronger light-matter coupling than in free space. Given the discrete symmetries of the photonic crystal, the mode of the guided light will be highly directional, offering the opportunity to engineer specific interactions depending on the location of the atoms with respect to one another. This allows one to implement different Hamiltonians for simulating quantum systems such as 2D Ising-like systems, as seen in quantum magnetism[3].

We report on our progress towards trapping 2D arrays of individual Cesium atoms using optical tweezers, near a 2D dielectric structure. Using a dual compartment vacuum system, we transfer cold Cesium atoms from a source chamber to a science chamber, containing a photonic crystal. Here, the atoms are recaptured and subsequently trapped in optical tweezers.

[1]: A. González-Tudela, C. L. Hung, D. E. Chang, J. I. Cirac, H. J. Kimble, Nat. Photon. 9, 320 (2015)
[2]: Xingsheng Luan, Jean-Baptiste Béguin, Alex P. Burgers, Zhongzhong Qin, Su-Peng Yu, Harry J. Kimble, Adv. Quantum Technol. 3, 2000008 (2020).
[3]: D. E. Chang, J. S. Douglas, A. González-Tudela, C.-L. Hung, H. J. Kimble, Rev. Mod. Phys. 90, 031002 (2018)

Presenter name: Jacob Thornfeldt Hansen

Poster session / Mo-26: *Degen. gases, many-body phys. & quant. sim.* ID365

Quantum control of ultracold NaCs ground state molecules

Authors: Ian Stevenson[1]; Niccolo Bigagli[1]; Aden Lam[1]; Claire Warner[1]; Weijun Yuan[1]; Siwei Zhang[1]; Sebastian Will[1]

[1] *Columbia University*

We report on the creation of sodium-cesium (NaCs) molecules in their rovibrational ground state [1], assembled from ultracold clouds of Na and Cs atoms [2,3]. Via one- and two-photon spectroscopy we have identified a pathway that allows us to produce the first ultracold ensembles of NaCs ground state molecules via stimulated Raman adiabatic passage (STIRAP). In the ground state we explore the rotational structure. We demonstrate strong Rabi coupling on the microwave transition between the ground and first excited rotational state, allowing us to coherently control the rotational state on extremely fast time scales with pi-pulse times on the scale of 10 nanoseconds. The long-lived rotational states can be used as qubits or to shield the molecules from two-body loss. We show preliminary results on microwave shielding of the molecules, along with early work on direct evaporation of NaCs. Progress in this direction may allow cooling towards quantum degeneracy, potentially opening the door towards a strongly dipolar Bose-Einstein condensate of ground state molecules.
[1] I. Stevenson et al., arXiv:2206.00652 (2022)
[2] C. Warner et al., Phys. Rev. A 104, 033302 (2021)
[3] A. Z. Lam et al., Phys. Rev. Res. 4, L022019 (2022)

Presenter name: Weijun Yuan

Poster session / Mo-27: *Degen. gases, many-body phys. & quant. sim.* ID375

Efficient production of an array of fully-quantum-state-controlled polar molecules

Authors: Gabriel Patenotte[.]; Lewis Picard[1]; Jessie Zhang[1]; Annie Park[1]

[1] *Harvard University*

Arrays of ultracold polar molecules exhibit long-range, long-lived dipole-dipole interactions that can be harnessed for the quantum simulation of matter, quantum computation, and precision measurements. Crucial to many of these proposals is the ability to produce adjacent pairs of molecules whose quantum states we can individually control. To that end, we detect vacancies in arrays of individually trapped Na and Cs atoms and use acousto-optic deflectors to rearrange the atoms into a vacant free-region. Each pair of Na and Cs is Raman sideband cooled and merged into the same trap, which we then magnetoassociate at a Feshbach resonance and transfer to the NaCs rovibronic ground state using a two-photon STIRAP sequence. Additionally, we performed spectroscopy of the NaCs $c^3\Sigma$ potential. We identified a 15 MHz wide intermediate state for our STIRAP transfer that is more efficient than a 120 MHz wide state used in our prior work. This efficient production of fully quantum-state-controlled polar molecules in optical tweezers will provide new opportunities for dipole-dipole interaction mediated quantum computation and quantum simulation applications.

Presenter name: Gabriel Patenotte

Quantum science with programmable Strontium arrays in a Hubbard lattice

Authors: Aaron Young[1]; William Eckner[1]; Nathan Schine[1]; Adam Kaufman[1]

[1] *JILA*

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Alkaline earth atoms and optical tweezer arrays are naturally complementary technologies. The atoms provide convenient transitions for high fidelity optical cooling and imaging, well-controlled internal states with extremely high quality factors, and switchable interactions. The tweezers further provide programmable control over those atoms' motional states and positions. These capabilities make this an attractive platform for studying quantum optics, with the ability to programmably prepare and detect Fock states of many indistinguishable, noninteracting bosons, and to study how those boson propagate through reconfigurable linear optical networks implemented with optical tweezers and an optical lattice. Conversely, this platform can also be used to study strongly interacting systems - namely collections of optical clock qubits that can be entangled via Rydberg interactions to study problems in quantum sensing, and simulations of spin models. The combination of universal control over optical clock qubits, coherent itinerance, and tunable interactions could ultimately be combined to study a large class of condensed matter Hubbard models.

Presenter name: Aaron W. Young

Magnetically mediated hole pairing in fermionic ladders of ultracold atoms

Authors: Thomas Chalopin[1]; Sarah Hirthe[1]; Dominik Bourgund[1]; Petar Bojović[1]; Annabelle Bohrdt[2]; Eugene Demler[3]; Fabian Grusdt[4]; Immanuel Bloch[1]; Timon Hilker[1]

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[4] *LMU Munich*

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The Fermi-Hubbard model is an iconic model of solid state physics that is believed to capture the intricate physics of strongly correlated phases of matter such as High-Tc superconductivity. Such a state of matter is supposedly achieved upon doping a cold antiferromagnetic Mott insulator. Pairing of dopants (holes), in particular, is considered to be a key mechanism for the occurrence of unconventional superconductivity.

Here, I will present our experimental observation of hole pairing due to magnetic correlations in a Fermi-Hubbard-type system in our Lithium quantum-gas microscope. We engineer mixed-dimensional Fermi-Hubbard two-leg ladders in which a potential offset between the legs suppresses the tunneling along the rungs, while enhancing spin exchange and singlet formation, thus drastically increasing the hole binding energy. We observe in particular that holes preferably sit on the same rung in order to maintain magnetic ordering, and we extract a binding energy on the order of the spin exchange energy. We furthermore find indications for repulsion between pairs when there are several hole pairs in the system.

Presenter name: Thomas Chalopin

Transport in the 2D Fermi-Hubbard model: Lessons from weak coupling

Authors: Thomas Kiely[1]; Erich Mueller[1]

[1] *Cornell University*

Recent cold atom experiments have observed bad and strange metal behaviors in strongly-interacting Fermi-Hubbard systems. Motivated by these results, we calculate the thermoelectric transport properties of a 2D Fermi-Hubbard system in the weak coupling limit using quantum kinetic theory. We find that many features attributed to strong correlations are also found at weak coupling. In particular, for temperatures $T > t$ the electrical resistivity is nearly linear in temperature despite the fact that the quasiparticle scattering rate is nonlinear and changes by nearly an order of magnitude. We argue that this asymptotic behavior is a general feature of systems with a finite spectral width, which implies that there is no MIR bound on the resistivity in single-band models. Due to nesting, the T-linear resistivity persists down to $T = 0$ at half filling. Our work sheds light on the transport regimes accessible in ultracold atom experiments, which can differ substantially from that of condensed matter systems. Disentangling these band-structure effects from the physics of strong correlations is a major challenge for future experiments.

Presenter name: Thomas Kiely

Poster session / Tu-6: *Degen. gases, many-body phys. & quant. sim.* ID63

Imprinting persistent currents in fermionic superfluid rings

Authors: Giulia Del Pace[1]; Klejdja Xhani[2]; Alessandro Muzi Falconi[3]; Marco Fedrizzi[2]; Nicola Grani[2]; Diego Hernandez Rajkov[2]; Massimo Inguscio[4]; Francesco Scazza[3]; Woo Jin Kwon[2]; Giacomo Roati[2]

[1] *EPFL*

[2] *INO-CNR and LENS*

[3] *Università degli Studi di Trieste*

[4] *Campus Biomedico di Roma, INO-CNR and LENS*

Persistent currents in a ring are one of the most striking manifestations of a quantum system coherence. The periodic boundary constrains the wavefunction phase to wind in a loop of an integer multiple of 2π, which, when nonzero, gives rise to a current. Besides being a proxy of quantum phase coherence, persistent currents represent a cornerstone for many applications, from precision sensing to quantum computing, that require a fast and controlled current injection and a reliable read-out of its magnitude. Here I present the experimental realization of a fast and on-demand generation of persistent currents in atomic Fermi superfluid rings and the investigation of the connection between their damping and vortex nucleation. We excite persistent current states of on-demand winding number by dynamically imprinting the phase winding in the ring with a tailored laser beam and we read-out the current state via an interferometric probe, which directly accesses the ring phase profile. We demonstrate our method to efficiently excite persistent currents of finite and controllable winding in the different interaction regimes of the BEC-BCS crossover. We then induce the current decay by inserting a small defect in the ring. For currents higher than a critical value, the obstacle triggers the emission of vortices that reduce the phase winding. Our work demonstrates fast and accurate control of persistent currents in fermionic superfluids, opening the route for their application in quantum technologies.

Presenter name: Giulia Del Pace

Poster session / Tu-7:   *Degen. gases, many-body phys. & quant. sim.*   ID74

Efimov universalities, Bose polarons and turbulence with ultracold 39K in a 3D box trap

Authors: Alec Cao[1]; Jiří Etrych[1]; Gevorg Martirosyan[1]; Lena Dogra[1]; Christoph Eigen[1]; Zoran Hadzibabic[1]

[1] *University of Cambridge*

We present on various experiments utilizing quantum ^{39}K gases trapped in a 3D optical box for investigations of few-body, many-body and far-from-equilibrium phenomena. The first result we present is a comprehensive characterization of F=1 manifold Feshbach resonances for magnetic fields up to 600G using loss spectroscopy and atom-dimer interferometry; these precision measurements enable us to examine Efimov and van-der-Waals universality across multiple resonances. Our second main result is the realization of a uniform system of Bose polarons. We spectroscopically probe the polaron spectral function with minimal density broadening from weak to resonant couplings, and find evidence for coherent quantum beats between repulsive polaron and an impurity-phonon bound state at strong repulsive interactions under a Ramsay protocol. As a third result, we experimentally establish an equation of state relating the energy flux to the Kolmogorov number of the turbulent cascade established under strong forcing of an interacting condensate. This equation of state is independent of the details of the driving and dissipation, independent of history, and can be rescaled into a single curve for different interaction parameters. Finally, we surprisingly demonstrate that even a shaken noninteracting condensate exhibits a self-similar scaling dynamics in momentum space with a subdiffusive energy growth, qualitatively akin to interacting turbulent behavior but quantitatively different.

Presenter name: Alec Cao

Poster session / Tu-8:   *Degen. gases, many-body phys. & quant. sim.*   ID87

Site-resolved imaging of a bosonic Mott insulator of 7Li atoms

Authors: Kiryang Kwon[1]; Junhyeok Hur[1]; Kyungtae Kim[2]; SeungJung Huh[1]; Jae-yoon Choi[1]

[1] *KAIST*

[2] *JILA*

In this poster, we report a quantum gas microscope of Lithium-7 atoms in a two-dimensional (2D) square lattice. Individual atoms in each lattice site are imaged by Raman sideband cooling in a hybrid potential of the 2D lattice and a single tightly focused optical sheet potential. With a high numerical aperture (NA=0.65) objective, we achieve a point spread function of 630nm (full width half maximum), which is small enough to resolve the lattice spacing (752nm). About 4000 photons were collected during 1s of exposure time with a detection fidelity of 98%. Using the magnetic Feshbach resonance, we produce a large-sized unity filling Mott insulator with 1500 atoms at low temperature. We engineer our potential on a single-site level with an optical potential generated by a digital micromirror device (DMD), which opens opportunities to further cool the temperature and explore many-body localized (MBL) phases.

Presenter name: Kiryang Kwon

Poster session / Tu-9:   *Degen. gases, many-body phys. & quant. sim.*   ID96

Towards a strontium quantum gas microscope

Authors: Vasiliy Makhalov[1]; Jonatan Hoeshele[1]; Sandra Buob[1]; Antonio Rubio Abadal[1]; Leticia Taruell[1]

[1] *ICFO – Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860*

Ultracold quantum gases of atoms or molecules have become an outstanding tool to create and study various quantum many-body systems. Thanks to their high degree of controllability, they can be considered as quantum simulators - special purpose analog quantum computers - to address specific problems. An important example is optical lattice systems, which enable the implementation of the Hubbard model and can be probed with single-site and single-atom resolution in quantum gas microscope experiments.

In our experiment at ICFO, Barcelona, we aim at the realization of an ultracold strontium quantum gas microscope and pursue several research directions. Particularly, the subwavelength spacing of an optical lattice together with the two-level system of strontium will present an ideal environment to study the collective effects of atom-photon scattering. Additionally, the large nuclear spin of the fermionic isotope will enable access to rich physics of SU(N 10) Fermi-Hubbard systems. A high-NA imaging system will provide single lattice site resolution, whereas spin-dependent shelving in the clock state will offer spin-resolved imaging. In my poster, I give an overview of our new machine for ultracold strontium and discuss the further steps.

Presenter name: Vasiliy Makhalov

Poster session / Tu-10: *Degen. gases, many-body phys. & quant. sim.* ID105

Towards a Fermi gas microscope with tunable lattice geometry

Authors: Martin Lebrat[1]; Muqing Xu[1]; Lev H Kendrick[1]; Anant Kale[1]; Markus Greiner.

[1] *Harvard University*

We report on experimental progress towards quantum gas microscopy of ultracold lithium-6 in low-noise optical lattices with tunable geometry. By overlapping a superlattice beam over a two-dimensional square lattice, our setup enables the site-resolved study of Fermi-Hubbard physics in triangular, hexagonal, dimerized and quasi-1D geometries. Such nonstandard band-structures are believed to host a variety of exotic strongly correlated phases that are hard to characterize in condensed-matter systems, such as the proposed spin liquid state in the triangular lattice Hubbard model or the pseudogap phase of the square lattice model. Dynamically changing the lattice geometry further allows preparation protocols that may help reduce temperatures below the limits of current experiments. Together with low heating rates provided by technical improvements on lattice noise and stability, this may help reach the yet unexplored low-temperature regime of the Hubbard phase diagram.

Presenter name: Martin Lebrat

Poster session / Tu-11:   *Degen. gases, many-body phys. & quant. sim.*   ID122

Realization of a ferromagnet in an atomic superfluid

Authors: Riccardo Cominotti˙; Anna Berti˙; Clement Dulin˙; Chiara Rogora˙; Giacomo Lamporesi˙; Alessandro Zenesini˙; Alessio Recati˙; Iacopo Carusotto˙; Gabriele Ferrari[1]

[1] *University of Trento*

Interactions in materials characterized by spin degrees of freedom play a crucial role in determining the magnetic properties both in the presence and in the absence of an external coherent drive. For instance, if the spin-dependent interaction is positive and strong as compared to the external drive the material behaves as a ferromagnet, otherwise it shows a paramagnetic response to external perturbations.

By means of accurate control of the spin degrees [1,2], and of polarization-resolved spatial imaging in a coherently-driven 23Na Bose-Einstein condensate we explore the magnetic phase diagram of an extended superfluid. In the limit of strong external driving or small spin-dependent interaction (low density) the system features a paramagnetic response whereby the polarization is determined by the frequency detuning of the drive, while in the opposite limit of strong spin interaction the systems shows typical ferromagnetic behaviour with hysteresis, formation of magnetic domain walls, and divergent magnetic susceptibility.

Using a similar experimental setup we perform complementary measurements of the spin dispersion relation of a two-component superfluid demonstrating the massive (gapped) character of collective excitations when the superfluid is subject to stationary resonant driving [3], and of the role of quantum torque under strongly nonstationary driving [4].

[1] A. Farolfi et al., Rev. Sci. Instrum. 90, 115114 (2019).
[2] A. Farolfi et al., Phys. Rev. A 104, 023326 (2021).
[3] R. Cominotti et al., Phys. Rev. Lett. 128, 210401 (2022).
[4] A. Farolfi et al., Nat. Phys. 17, 1359 (2021).

Presenter name: Gabriele Ferrari

Poster session / Tu-12:   *Degen. gases, many-body phys. & quant. sim.*   ID128

Progress on Zeeman slowing of CaF

Authors: Timo Maximilian Lukas Poll[1]; Mariia Stepanova[1]; Paul Kaebert[1]; Supeng Xu[1]; Mirco Siercke[1]; Silke Ospelkaus[1]

[1] *Leibniz University Hannover, Institute of Quantum Optics, Germany*

Recently, great progress has been made in direct laser cooling of molecules to temperatures close to absolute zero. However, experiments are limited by the number of molecules that can be captured from molecular beams using typical laser-based trapping methods. In Petzold et al. 2018, we proposed to transfer Zeeman deceleration to laser-coolable molecules and thus substantially increase the number of molecules that can be captured by e.g. magneto-optical traps. Here, we now present our characterisation of the Zeeman force for CaF molecules. We find excellent agreement of the force with an optical Bloch equation model. This shows that the generated force profile can compress the initial molecular velocity distribution from a standard buffer gas cell to the velocity required for trapping in a magneto-optical trap (MOT). We present the current status of our experiment as well as theoretical work on a novel Bayesian-optimised molecular MOT scheme for CaF molecules.

Presenter name: Timo Maximilian Lukas Poll

Poster session / Tu-13:   *Degen. gases, many-body phys. & quant. sim.*   ID133

tunneling times and interaction-driven spin rotations in a two-component BEC

Authors: David Spierings[1]; Joseph McGowan[1]; Nick Mantella[1]; Harshil Neeraj[1]; Joseph Thywissen[1]; Aephraim Steinberg[1]

[1] *University of Toronto*

How much time does a tunneling particle spend in a barrier? A Larmor clock, one proposal to answer this question, measures the interaction between the particle and the barrier region using the spin degree of freedom of the particle to clock the dwell time inside the barrier. We report on precise Larmor time measurements of a Bose-Einstein condensate of 87Rb atoms tunneling through an optical barrier. We observe that atoms generally spend less time tunneling through higher barriers and that this time decreases for lower energy particles, confirming longstanding predictions of tunneling times. In addition, we present evidence of spin waves generated in the reflected portion of the condensate. Due to the coincidence of scattering lengths in 87Rb, a BEC in a mixture of two hyperfine states behaves as a phase-coherent yet distinguishable two-component fluid. Reflection from the barrier creates a counter-propagating matter wave with spin partly transverse to the spin of the forward-going wave, initiating interaction-driven rotations due to the different interaction energies experienced by parallel versus anti-parallel spins. We observe one oscillation of a spin wave for low Rabi frequencies and study the transition where spin rotations become independent of the external coupling and instead are dominated by the interaction-driven effects.

Presenter name: David Spierings

Poster session / Tu-14: *Degen. gases, many-body phys. & quant. sim.* ID148

Time-dependent variational Monte Carlo study of the dynamic response of bosons in an optical lattice

Authors: Mathias Gartner[1]; Ferran Mazzanti[2]; Robert E. Zillich[1]

[1] *Johannes Kepler University Linz*

[2] *Departament de Fisica, Universitat Politècnica de Catalunya*

We study the dynamic response of bosons in a one-dimensional optical lattice and obtain the dynamic structure factor $S(k, \omega)$ for perturbations in the linear regime, as well as the nonlinear response to strong density perturbations [1]. In our work, we use a continuous description of the system. Based on the time-dependent variational Monte Carlo method (tVMC) [2], we simulate the time propagation of a parametrized many-body wavefunction responding to an external probe pulse. A Jastrow-Feenberg ansatz with single particle and pair correlation functions is used as the model wavefunction.

For deep optical lattices we can compare $S(k, \omega)$ to exact diagonalization results obtained on a lattice in the Bose-Hubbard limit. When considering shallow optical lattices, the influence of higher Bloch bands is observed, indicating that the treatment in continuous space is appropriate for simulating the dynamics of the system. The nonlinear response to strong pulses, with amplitudes equal to the optical lattice depth and a fixed wave number, is also investigated. From the power spectrum of the density fluctuations we can again infer the full excitation spectrum, albeit broadened, due to higher harmonic generation. In addition, we use different pulse strengths to investigate the transition from linear to nonlinear response. A remarkable feature of tVMC is that the full excitation spectrum can also be retrieved from the power spectrum of the density fluctuations due to the stochastic noise inherent in any Monte Carlo method, without applying an actual perturbation.

[1] M. Gartner, F. Mazzanti and R.E. Zillich, Time-dependent variational Monte Carlo study of the dynamic structure factor for bosons in an optical lattice, arXiv preprint arXiv:2202.07535 (2022).
[2] G. Carleo, F. Becca, M. Schiró and M. Fabrizio, Localization and Glassy Dynamics Of ManyBody Quantum Systems, Scientific Reports 2(1), 243 (2012)

Presenter name: Mathias Gartner

Poster session / Tu-15:   *Degen. gases, many-body phys. & quant. sim.*   ID161

Quantum correction to Josephson oscillations

Authors: Koichiro Furutani[1]; Jacques Tempere[2]; Luca Salasnich[1]

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We theoretically investigate a bosonic Josephson junction by using the path-integral formalism with relative phase and population imbalance as dynamical variables. Starting from a Lagrangian of a Bose Josephson junction, we derive an action only in terms of relative phase by performing functional integration over the population imbalance. We then analyze the quantum only-phase action, which formally contains all of the quantum corrections. To the second order in the derivative expansion and to the lowest order in $\hbar$, we finally obtain the quantum correction to the Josephson frequency of oscillation in the Josephson regime [1]. The identical quantum correction is found also by adopting an alternative approach. While the estimated quantum correction to the Josephson frequency is relatively small based on current experimental setups, we expect that the correction can be significant by appropriately tuning some parameters such as the onsite interaction strength in an atomic Josephson junction or the capacitance in a superconducting Josephson circuit. Our predictions would be a useful theoretical tool for experiments with atomic or superconducting Josephson junctions.

[1] K. Furutani, J. Tempere, and L. Salasnich, Phys. Rev. B **105**, 134510 (2022).

Presenter name: Koichiro Furutani

Poster session / Tu-16:   *Degen. gases, many-body phys. & quant. sim.*   ID179

Binary collisions between quantum droplets: role of the Weber number

Authors: Rocio Jauregui[1]; Santiago Caballero[1]; Ernesto Alba-Arroyo[1]

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A theoretical analysis of the low energy surface excitations of quantum droplets formed by binary mixtures of ultracold dilute Bose gases is performed. Reliable expressions for the surface tension of the droplets are introduced based on the Thouless variational theorem. The Weber number can then be calculated as a measure of the relative importance of the inertia of the fluid in terms of the kinetic energy compared to its surface tension. By numerically evaluating the evolution of the droplets under the extended Gross-Pitaevskii equation, several regimes on the outcomes of frontal collisions of quantum droplets are identified. They range from the coalescence of the quantum droplets to their disintegration into smaller droplets. Those regimes are shown to be directly correlated to the Weber number. The numerical simulations include atoms losses of the droplets derived from self- evaporation and three–body scattering for both homo– and hetero–nuclear mixtures.

Presenter name: Rocio Jauregui

Poster session / Tu-17:   *Degen. gases, many-body phys. & quant. sim.*   ID193

A modified variational method for a quantum gas in a constrained surface

Authors: Ana Karen Cuervo Montiel[1]; Freddy Jackson Poveda Cuevas[2]

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[2] *Cátedras Conacyt - Instituto de Física - Universidad Nacional Autónoma de México*

Confined quantum gases in a toroidal-like potential can be studied by a variational method using Gross-Pitaevskii-like equations. The variational approach determines the dynamics of the quantum cloud, as the evolution of the aspect ratio during the free expansion of the cloud and the collective modes. We adapted the variational method to parametrize on a curved surface and effective dynamics. We use the thin-layer quantization scheme, focusing on three-dimensional surfaces, thus resorting to the Schrödinger equation for a particle with constrained dynamics to a curved surface. We propose a hybrid Lagrangian density and split the wave function into two parts: the normal and a tangential component to the surface that allow us to study the system through the extension of the variational method. Finally, we obtain the equations of motion that describe the dynamics separately in the normal and tangential parts on the surface.

Presenter name: Ana Karen Cuervo Montiel

Poster session / Tu-18: *Degen. gases, many-body phys. & quant. sim.* ID212

Large spin atoms in optical lattices : spin textures and correlations

Authors: Bruno Laburthe-Tolra[1]; Youssef Aziz-Alaoui[1]; Laurent Vernac[2]; Andrea Litvinov[1]; Pierre Bataille[1]; Martin Robert-de-Saint-Vincent[1]; Bihui Zhu[3]; Sean Robert Muleady[4]; Ana-Maria Rey[4]; Tommaso Roscilde[5]

[1] *CNRS - Paris North University USPN*

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Our experimental projects at the Laser Physics Institute (North Paris University) aim at characterizing entanglement for many-body systems made of large spin atoms. For this, we developed two experimental set-ups : one with large-spin strontium fermionic atoms, with spin-independent contact interactions; one with large-spin chromium bosonic atoms, with spin-dependent long-range dipole-dipole interactions.

I will describe our first measurements of the spin distribution of the SU(N) Fermi gas made of strontium atoms. For this, we used a spin-orbit coupling scheme, where a retroreflected laser beam selectively diffracts two spin components in opposite directions. Spin sensitivity is provided by sweeping through a magnetic-field sensitive transition while dark states ensure that spontaneous emission remains low.

On the chromium machine, we investigated the spin dynamics and quantum thermalization of a macroscopic ensemble of S = 3 spins initially prepared in a pure coherent spin state. The experiment uses a unit-filled array of 10 thousand chromium atoms in a three dimensional optical lattice. Atoms interact at long distance under the effect of magnetic dipole-dipole interactions, realizing the spin-3 XXZ Heisenberg model with long-range couplings. We investigated the build-up of quantum correlations in this many-body system. For this, we measured collective properties such as the total population in the seven different Zeeman states, or the collective spin length. We also found that the measurement of magnetization fluctuations provides direct quantitative estimates for two-body correlations.

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Lucas Gabardos et al., Phys. Rev. Lett. 125, 143401 (2020)
P. Bataille et al., Phys. Rev. A 102, 013317 (2020)

Presenter name: Bruno Laburthe-Tolra

Poster session / Tu-19:   *Degen. gases, many-body phys. & quant. sim.*   ID240

Mesoscopic transport with a weakly-interacting Bose gas

Author: Shun Uchino[1]

[1] *Japan Atomic Energy Agency*

Ultracold atomic gases play crucial roles in revealing nontrivial quantum transport phenomena. Especially, quantum transport of weakly-interacting Bose gases would be interesting in that the realizations with condensed-matter systems are difficult. In this poster, I focus on two-terminal transport systems with Bose-Einstein condensates. In spite of the formal similarity with fermionic superconducting systems, it is shown that the current-bias characteristics in Bose-Einstein condensates is quite different due to the presence of a unique transport process existing in the condensates.

Presenter name: Shun Uchino

Poster session / Tu-20:   *Degen. gases, many-body phys. & quant. sim.*   ID255

Towards microwave shielding of ultracold SrF molecules

Authors: Geoffrey Zheng[1]; Thomas Langin[1]; Varun Jorapur[1]; Qian Wang[1]; David DeMille[2]

[1] *University of Chicago*

[2] *University of Chicago & Argonne National Laboratory*

Quantum degenerate gases of ultracold dipolar molecules present a promising platform for advances in quantum simulation, quantum chemistry, and searches for physics beyond the Standard Model. Direct laser cooling of dipolar molecules is one successful method for achieving ultracold temperatures. Currently, we use sub-Doppler Λ-enhanced gray molasses cooling to load SrF molecules into an optical dipole trap. We have trapped ~ 160 SrF molecules at temperatures as low as 15 μK in a 420 μK deep trap using this approach. However, any significant increase in the phase space density of our molecular gas will likely be limited by inelastic losses caused e.g. by the barrierless chemical reaction $SrF + SrF \rightarrow SrF_2 + Sr$. Here we report our plans to surmount this challenge by using circularly polarized microwaves to create a repulsive interaction between the SrF molecules. We generate these microwaves by combining two orthogonal polarizations with controllable phase and amplitude offsets onto an orthomode transducer, and then deliver them to the molecules via a conical horn and ellipsoidal mirror. Successful implementation of this scheme should clear a path to achieving a quantum degenerate gas of SrF molecules.

Presenter name: Geoffrey Zheng

Poster session / Tu-21: *Degen. gases, many-body phys. & quant. sim.* ID262

Topological electromagnetic effects and higher second Chern numbers in Four-Dimensional gapped phases

Authors: Giandomenico Palumbo[1]; Yanqing Zhu[2]; Zhen Zheng[2]; Z. D. Wang[2]

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Higher-dimensional topological phases play a key role in understanding the lower-dimensional topological phases and the related topological responses through a dimensional reduction procedure. In this work, we present a Dirac-type model of four-dimensional (4D) Z2 topological insulator (TI) protected by CP-symmetry, whose 3D boundary supports an odd number of Dirac cones. A specific perturbation splits each bulk massive Dirac cone into two valleys separated in energy-momentum space with opposite second Chern numbers, in which the 3D boundary modes become a nodal sphere or a Weyl semimetallic phase. By introducing the electromagnetic (EM) and pseudo-EM fields, exotic topological responses of our 4D system are revealed, which are found to be described by the (4+1)D mixed Chern-Simons theories in the low-energy regime. Notably, several topological phase transitions occur from a CP-broken Z2 TI to a Z TI when the bulk gap closes by giving rise to exotic double-nodal-line/nodal-hyper-torus gapless phases. Finally, we propose to probe experimentally these topological effects in cold atoms.

Presenter name: Giandomenico Palumbo

Poster session / Tu-22: *Degen. gases, many-body phys. & quant. sim.* ID283

Self-pinning transition in a mixture of two nonidentical Luttinger Liquids

Authors: Tim Keller[1]; Serhan Seyyare Aksu[1]; Thomas Fogarty[1]; Thomas Busch[1]

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The pinning quantum phase transition can be observed in both weakly interacting quantum many-body systems described by a 1D Bose-Hubbard model and strongly interacting 1D systems modelled by Luttinger liquid theory. In both these cases an ultra-cold quantum gas can be driven to Mott-insulating state by imposing an infinitesimal small external lattice potential [1]

Recently an analogue to this transition was found for a Tonks-Girardeau gas that is immersed in a Bose-Einstein condensate, which corresponds to a situation of self-pinning state without imposing any external lattice potential [2].

Based on these studies, I present our work on this phase transition by studying a mixture two nonidentical Luttinger liquids, whose physical properties can be adjusted from being weakly to strongly correlated. In addition the system allows one to tune the interaction between the components, which therefore gives access to the full phase diagram of the two-component gas. While we are particularly interested in the behaviour of the phase transition as a function of correlations, I will also point out the implications for these systems to act as phonon-carrying matter wave lattices.

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[2] T. Keller, T. Fogarty and T. Busch, Self-Pinning Transition of a Tonks-Girardeau Gas in a Bose-Einstein Condensate, Phys. Rev. Lett., 128, 053401 (2022)

Presenter name: Serhan Seyyare Aksu

Poster session / Tu-23:   *Degen. gases, many-body phys. & quant. sim.*   ID297

Striped self-bound dipolar droplets

Authors: Clemens Staudinger[1]; Diana Hufnagl[2]; Ferran Mazzanti[3]; Robert Zillich[4]

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[2] *Johann Radon Institute for Computational and Applied Mathematics and MathConsult GmbH*

[3] *Departament de Fisica, Universitat Politècnica de Catalunya*

[4] *Johannes Kepler University*

We investigate a system of dipolar atoms confined to move on a two dimensional plane. The dipole moments are all parallel and aligned in a direction that does not necessarily coincide with the normal to the plane. As a result of the attractive and repulsive components of the dipole-dipole interaction, the system can form a self-bound system, which is stabilized by quantum fluctuations. Tilting the dipoles tunes the anisotropy of the dipole-dipole interaction and offers the possibility to trigger a spatial density modulation. In this work we combine those two aspects and investigate the formation of a self-bound and striped phase, which has been realized in experiments with actual dipolar droplets. We use a variational method based on the hypernetted-chain Euler-Lagrange optimization of a Jastrow-Feenberg ansatz for the many-body wave function to study the ground state properties of the system. This method takes into account quantum fluctuations in a nonperturbative way and is capable of describing strongly correlated systems. We also perform exact diffusion Monte Carlo simulations for comparison.

Presenter name: Zillich, Robert

Poster session / Tu-24:   *Degen. gases, many-body phys. & quant. sim.*   ID309

Nonequilbrium states of driven-dissipative quantum gases

Author: André Eckardt[1]

[1] *TU Berlin*

A system of ultracold atoms can be brought in contact with a thermal bath by letting it interact weakly with a large cloud of another atomic species. We consider atoms in a time-periodically driven optical lattice in contact with an interacting Bose condensate and microscopically model them using Floquet-Born-Markov theory. The interplay of driving and dissipation will guide these systems into nonequilibrium steady states. Compared to the usual adiabatic state preparation, suffering from nonadiabatic excitation processes, this scenario can have two advantages; it is robust, since energy (and entropy) can be dumped into the bath, and it allows for the preparation of interesting states beyond the strict constraints of thermal equilibrium. I will present two examples in rather different regimes: (i) In a system of fermions loaded into the Floquet-topological band structure of a hexagonal lattice created by high-frequency driving, the coupling to the environment allows to "cool" almost all particles into a single band so that a topological insulator giving rise to a quantized Hall response is prepared [1]. (ii) Subjecting a one-dimensional bosonic system to a spatially local drive of intermediate frequency that resonantly excites (heats) the system, the interplay of driving and dissipation is found to give rise to the formation of a nonequilibrium Bose condensate in a subspace that approximately decouples from the drive [2]. Finally, I will also address the (experimental and numerical) observation of a dynamical phase transition occurring at a critical time during the bath-induced relaxation dynamics of an open system [3].

[1] A. Schnell and A. Eckardt.: Stabilizing a Floquet topological insulator in a driven optical lattice by bath engineering (in preparation).
[2] A. Schnell, L.-N. Wu, A. Widera, A. Eckardt.: Floquet-heating-induced nonequilibrium Bose condensation in an open optical lattice (preprint, arXiv:2204.07147).
[3] L.-N. Wu, J. Nettersheim, J. Feß, A. Schnell, S. Burgardt, S. Hiebel, D. Adam, A.E., A. Widera, A. Eckardt: Dynamical phase transition in an open quantum system (in preparation).

Presenter name: Eckardt, André

Poster session / Tu-25: *Degen. gases, many-body phys. & quant. sim.* ID319

Unitary fermionic p-wave interactions in a 3D optical lattice

Authors: Vijin Venu[1]; Peihang Xu[1]; Frank Corapi[1]; Robyn Learn[1]; Mikhail Mamaev[2]; Thomas Bilitewski[2]; Jose P. D'Incao[2]; Cora J. Fujiwara[1]; Ana Maria Rey[2]; Joseph H. Thywissen[1]

[1] *Department of Physics and CQIQC, University of Toronto*

[2] *JILA, NIST and Department of Physics, University of Colorado, Boulder*

Resonantly enhanced and controllable p-wave interactions in ultracold atomic systems are a promising test bed for realizing unconventional superconductors and superfluids with non-trivial transport properties. However, p-wave and other antisymmetric interactions are weak in naturally occurring systems, and their enhancement via the Feshbach mechanism has been limited by three-body loss. Here, we report on spectroscopic measurements of Feshbach-enhanced p-wave interactions of ^{40}K, where three-body loss is suppressed by loading pairs of spin polarized atoms into a multiband 3D optical lattice. Our measurements extend up to the unitary limit characterized by a diverging p-wave scattering volume. These measurements show excellent agreements to an exact solution for two harmonically confined atoms interacting via a p-wave pseudopotential, and to numerical solutions using an ab-initio interaction potential. We also demonstrate the coherence of the conversion process between noninteracting and strongly interacting atomic pairs by measuring Rabi oscillations. Furthermore, we demonstrate that losses of p-wave interacting pairs are limited by the intrinsic lifetime of the free-space molecular dimer, and we observe lifetimes that are fifty times larger than previous measurements in ^{40}K.

Presenter name: Vijin Venu

Poster session / Tu-26:   *Degen. gases, many-body phys. & quant. sim.*   ID330

Collective effects in dissipative quantum cellular automata

Authors: Javad Kazemi[1]; Hendrik Weimer[1]

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Programming irreversible dynamical rules of cellular automata into nonunitary interactions of quantum systems appears to be a promising route to studying novel collective effects. Considering a master-equation embedding of classical cellular automata, we first investigate the unexplored area of computability aspects of Markovian quantum dynamics. We introduce a novel dynamical class of open quantum many-body systems that allows studying the interplay between computational properties and quantum effects. Strikingly, we demonstrate that computational unpredictability can coexist with quantum entanglement and that it can be studied within present experiments. Next, we present a quantum version of a probabilistic majority-voting cellular automaton to address a long-standing controversy about the existence and limits of bistable behavior in the stationary states of open quantum systems. We find the first instance of genuine bistability in such systems which is driven by the breaking of detailed balance in the nonequilibrium steady state.

Presenter name: Javad Kazemi

Poster session / Tu-27: *Degen. gases, many-body phys. & quant. sim.* ID345

Dipolar quantum droplets and supersolids

Author: Tilman Pfau[1]

[1] *5. Physikalisches Institut and Center for Integrated Quantum Science and Technology (IQST), Universität Stuttgart, Germany*

Dipolar interactions are fundamentally different from the usual van der Waals forces in real gases. Besides the anisotropy the dipolar interaction is nonlocal and as such allows for self organized structure formation [1]. In 2015 we could observe the formation of a stable droplet crystal and found that this unexpected stability is due to beyond mean-field quantum corrections of the Lee-Huang-Yang type. When arranged in a 1D array also phase coherence between the droplets was observed, which was first evidence for a supersolid state of matter. Upon crossing the transition to the dipolar supersolid a Goldstone mode appears, which we have observed. The existence of this mode proofs the superfluid stiffness or the so-called phase rigidity of this new state of matter. We have also studied the static structure factor across the transition which allows to show that the characteristic fluctuations correspond to elementary excitations such as the roton modes, and that the supersolid state supports both superfluid as well as crystal phonons. A recent review on the discovery of quantum droplets and dipolar supersolids can be found in ref. [2].

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[1] review: T. Lahaye, et al., Rep. Prog. Phys. 72, 126401 (2009)
[2] review: F. Böttcher et al. Reports on Progress in Physics 84, 012403 (2021)

Presenter name: Tilman Pfau

Poster session / Tu-28: *Degen. gases, many-body phys. & quant. sim.* ID366

Wave turbulence in a homogenous 2D Bose gas

Authors: Andrey Karailiev[1]; Martin Gazo˙; Panagiotis Christodoulou[1]; Mohamed Warda[1]; Nishant Dogra[1]; Julian Schmitt[2]; Maciej Galka[1]; Zoran Hadzibabic[1]

[1] *University of Cambridge*

[2] *University of Bonn*

Turbulence is a multiscale phenomenon, found in systems ranging from nonlinear optics to the dynamics of the early universe. While turbulence escapes a complete microscopic understanding it is commonly associated with cascades, transporting system-specific conserved quantities, across different length scales.

Here, we employ a two-dimensional and homogenous ultracold Bose gas – a system with a high degree of experimental tunability – to study wave turbulence. A time-varying magnetic field gradient is used to excite a longest wavelength phonon mode, which under strong driving forms a direct energy cascade from low wavenumbers to high wavenumbers, where the dissipation scale lies. Using complimentary techniques, the system is probed on all length and time scales providing a view from individual quantum states to the full momentum distribution. We reveal two major theoretical cornerstones of turbulence formation: the establishment of the isotropic direct cascade, characterised by a power law, under anisotropic forcing; and the spatiotemporal scaling of the momentum distribution at times before any energy dissipation.

Rather than simply driving the longest wavelength mode, we are also able to excite shorter wavelength modes lying at intermediate wavenumbers using a Digital Micromirror Device. In this scenario, a dual system of two cascades where energy propagates to higher wavenumbers and particle number to lower wavenumbers is expected.

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https://arxiv.org/abs/2203.09514

Presenter name: Andrey Karailiev

Poster session / Tu-29: *Degen. gases, many-body phys. & quant. sim.* ID376

Site-resolved rotational state control of an optical tweezer array of ultracold dipolar molecules

Authors: Lewis Picard[1]; Annie Park[1]; Gabriel Patenotte; Jessie Zhang[1]; Kang-Kuen Ni[2]

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[2] *Department of Chemistry and Chemical Biology, Harvard University, Cambridge, Massachusetts 02138, USA, Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*

Ultracold polar molecules are able to interact at long-range via electric dipole-dipole interactions, which can be used to generate entanglement between distant molecules by coherently coupling their rotational quantum states. This capability makes such molecules an attractive platform for simulation of quantum matter and for quantum computing. We present our recent work on coherent control of the rotational and hyperfine degrees of freedom of a 1D array of ultracold NaCs molecules in optical tweezers. We perform coherent microwave spectroscopy of the molecules in the rotational ground and first excited state manifold. We further demonstrate site-selective excitation of individual molecules using a global microwave pulse by varying the light-shift induced by the tweezer beams at different sites, which allows us to arbitrarily position rotational excitations in our molecule array. Finally, we present our progress towards engineering coherent transfer of rotational excitations between sites via dipole-dipole coupling.

Presenter name: Lewis Picard

Poster session / Tu-30: *Degen. gases, many-body phys. & quant. sim.* ID389

Observation of stochastic wavefunction evolution from dispersively-measured Bose-Einstein condensates

Authors: Emine Altuntas[1]; Ian Spielman[1]

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A fundamental tenet of quantum mechanics is that measurements change a system's wavefunction to that most consistent with the measurement outcome, even if no observer is present. Weak measurements produce only limited information about the system, and as a result only minimally change the system state. In this context, the interaction of a nearly closed quantum system with its environment can be described as a continuous weak measurement process. Bose-Einstein condensates (BECs) offer multiple weak measurement techniques, that yield a controlled reservoir and consequently allow time-resolved study of the system evolution. We theoretically and experimentally characterize the quantum projection noise in atomic BECs weakly measured by the light scattered from a far-from resonant, i.e., dispersivly interacting, laser beam. We quantify the resulting wavefunction change with two observations: the contrast in a Ramsey interferometer, and the deposited energy. Next, we present a versatile high-resolution ultracold atom microscope: a combined hardware/software system that recovers near-diffraction limited performance and minimizes the information loss. Our high-fidelity digital correction technique reduces the contribution of photon shot noise to density-density correlation measurements, which would otherwise contaminate the quantum projection noise signal in weak measurements [1]. We demonstrate our aberration compensation technique using phase contrast imaging, a dispersive homodyne detection technique directly applicable to quantum back-action limited measurements.

[1] E. Altuntas, and I. B. Spielman, Physical Review Research, 3, 043087 (2021).

Presenter name: Emine Altuntas

Poster session / We-3:   *Degen. gases, many-body phys. & quant. sim.*   ID10

Rydberg atoms in Bose-Einstein condensed environments: cold bubble chambers and mesoscopic entanglement

Authors: Sebastian Wuster[1]; Sidharth Rammohan[2]; Shivakant Tiwari[2]; Aritra Mishra[2]; Abhijit Pendse[2]; Anil K Chauhan[2]; Rejish Nath[3]; Felix Engel[4]; Marcel Wagner[5]; Richard Schmidt[5]; Florian Meinert[6]; Alexander Eisfeld[7]

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[5] *Max-Planck-Institute of Quantum Optics and MCQST, Garching, Germany*

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Rydberg Atoms in highly excited electronic states with *n=30-200* can be excited within Bose-Einstein condensates (BECs), and while lifetimes are shorter than in vacuum [1,2], these atoms live long enough to cause a response of the BEC mean field [3]. During this, thousands of ground-state atoms are present within the Rydberg orbit, allowing the study of atoms moving within atoms [4].

We present beyond-mean field models of the joint Rydberg-BEC dynamics, showing how either can be used to probe the other.

For multiple Rydberg atoms in a single electronic state, we show that the phase coherence of the condensate allows the tracking of mobile Rydberg impurities akin to the function of bubble-chambers in particle physics [5]. For a single Rydberg atom with multiple electronic states, we provide spectral densities of the BEC as a decohering environment [6], and show that the BEC can image a signature of the entangling evolution that causes Rydberg q-bit decoherence [7] or serve as nonMarkovian environment for quantum simulations.

[1] Schlagmüller *et al.* PRX **6** (2016) 031020.
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[4] Tiwari *et al.* arXiv:2111.05031 (2021).
[5] Tiwari *et al.* PRA **99** (2019) 043616.
[6] Rammohan *et al.* PRA **103** (2021) 063307.
[7] Rammohan *et al.* PRA(Letters) **104** (2021) L060202.

Presenter name: Sebastian Wuster

Entanglement of the macroscopic spins of two spatially separated Bose-Einstein condensates

Authors: Paolo Colciaghi[1]; Yifan Li[1]; Philipp Treutlein[1]; Tilman Zibold[1]

[1] *University of Basel*

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We experimentally investigate the entanglement of two spatially separated many particle systems. Our experiments are based on a two component pseudo spin-1/2 Bose Einstein condensate of ^{87}Rb on an atom chip. By engineering the interatomic interactions through state dependent trapping we are able to produce entangled spin-squeezed states in this system. Using coherent spin manipulations we split this entangled many-particle state into two halves in spin space and magnetic field gradients allow us to separate the two two-component BECs spatially by more than 40 μm. Our technique allows us to individually address the collective spins of the two BECs after splitting thereby realizing arbitrary spin measurements on the two systems. Their correlations allow to infer measurement results of noncommuting spin observables in one system from measurements on the other, demonstrating the entanglement of the two Bose-Einstein condensed clouds of roughly 800 atoms each. Besides the interest in understanding fundamental aspects of entanglement of many-body systems, our experiments enable new investigations in quantum enhanced metrology using spatially split probes.

Presenter name: Paolo Colciaghi

Entanglement dynamics of bosons trapped in a 1D optical lattice

Authors: Shion Yamashika[1]; Ryosuke Yoshii[2]; Daichi Kagamihara[3]; Shunji Tsuchiya[1]

[1] *Chuo University*

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Quantum entanglement has attracted much attention in the study of quantum many-body systems because it plays important roles in various phenomena such as thermalization of isolated quantum systems. Especially, it is remarkable that the 2nd-order Renyi entropy (RE), which is a measure of entanglement, has been successfully measured in the system of bosons trapped in a 1D optical lattice.

Motivated the experimental development, we study entanglement dynamics of bosons in a 1D optical lattice. Specifically, we calculate the time-evolution of the RE when the system is quenched from the deep Mott insulating (MI) regime. For quench within the MI regime, we derive the analytic expression for the time-evolution of RE and show that it oscillates with the period determined by the strength of the on-site interaction and finally converges to a certain value proportional to the subsystem size. On the other hand, for quench into the superfluid (SF) regime, RE does not oscillate but increases almost linearly and converges to a certain value that is also proportional to the subsystem size. We also show that the behavior of the 2nd-order RE exhibits distinct features depending of whether the system is quenched into the SF or MI phases. This implies that the signature of the SF-MI phase transition appears in the entanglement dynamics.

Presenter name: Shion Yamashika

Poster session / We-6: *Degen. gases, many-body phys. & quant. sim.* ID65

A new experiment on atomic tweezer arrays in a cryostat

Authors: Schymik Kai-Niklas[1]; Bruno Ximenez[2]; Étienne Bloch[2]; Davide Dreon[2]; Adrien Signoles[2]; Florence Nogrette[1]; Daniel Barredo[3]; Antoine Browaeys[1]; Thierry Lahaye[1]

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Optical-tweezer arrays are a powerful platform for realising analog and digital quantum simulators. However, they share the scalability problem common to all quantum hardware. Here, we present a new experimental setup that integrates the tweezer technology in a cryogenic environment. At 4K, we are able to measure a vacuum-limited lifetime of more than 6000 seconds, which represents a two-order-of-magnitude improvement over room temperature setups [1]. In addition, we have implemented an optimised trap loading equalisation procedure that, in combination with the extended lifetime, allows us to build arrays with more than 300 atoms while maintaining high accuracy of defect-free realisations.

These results are the first step towards Rydberg quantum simulators with more than a thousand particles.

[1] Kai-Niklas Schymik, Sara Pancaldi, Florence Nogrette, Daniel Barredo, Julien Paris, Antoine Browaeys, and Thierry Lahaye, *Single Atoms with 6000-Second Trapping Lifetimes in Optical-Tweezer Arrays at Cryogenic Temperatures,* Phys. Rev. Applied 16, 034013 (2021)

Presenter name: Davide Dreon

Observation of Cooper pairs in a mesoscopic 2D Fermi gas

Author: Marvin Holten[1]

Co-authors: Luca Bayha [1]; Keerthan Subramanian [1]; Sandra Brandstetter [1]; Carl Heintze [1]; Philipp Lunt [1]; Philipp Preiss [1]; Selim Jochim [1]

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Pairing is the fundamental requirement for fermionic superfluidity and superconductivity. To understand the mechanism behind pair formation is an ongoing challenge in the study of many strongly correlated fermionic systems.

On this poster, I present the direct observation of Cooper pairs in our experiment. We have implemented a fluorescence imaging technique that allows us to extract the full in-situ momentum distribution with single particle and spin resolution. We apply it to a mesoscopic Fermi gas, prepared deterministically in the ground state of a two-dimensional harmonic oscillator. Our ultracold gas allows us to tune freely between a completely noninteracting unpaired system and weak attractions where we find Cooper pair correlations at the Fermi surface. When increasing the interactions even further, the pair character is modified and the pairs gradually turn into tightly bound dimers. The collective behavior that we discover in our mesoscopic system is closely related to observations in nuclear physics or metallic grains. Our method provides a new pathway to study many of the outstanding questions concerning fermionic pairing, for example in imbalanced systems or the normal phase.

Presenter name: Marvin Holten

https://drive.google.com/file/d/1FQRI8EKqYa-Rbg8iMmZ___rCKqTLXyIrS/view?usp=sharing

Machine learning classification of two-dimensional vortex configurations

Authors: RAMA SHARMA[1]; TAPIO SIMULA[1]

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We consider computer generated configurations of quantized vortices in planar superfluid Bose–Einstein condensates. We show that unsupervised machine learning technology can successfully be used for classifying such vortex configurations to identify prominent vortex phases of matter [1]. The machine learning approach could thus be applied for automatically classifying large data sets of vortex on figurations obtainable by experiments on two-dimensional quantum turbulence.

[1] R. Sharma and T.P. Simula, Machine-learning classification of two-dimensional vortex configurations, Physical Review A, 105, 033301 (2022).

Presenter name: RAMA SHARMA

Poster session / We-9: *Degen. gases, many-body phys. & quant. sim.* ID97

Breakdown of topological transport in a Hubbard-Thouless pump

Authors: Zijie Zhu[1]; Anne-Sophie Walter[1]; Marius Gaechter[1]; Joaquin Minguzzi[1]; Stephan Roschinski[1]; Kilian Sandholzer[1]; Konrad Viebahn[1]; Tilman Esslinger[1]

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The fate of topological transport in the strongly correlated regime raises fundamental questions on the role of geometry in quantum many-body physics. A paradigm of quantised transport is the topological Thouless pump, which represents the one-dimensional, dynamic analogue of the quantum Hall effect. A few experiments have explored the effects of interactions on Thouless pumping in two-body and optical mean-field systems, but the strongly correlated regime has so far remained out of reach. Here, we experimentally detect the breakdown of topological transport due to strong Hubbard interactions in a fermionic Thouless pump, facilitated by a dynamical optical superlattice. We observe the deviation from quantised pumping for repulsive Hubbard U, which we attribute to pinned atoms in a Mott insulator. On the attractive side another mechanism is reducing the pumping efficiency: a smaller energy gap for pair pumping makes the evolution less adiabatic [1]. The dynamical superlattice operated at a single frequency establishes a novel platform for studying topology in the presence of strong correlations in one, two, and possibly three dimensions, including avenues to fractional transport.

Presenter name: Zhu, Zijie

Poster session / We-10:   *Degen. gases, many-body phys. & quant. sim.*   ID112

Mutual friction and diffusion of two-dimensional quantum vortices

Authors: Zain Mehdi[1]; Joseph Hope[1]; Stuart Szigeti[1]; Ashton Bradley[2]

[1] *Department of Quantum Science and Technology and Department of Fundamental and Theoretical Physics, Research School of Physics, Australian National University*

[2] *The Dodd-Walls Centre for Photonic and Quantum Technologies, Department of Physics, University of Otago*

We present a microscopic theory of thermally-damped vortex motion in oblate atomic superfluids that accounts for previously neglected number-conserving interactions between superfluid and thermal atoms. This mechanism causes dissipation of vortex energy due to mutual friction, as well as Brownian motion of vortices due to thermal fluctuations. We present an analytic expression for the dimensionless mutual friction coefficient that gives excellent quantitative agreement with experimentally measured values, without any fitted parameters. Our work provides a microscopic origin for the damping and Brownian motion of quantized vortices in two-dimensional atomic superfluids, which has previously been limited to phenomenology.

Presenter name: Zain Mehdi

Poster session / We-11:   *Degen. gases, many-body phys. & quant. sim.*   ID124

FermiQP: a fermion quantum processor

Authors: Philipp Preiss[1]; Janet Qesja[1]; Maximilian Schattauer[1]; Andreas von Haaren[1]; Robin Groth[1]; Timon Hilker[1]; Immanuel Bloch[1]

[1] *Max Planck Institute for Quantum Optics*

The most challenging problems from materials science and quantum chemistry involve strongly correlated states of mobile fermions. Mapping such itinerant systems to effective spin-1/2 systems realized on most quantum computing prototypes comes with a large computational overhead. New types of quantum processors based on inherently fermionic computation are therefore needed.

FermiQP will deliver a quantum processor based on ultracold fermionic Lithium operable in two modes. The analogue quantum gas microscopy mode will be using the fermionic nature of Lithium 6 to perform large-scale simulations of the Fermi-Hubbard model. The digital mode will enable quantum computation using spins manipulated by laser-driven single-qubit and superlattice-based global two-qubit gates allowing for universal programming. The device will thus enable new hybrid quantum computation schemes, where digital gate sequences are used for the initialization and readout of inherently fermionic analog quantum simulations. I will present the plans for and the current status of the FermiQP demonstrator.

Presenter name: Philipp Preiss

Poster session / We-12:   *Degen. gases, many-body phys. & quant. sim.*   ID130

Long-lived phantom helix states in Heisenberg quantum magnets

Authors: Hanzhen Lin[1]; Ivana Dimitrova[2]; Paul Niklas Jepsen[1]; Wen Wei Ho[3]; Wolfgang Ketterle[1]; Yair Margalit[1]; Yoo Kyung Lee[1]

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[2] *Harvard University*

[3] *Stanford University*

Exact solutions for quantum many-body systems are rare, but provide valuable insights for the description of universal phenomena. Recently, specific solutions of the Bethe ansatz equations for 1D anisotropic Heisenberg models were found that can carry macroscopic momentum yet no energy on top of the ferromagnetically ordered "vacuum" state, dubbed phantom Bethe states. As a consequence of these phantom Bethe states, simple spin helix states at special wave-vector becomes exact eigenstates of these systems.

With ultracold Li-7 atoms on optical lattices, we can simulate the anisotropic Heisenberg model, and tune the interaction anisotropy with Feshbach resonance. Here, we show experimentally that there exist special helical spin patterns in 1D chains which are long-lived, relaxing only very slowly in dynamics. The wave-vector of these special helices also shifts with the anisotropy parameter. These results confirming theoretical predictions.

As the wave-vector of the spin helix is determined by the anisotropy parameter, we use these phantom spin helices to directly measure the interaction anisotropy at different magnetic fields around Feshbach resonances. The measured anisotropy agrees well with the predictions based on super-exchange and Bose Hubbard model with perturbative interaction far from the Feshbach resonance, but we found discrepancies very close to the Feshbach resonance. This demonstrated the importance of higher order processes like bond charge tunneling close to the resonance, and reveals other processes not considered before (presented in detail in a separate poster).

We also generalize the theoretical description to higher dimensions and other nonintegrable systems, and find analogous stable spin helices, which should show nonthermalizing dynamics associated with so-called quantum many-body scars. These results have implications for the quantum simulation of spin physics, as well as many-body dynamics.

Presenter name: Hanzhen Lin

Poster session / We-13:   *Degen. gases, many-body phys. & quant. sim.*   ID136

Atom camera: super-resolution imaging of an optical field with a single ultracold atom in an optical tweezers

Authors: Takafumi Tomita[1]; Rene Villela[1]; Yeelai Chew[1]; Mahesh Tirumalasetty Panduranga[1]; Hiroto Sakai[2]; Keisuke Nishimura[2]; Taro Ando[2]; Sylvain de Léséleuc[1]; Kenji Ohmori[1]

[1] *Institute for Molecular Science, National Institutes of Natural Sciences*

[2] *Central Research Laboratory, Hamamatsu Photonics K.K*

In a cold-atom experiment with an optical tweezers array, a laser beam with a designed wavefront is focused through a high numerical-aperture objective lens to form an arbitrarily shaped light pattern on the focal plane in a vacuum chamber [1, 2, 3]. Accordingly, the pattern is often deteriorated by aberrations in optical components and thereby should be monitored and evaluated *in situ*. However, it is difficult to do so due to the difficulty of accessing the focal plane in a vacuum chamber.

We will report on an "atom camera" method that we have developed for imaging the light pattern with a single ^{87}Rb atom in an optical tweezers. We sense the intensity and polarization profiles of a light pattern at the atom position that manifest themselves in the light shift of the hyperfine transition. By scanning the atom position in steps of sub-micrometers, we reconstruct high-resolution 2D images of the intensity and polarization. The resolution is limited only by the uncertainty of the atom position, which is reduced down to the level of quantum fluctuations ($\sim$ 30 nm) by cooling the atom to the motional ground state of the tweezers [3], thus far better than the diffraction limit at optical wavelengths. This technique serves as an important tool for the design and evaluation of submicron-scale light patterns.

[1] A.Browaeys and T. Lahaye, Nat. Phys. **16**, 132-142 (2020).
[2] F. Nogrette *et al.*, PRX **4**, 021034 (2014).
[3] Y. Chew *et al.*, arXiv: 2111.12314.

Presenter name: Takafumi Tomita

Poster session / We-14: *Degen. gases, many-body phys. & quant. sim.* ID150

Emergence of hydrodynamics and pairing in a two-dimensional few fermion system

Authors: Sandra Brandstetter[1]; Carl Heintze[1]; Philipp Lunt[1]; Keerthan Subramanian[1]; Marvin Holten[1]; Selim Jochim[1]

[1] *University of Heidelberg*

Fermionic quantum systems with a tuneable atom number have proven to be a viable platform for exploring the emergence of many-body phenomena. In our experimental setup we can deterministically prepare few-body fermionic quantum systems in a two-dimensional harmonic potential with stable closed-shell configurations.

Using a time-of-flight expansion in combination with our imaging technique, which provides spin and single atom resolution simultaneously, we can explore correlations of atoms in different spin states in momentum space. This has recently lead us to the observation of Cooper pairs (1). We have recently extended our imaging technique to real space, by magnifying the matterwave. Similar to technique demonstrated in (2), we have developed a matterwave optics technique to expand the wavefunction prior to fluorescence imaging. This allows us to resolve it with our existing imaging setup, giving us access to correlations and small structures in both real and momentum space.

We now utilize this expanded imaging scheme to investigate the emergence of hydrodynamic behaviour in dependence on particle number and interaction strength. By preparing closed shell configurations of an elliptic harmonic oscillator, we can directly observe the inversion of the aspect ratio at particle numbers as low as five atoms per spin state. Additionally, we see an enhancement of pair correlations after an interacting expansion. We directly study this formation of pairs by magnifying the real space wave function after different short interacting expansion times.

(1) Holten et al. arXiv: 2109.11511 (2021) accepted in Nature
(2) Asteria et al. Nature 599, 571-575 (2021)

Presenter name: Sandra Brandstetter

Poster session / We-15:   *Degen. gases, many-body phys. & quant. sim.*   ID42

Heat rectification in ion crystals

Authors: Marisa Pons[1]; Miguel Ángel Simón[1]; Sofia Martinez-Garaot[1]; Juan Gonzalo Muga[1]

[1] *University of the Basque Country*

Heat rectification, firstly observed in 1936 by Starr [1], is the physical phenomenon, analogous to electrical current rectification in diodes, in which heat current through a device or medium is not symmetric with respect to the exchange of the baths at the boundaries. In the limiting case the device allows heat to propagate in one direction from the hot to the cold bath while it behaves as a thermal insulator in the opposite direction when the baths are exchanged. In 2002 a paper by Terraneo [2] demonstrated heat rectification numerically for a chain of nonlinear oscillators in contact with two thermal baths at different temperatures. Since then, there has been a growing interest in heat rectification [3,4], and the field remains very active because of the potential applications in fundamental science and technology, and the fact that none of the proposals so far appears to be efficient and robust for practical purposes.

In this work, we study heat rectification in linear chains of ions in trap lattices with graded trapping frequencies, in contact with thermal baths implemented by optical molasses. To calculate the local temperatures and heat currents we find the stationary state by solving a system of algebraic equations [5]. This approach is much faster than the usual method that integrates the dynamical equations of the system and averages over noise realizations. We also show that even though, in early times, some kind of anharmonicity, i.e. nonlinear forces, in the substrate potential or in the particle-particle interactions, was identified as a fundamental requisite for rectification, we show that asymmetric heat transport is found in this linear system if both the bath temperatures and the temperature dependent bath-system couplings are also exchanged. We can also show that it is the match/mismatch of the phonon bands (power spectra) the mechanism that governs the heat transport in the chain, allowing it when the bands match or obstructing it if they mismatch [6].

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[5] M. A. Simón, S. Martínez-Garaot, M. Pons, and J. G. Muga, Phys. Rev. E 100, 032109 (2019).
[6] M. A. Simón, A. Alaña, M. Pons, A. Ruiz-García, and J. G. Muga, Phys. Rev. E 103, 012134 (2021).

Presenter name: Marisa Pons

Poster session / We-16:   *Degen. gases, many-body phys. & quant. sim.*   ID182

Evaporation and large arrays of laser cooled CaF molecules

Authors: Scarlett S. Yu[1]; Loic Anderegg[1]; Yicheng Bao[1]; Sean Burchesky[1]; Derick Gonzalez-Acevedo[1]; Eunmi Chae[2]; Kang-Kuen Ni[1]; Wolfgang Ketterle[3]; John Doyle[1]

[1] *Harvard University*

[2] *Korea University*

[3] *MIT*

The wide-ranging scientific applications of ultracold molecules have inspired significant efforts in cooling and controlling molecules in the single quantum state level. Many potential applications are still hampered by the finite temperatures experimentally achieved. As temperatures are reduced further, motional decoherence rates are suppressed and fidelities increase, opening new opportunities for quantum simulations and computation. One of the most successful cooling methods for atomic species, evaporative cooling, requires a high elastic rate and large ratio of elastic to inelastic collisions. While this ratio is typically low for most molecules, using microwaves we engineer a repulsive barrier between molecules, shielding inelastic losses while increasing the rate of elastic collisions. Using optically trapped CaF molecules, we demonstrate that the elastic rate can be increased while the inelastic loss is suppressed to reach a ratio of 50. By adiabatically lowering the trap depth to force evaporate of the hottest molecules, we observed a drop in temperature of the sample when shielding was enabled compared to a control sample without shielding. Future improvements in initial density and number would allow for more effective evaporation. Evaporative cooling is useful for bulk samples, but to use molecules in single optical tweezer arrays requires single particle cooling. To this end we report progress towards sideband cooling of CaF molecules to the ground motional state of an optical tweezer.

Presenter name: Scarlett S. Yu

Poster session / We-17: *Degen. gases, many-body phys. & quant. sim.* ID197

Faraday waves in strongly interacting superfluids

Authors: Diego Hernández-Rajkov[1]; José Eduardo Padilla-Castillo[1]; Alejandra del Río-Lima[1]; Andrés Gutiérrez-Valdés[1]; Freddy Jackson Poveda-Cuevas[2]; Jorge Amin Seman Harutinian[1]

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The study of collective excitations in superfluids systems has been an active and important research topic since the very beginning of the exploration of quantum fluids. Their study offers the possibility of probing several important properties of these systems, such as the spectrum of excitations, or the equation of state.

Here we present our work on the observation and study of Faraday waves in a cigar-shaped Fermi superfluid composed by a two-component spin mixture of ^{6}Li atoms. These waves are a type of collective excitation that arises as a periodic spatial and temporal modulation of the gas density profile.

In our setup, Faraday waves are parametrically excited by modulating the radial frequency of the trap. We characterize the phenomenon as a function of the interaction parameter by means of a Feshbach resonance. We probe the superfluid excitation spectrum by extracting an effective 1D speed of sound for different values of the interaction parameter, in good agreement with numerical simulations. Finally, we perform a stability analysis in the parameter space using a simplified model and we show the emergence of the Faraday waves as unstable solutions to a Mathieu-like equation

Presenter name: Jorge Amin Seman Harutinian

Poster session / We-18:   *Degen. gases, many-body phys. & quant. sim.*   ID220

Quantum caustics in many-body dynamics

Authors: Duncan O'Dell[1]; Wyatt Kirkby[2]

[1] *McMaster University*

[2] *University of Innsbruck*

Caustics are singularities arising from natural focusing and are well known in optics but also occur in any system that has waves including quantum waves. Caustics take on universal shapes that are described by catastrophe theory and dominate interference patterns in the semiclassical regime.

My group has been extending these ideas to quantum fields, such as those found in the sine-Gordon and Bose-Hubbard models. Our physical motivation is to describe the dynamics of Bose-Einstein condensates (BECs) following a sudden quench, including the cases of two and three independent BECs that are suddenly coupled together.

Our theoretical simulations [1] of the dynamics of these low-dimensional many-body systems following the quench shows that caustics form in Fock space over time and this seems to be a generic phenomenon. Furthermore, the caustics are singular in the mean-field theory but are regulated and adopt universal interference patterns in the full many-body theory. These caustics represent a form of universal quantum many-body dynamics associated with singularities in the underlying classical dynamics.

[1] Caustics in quantum many-body dynamics, W. Kirkby, Y. Yee, K. Shi and D.H.J. O'Dell, Phys. Rev. Research 4, 013105 (2022).

Presenter name: Duncan O'Dell

Poster session / We-19: *Degen. gases, many-body phys. & quant. sim.* ID246

Velocity selective resonances from a novel optical force

Authors: Yifan Fang[1]; Edoardo Buonocore[1]; Michael Wahl[1]; Harold Metcalf[1]

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Optical forces on atoms derive from the momentum exchange between the atoms and an incident light field [1]. Atoms cannot absorb the linear momentum of light into their internal coordinates the same way as energy ($\hbar\omega_\ell$) and angular momentum ($\Delta\ell = \pm 1$), so absorption or emission must involve atomic motion, usually in the form of a recoil momentum $\Delta p \equiv \hbar\omega_\ell/c \equiv \hbar k$. Since this is small compared to typical atomic momenta, it must be repeated many times to make a significant velocity change. Typically an excitation is followed by a spontaneous emission and then repeated to achieve the multiple momentum exchanges. The strength of such optical forces on atoms depends on the rate of this exchange and this is usually limited by the excited state lifetime τ, so the force scales with $\Delta p/\Delta t = \hbar k/\tau \equiv \hbar k\gamma$. In practice, excitation also takes time so the maximum value of this radiative force is given by $F_{\rm rad} \equiv \hbar k\gamma/2$ for light tuned on resonance.

Instead of spontaneous emission, we have been using stimulated emission to increase the momentum exchange rate, where we choose the stimulating light to have a $\vec{k}$-vector opposite to that of the exciting light so that the net momentum transfer becomes $2\hbar k$. A rapidly cycling, absorption-stimulated emission sequence from counter-propagating beams can lead to a very large force [2], $F_{\rm ARP} \gg F_{\rm rad} \equiv \hbar k\gamma/2$. We use a series of properly tailored pulses designed to cause absorption-stimulated emission cycles that produce a strong, unidirectional force. The optical frequency of each pulse is swept to enable adiabatic rapid passage (ARP) because such pulses invert populations more efficiently than π-pulses. Such ARP forces have been demonstrated for atoms initially at rest to be much stronger than ordinary radiative forces [3-7]. We have explored how this very strong force depends on atomic velocity and found surprising enhancement at certain regularly-spaced velocities [7,8]. These will be discussed, but they seem to occur when atoms travel approximately an integer number of wavelengths between ARP pulses.

In our experiments, a well-collimated beam of atoms is deflected by the ARP force and their spatial distribution is recorded by an MCP-phosphor-screen combination. Because the atoms have a significant longitudinal velocity spread that is unaffected by the light beams, their spatial distribution is spread out. Nevertheless, there are distinct, regularly spaced peaks at velocities that approximately correspond to "resonant" velocities.

An important criterion for a cooling force is a velocity dependence that is finite over some velocity range but vanishes at other velocities so that atoms accumulate in the region of velocity space where the force is zero or very small. Atomic motion in the lab frame corresponds to Doppler-shifted frequencies in the atomic frame, so we use oppositely detuned laser beams to simulate a velocity v_{at}. For large v_{at} we use two different lasers, but the coherent momentum exchange requires phase locking them [8]. This has been implemented and the first results show that the force is nearly constant at low v_{at} but decreases at higher v_{at}. For an ARP frequency sweep range of $\pm\delta_0$, one intuitively expects an effective force range of v_{at} between $1/4$ and $1/2$ of $\pm\delta_0/k$, and our initial measurements corroborate this.

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[2] A. Goepfert, I. Bloch, D. Haubrich, F. Lison, R. Schütze, R. Wynands, and D. Meschede, Phys. Rev. A 56, R3354 (1997).
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[8] J. Elgin, Ph.D Thesis, Stony Brook University, 2015.

Presenter name: Harold Metcalf

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Poster session / We-20:   *Degen. gases, many-body phys. & quant. sim.*   ID256

Feshbach-enhanced odd- and even-wave interactions between identical fermions in quasi-one-dimensional confinement

Authors: Kevin G. S. Xie[1]; Kenneth G. Jackson[1]; Colin J. Dale[1]; Ben A. Olsen[2]; Jeff Maki[3]; Shizhong Zhang[3]; Joseph H. Thywissen[1]

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Spin-polarized Fermi gases in low dimensions offer a pathway to the quantum simulation of matter. Through a Feshbach mechanism the p-wave ($L = 1$) interactions governing these systems, which are suppressed by a centrifugal barrier at low energy, may be tuned and enhanced by a magnetic field. In doing so one may realize phenomena as diverse as chiral superfluidity in two dimensions to topological qubits in the form of Majorana fermions in a Kitaev chain in one dimension. We study the short-range correlations between atoms in an ensemble of quasi-one-dimensional (quasi-1D) tubes of fermionic potassium realized with a two-dimensional optical lattice. The p-wave contact in 1D is measured for the first time through few-body correlations that manifest in the high-momentum tail of radio-frequency spectroscopy. By varying magnetic field and lattice depth we observe that the odd-wave resonance is shifted by confinement, energetically narrow, and limited from reaching unitarity by loss. In a greater field range, we observe additional features due to orbital singlet collisional states facilitated by population in transverse excited bands. Such states are exchange anti-symmetric in the transverse confinement direction, resulting in axial even-wave character that exhibits broad energetic width and orders of magnitude larger correlation strength than the odd-wave case. These emergent even-wave collisions open new possibilities for strongly interacting p-wave systems and quantum simulation in low dimensions.

Presenter name: Kevin G. S. Xie

Poster session / We-21: *Degen. gases, many-body phys. & quant. sim.* ID285

Exploring the supersolid stripe phase in a spin-orbit coupled gas with unequal interactions

Authors: Ramon Ramos[1]; Craig Chisholm[1]; Leticia Tarruell[1]

[1] *ICFO - The Institute of Photonic Sciences*

Initially considered in the context of solid helium, the exotic supersolid phase is characterized by the spontaneous breaking of gauge and spatial translation symmetries. This implies acquiring the phase coherence of a superfluid and the crystalline structure of a solid. The long-sought regime has been recently observed for cavity-coupled atomic systems [1], dipolar gases [2-4] and spin-orbit coupled [5,6] (SOC) systems. Although evidence of supersolidity was shown for the latter, further exploration is hindered by the low contrast of the density modulation and its fragility.

Here, we present theoretical and experimental results on the exploration of the supersolid phase in a ^{39}K spin-orbit coupled Bose Einstein condensate. We show that the stripe phase becomes more stable than in state-of-the-art experiments in rubidium. The reason is that the atomic interactions of the two-component condensate can be modified to be weakly attractive (miscible), favouring the striped regime. Thanks to the high contrast of the density modulation, the supersolid phase has a peculiar excitation spectrum manifested in the strong modification of the collective modes [7], which we numerically investigate for realistic parameters. Moreover, we present our experimental strategy to directly observe the density modulation of the supersolid in our system by increasing the imaging resolution using matter-wave lensing. This work aims to explore the differences and similarities between the SOC supersolid and realizations in other systems, highlighting the inherent features of a supersolid and the characteristics of each system.

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Presenter name: Ramon Ramos

Poster session / We-22: *Degen. gases, many-body phys. & quant. sim.* ID299

Light-induced correlations in cold dysprosium atoms

Authors: Ishan Varma[1]; Marvin Proske[1]; Niels Petersen[1]; Patrick Windpassinger[1]

[1] *Johannes Gutenberg University*

With the evergrowing interest in quantum cooperativity, comes an ongoing effort to study light-induced correlations in atomic media. In these typically extreme dense regimes, with atomic distances below the scattering lights wavelength, a direct matter-matter coupling is introduced by electric and magnetic interactions. We intend to study light-matter interactions in dense dipolar media with large magnetic moments to explore the impact of magnetic dipole-dipole interactions onto the cooperative response of the sample. With the largest groundstate magnetic moment in the periodic table (10 Bohr-magneton), Dysprosium is the perfect choice for these experiments.

This poster reports on our recent work to generate dense ultracold dysprosium clouds utilizing a microscopic optical dipole trap. Further, we give a perspective on future adaptations of this technique with a self-built science cell, that serves as a highly accessible platform to manipulate the atomic cloud. The small dimensions of the cell allow for extremely tight optical dipole trapping and precise magnetic field control at the position of the atoms.

Presenter name: Ishan Varma

Poster session / We-23: *Degen. gases, many-body phys. & quant. sim.* ID311

Probing Hubble attenuation and amplification in an expanding and contracting Bose-Einstein condensate

Authors: Swarnav Banik[1]; Monica Gutierrez Galan[1]; Hector Sosa-Martinez[1]; Madison Anderson[1]; Stephen Eckel[2]; Ian Spielman[1]; Gretchen Campbell[1]

[1] *Joint Quantum Institute, National Institute of Standards and Technology, and University of Maryland*

[2] *Sensor Sciences Division, National Institute of Standards and Technology*

In cosmology, the relativistic scalar fields that cause the universe to expand are damped by Hubble friction, which is due to the dilation of the underlying spacetime metric. Here, we have simulated the Hubble friction using a toroidal Bose-Einstein condensate (BEC) of 23Na atoms, in which the phonon fields can serve as an analogy to the cosmological scalar fields. We experimentally measure both Hubble attenuation and amplification, with five-fold better accuracy, by expanding and contracting the BEC universe. We discover temporal phase-dependent attenuation and amplification of the phonon field, which is only possible under nonadiabatic processes and is not described by the theoretical model. The measured strength of the Hubble friction disagrees with recent theories.

Presenter name: Yanda Geng

Realization of dipolar XY quantum ferro & antiferromagnets with arrays of Rydberg atoms

Author: guillaume bornet[1]

[1] *LCF*

In this poster we present the realization of ferromagnets (FM) and antiferromagnets (AFM) for square arrays up to 100 atoms realizing the dipolar XY model. Our platform is based on individual atoms of rubidium trapped in arrays of optical tweezers. We encode the effective spin on two Rydberg states. The coupling between the spins results from the resonant dipole-dipole interaction, varying as $1/r^3$. Our preparation of the phase relies on an adiabatic procedure starting from a classical anti-ferromagnetic state prepared by using local energy shifts which are induced by onsite addressing beams. The FM and AFM states are respectively the highest and the lowest energy state of the dipolar XY model.

To investigate these states, we first measure the dynamics of the magnetizations and the growth of correlations along different directions as we enter the FM (AFM) phase. We show that the two phases emerge for different critical values of the control parameters during the adiabatic procedure. This difference is explained by the weak frustration induced by the long-range tail of the dipolar interaction for the AFM case. Finally, by analyzing the spatial profile of the correlations we show the presence of a long-range order for the FM, feature that vanishes for the AFM, consistent with the existence of a weakly frustrated order.

Presenter name: Guillaume BORNET

Poster session / We-25:   *Degen. gases, many-body phys. & quant. sim.*   ID331

Entanglement generation in multilevel atomic arrays with dipolar interactions

Authors: Sanaa Agarwal[1]; Asier Piñeiro Orioli[1]; Ana Maria Rey[1]

[1] *JILA, NIST and Department of Physics, University of Colorado, Boulder*

We investigate the driven-dissipative dynamics of 1D arrays of multilevel atoms interacting via photon mediated dipole-dipole interactions and trapped at subwavelength scales. In contrast to two-level atoms, we show that multilevel atoms in the low excitation (weak drive) regime can become strongly entangled. The entanglement arises from the action of a nontrivial effective Hamiltonian and jump operators that contain multibody terms acting on the ground state manifold, and survives even after turning off the drive. We propose to use the $\sim 2.9\mu$m transition between $^3P_2 \leftrightarrow {}^3D_3$ in ^{88}Sr with 389nm trapping light as an ideal experimental platform for validating our predictions and as a novel quantum interface for the exploration of complex many-body phenomena emerging from light-matter interactions.

Presenter name: Sanaa Agarwal

Exploring sound excitations in 2D Bose gases

Authors: Martin Gazo[1]; Andrey Karailiev[1]; Mohamed Warda[1]; Nishant Dogra[1]; Julian Schmitt[2]; Maciej Gałka[1]; Panagiotis Christodoulou[1]; Zoran Hadzibabic[1]

[1] *University of Cambridge*

[2] *University of Bonn*

An interacting two-dimensional (2D) Bose gas becomes superfluid below a critical temperature through the BKT mechanism. In this phase, under hydrodynamic conditions where collisions keep the gas in local thermodynamic equilibrium, Landau's two-fluid model predicts the existence of two distinct sound-like excitations. These, so-called first and second sounds, have recently been observed in 2D [1], verifying the validity of the two-fluid model for a 2D superfluid. In the opposite limit of infrequent collisions, a distinct sound wave originating from the mean-field interactions of the quasicondensate is predicted to prevail even in the absence of the superfluid [2]; this 'collisionless' sound has also been observed in experiments [3].

Here, aiming to bridge the gap between the above observations, we extend our previous measurements [1] to explore the sound excitations of the interacting 2D ^{39}K Bose gas throughout the crossover between the hydrodynamic and the collisionless limits. To control the nature of the induced sound waves, we vary the wavelength of sound excitations by directly exciting higher-wavevector modes using a digital micromirror device (DMD). This allows us to study the crossover from hydrodynamic to collisionless sound under the same conditions of the gas, including the different damping mechanisms of these sound modes. Moreover, we also probe sound waves at various temperatures, to connect the hydrodynamic sound modes with the well-known zero-temperature (collisionless) Bogoliubov excitations.

[1] Christodoulou, Panagiotis, et al. "Observation of first and second sound in a BKT superfluid." Nature 594.7862 (2021): 191-194.

[2] Ota, Miki, et al. "Collisionless sound in a uniform two-dimensional Bose gas." Physical Review Letters 121.14 (2018): 145302.

[3] Ville, J. L., et al. "Sound propagation in a uniform superfluid two-dimensional Bose gas." Physical Review Letters 121.14 (2018): 145301.

Presenter name: Martin Gazo

Negative absolute temperature state in a triangular optical lattice

Authors: Mehedi Hasan[1]; Luca Donini[1]; Sompob Shanokprasith[1]; Dan Braund[1]; Max Melchner[1]; Dan Reed[1]; Tiffany Harte[1]; Ulrich Schneider[1]

[1] *University of Cambridge*

Negative absolute temperature entails a situation where the entropy of a system reduces as the internal energy increases. As the idea was put forward by N. Ramsey in the 1950s [1], the concept of negative absolute temperature has been actively discussed, and has led to the eventual observation with cold atoms in a square lattice [2]. In this poster, we describe our experiment with K(39) atoms on the observation of negative absolute temperature in a triangular optical lattice — a nonbipartite lattice containing geometric frustration. Due to its nonbipartite nature, the lowest energy band of a triangular lattice hosts two nonequivalent highest-energy points (K and K' points in Fig. 1(a)) that are not connected via a reciprocal lattice vector. We study the influence of these nonequivalent points by comparing positive and negative temperature states in this lattice. In Fig. 1(b), atoms in negative absolute temperature state are shown in the superfluid state where the atoms occupy the two highest energy points equally.
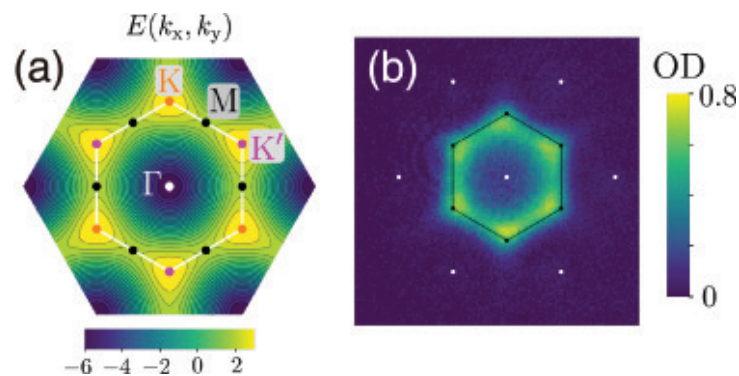
Figure 1: (a) The band structure of the first band for a triangular optical lattice. The inequivalent energy maxima are located at the K and K' points while the minimum of the energy is at the Γ point. (b) The measured optical density after an 11 ms time-of-flight, of a negative temperature gas. The region enclosed by the black thin lines represents the first Brillouin zone.

Moreover, we have created a phase-stabilized optical Kagome lattice by superimposing a 532-nm triangular lattice and a 1064-nm honeycomb lattice. We have also observed the superfluid to Mott insulator transition in the Kagome lattice.

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Presenter name: Mehedi Hasan

Poster session / We-28: *Degen. gases, many-body phys. & quant. sim.* ID380

A Quantum gas microscope for RbCs and KCs rovibration ground state molecules

Authors: Alex Matthies[1]; Jonathan Mortlock[1]; Adarsh Raghuram[1]; Andrew Innes[1]; Sarah Bromley[1]; Simon Cornish[1]

[1] *Durham University*

Quantum gas microscopes are a powerful tool which can be used to study particles confined to an optical lattice. By fluorescing trapped particles under an objective with a high numerical aperture it is possible to obtain single site resolution of the optical lattice. This has already been demonstrated with atoms and has paved the way for a novel platform for simulation experiments for lattice potentials. However, in optical lattices atoms have poor interactions between neighbouring sites. Here, we present our progress towards a quantum gas microscope for RbCs and KCs molecules. With molecules the issue of poor interactions is mitigated owing to the dipole - dipole interactions exhibited by molecules in neighbouring sites allowing us to more readily probe the relevant terms in the lattice Hamiltonian.

Presenter name: Andrew Innes

Poster session / We-29:   *Degen. gases, many-body phys. & quant. sim.*   ID269

Toward a 1D chain Of cold Rydberg atoms next to an optical nanofiber

Authors: Dylan Brown[1]; Alexey Vylegzhanin[2]; Aswathy Raj[2]; Sile Nic Chormaic[2]

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Combining cold Rydberg atoms with an optical nanofiber (ONF) apparatus provides a platform for both investigating the generation and manipulation of Rydberg atoms, but also an ideal way for generating a 1D chains of Rydberg atoms using the strong interactions of atom-ONF hybrid systems combined with the ability to trap atoms at the surface of the fiber in a 1D chain.

The evanescent field produced via the tight confinement of the light in an ONF allows for strong light-matter interactions for relatively low laser powers, and the easy interfacing with existing optical systems makes it an ideal system for the development of quantum technologies. Atom based ONF systems have shown great success in the field of atom optics, and with our recent success of exciting atoms to the Rydberg state via the evanescent field of the fiber [1], are now a potential new platform for developing Rydberg based quantum information systems.

Rydberg atoms, with their large electric field sensitivity and strong inter-atomic interactions leading to the famed Rydberg blockade, are a strong candidate for quantum information systems and have been a topic of significant interest over the past years.

ONF systems have been used to trap atoms at the surface of the fiber using two-color dipole traps, one providing the attractive potential, and the other providing a repulsive potential forms a potential minima a small distance on the order of 200nm from the fiber surface. Carefully selecting the wavelengths of the dipole trap, a magic wavelength condition [2] for Rydberg states can allow for the trapping of both the Rydberg and the ground state of the atoms in the same potential.

We present our results on the experimental excitation of Rydberg atoms next to an optical nanofiber and present the plans for extending our dipole trap for ground state atoms to also allow for the trapping of Rydberg atoms at the surface of the fiber, paving the way for experiments such as the investigation of 1D many body systems and the development of quantum gates.

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2. Jiandong Bai, Shuo Liu, Jun He and Junmin Wang, "Towards implementation of a magic optical-dipole trap for confining ground-state and Rydberg-state cesium cold atoms", J. Phys. B: At. Mol. Opt. Phys. 53, 155302, 2022

Presenter name: Dylan Brown

Poster session / Th-3:   *Degen. gases, many-body phys. & quant. sim.*   ID12

Ytterbium nuclear-spin qubits in an optical tweezer array

Authors: Alec Jenkins[1]; Joanna W. Lis[1]; Aruku Senoo[1]; William F. McGrew[1]; Adam M. Kaufman[1]

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Optical tweezer arrays of Alkaline earth-like atoms are promising for applications in quantum information and metrology. Here, we describe a tweezer platform for trapping and manipulating arrays of ^{171}Yb atoms [1]. We demonstrate favorable qubit properties of the nuclear spin $I = 1/2$, including seconds-scale coherence times and sub-microsecond single-qubit gates. We further show that single ^{171}Yb atoms can be loaded with $> 90\%$ efficiency into each tweezer, and we employ Raman sideband cooling to prepare atoms in the motional ground states of the tweezers. Lastly, we present recent progress, utilizing $^3P_0$ clock and Rydberg state control, towards the realization of mid-circuit measurement and two-qubit Rydberg gates.

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Presenter name: Alec Jenkins

Poster session / Th-4:   *Degen. gases, many-body phys. & quant. sim.*   ID19

Engineering a fractional quantum Hall state of bosons in an optical lattice

Authors: Sooshin Kim[1]; Julian Léonard[1]; Joyce Kwan[1]; Perrin Segura[1]; Markus Greiner[1]

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Realization of strongly interacting particles under the presence of a magnetic field can lead to novel phases of matter with topological order. Here, we demonstrate adiabatic preparation of the ground state of a two-particle Harper-Hofstadter system under different fluxes with ultracold bosonic ^{8}7Rb atoms in an optical lattice. A superimposed running lattice of two Raman beams and a magnetic field gradient are utilized to apply a tunable synthetic gauge field on the atoms. With the single-site resolution provided by our quantum gas microscope, we explore the ground-state fidelity of our protocol over the space of multiple parameters. There are more observables being studied to exhibit phase transition into the fractional quantum Hall state. Our study presents characterization of passage towards topological states in optical-lattice experiments.

Presenter name: Sooshin Kim

Poster session / Th-5: *Degen. gases, many-body phys. & quant. sim.* ID32

Violation of the Leggett-Garg inequality for a Bose condensate in a double-well potential

Authors: Tsubasa Sakamoto[1]; Ryosuke Yoshii[2]; Shunji Tsuchiya[3]

[1] *Chuo university*

[2] *Sanyo-Onoda City University*

[3] *Chuo University*

The Leggett-Garg (LG) inequality tells us whether or not the dynamics of the macro- scopic system obeys macrorealism, which consists of the assumptions put forward by Leggett and Garg. Violation of the LG inequality implies either the absence of a realistic description of the system or the impossibility of measuring the system noninvasively. In recent works, the LG inequality is experimentally examined in a superconducting flux qubit.

In our study, we discuss the violation of the LG inequality for a Bose condensate in a double-well potential. For the closed system, we clarify the region of the parameters where the LG inequality is violated. For the open system, coupled to a single bosonic mode, we obtain the collapse and revival of the occupation probabilities of the state in a double-well potential, which recursively violates the LG inequality. Furthermore, we reveal the dependence of the violation of the LG inequality on both the coupling strength and the maximum energy of the bath.

Presenter name: Tsubasa Sakamoto

Poster session / Th-6:   *Degen. gases, many-body phys. & quant. sim.*   ID68

Cavity-induced density wave ordering in strongly correlated Fermi gases

Authors: Victor Helson[1]; Jean-Philippe Brantut[1]; Giulia del Pace[1]; Timo Zwettler[1]; Tabea Bühler[1]

[1] *Institute of Physics, Ecole Polytechnique Fédérale de Lausanne*

The interplay of pairing with density wave order is one of the most prominent feature of strongly correlated electronics systems, such as high temperature superconductors. We have realized a Fermi gas with short and long range interactions, independently and simultaneously controllable. Starting from a quantum degenerate, unitary Fermi in a cavity [1-4], we pump the system from the side in the dispersive regime to yield a tunable photon-mediated interaction that favors the self-organization of atoms into a density wave order. We show that this interaction is broadly tunable, and study the onset of density wave ordering in the crossover from BEC to BCS. Our observations are compared with a mean field theory. Our system offers a new way to study competing orders in strongly correlated matter.

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[2] K. Roux, V. Helson, H. Konishi, and J. P. Brantut, "Cavity-assisted preparation and detection of a unitary Fermi gas," New J. Phys., vol. 23, no. 4, p. 043029, Apr. 2021, doi: 10.1088/1367-2630/abeb91.
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Presenter name: Victor Helson

Poster session / Th-7: *Degen. gases, many-body phys. & quant. sim.* ID81

Exploring topology in synthetic quantum Hall systems using atomic dysprosium

Authors: Aurélien Fabre[1]; Jean-Baptiste Bouhiron[1]; Tanish Satoor[1]; Quentin Redon[1]; Qi Liu[1]; Raphael Lopes[1]; Sylvain Nascimbene[1]

[1] *Laboratoire Kastler Brossel, Collège de France, CNRS, ENS-PSL University, Sorbonne Université*

Topological quantum states are associated with integer invariants and are thus protected from continuous small deformations of the system. Topological invariants ensure the robustness of various phenomena, e.g. the quantized Hall conductance in two-dimensional electron gases subjected to a magnetic field, and are promising tools in different fields of physics, such as quantum computation. Phases characterized with nontrivial topological invariants have been widely studied in the context of the integer and fractional quantum Hall effects and of topological insulators, both theoretically and experimentally.

Recently, the concept of synthetic dimension has attracted attention as it allows extending current studies to more exotic geometries. It relies on internal degrees of freedom to simulate an extra dimension, with an additional flexibility on its properties compared to a real physical dimension.

In this poster, I will present some recent experimental works on quantum Hall systems using ultracold samples of atomic dysprosium. We benefit from the large total angular momentum $J=8$ of dysprosium atoms in their electronic ground state to simulate a synthetic dimension, with $2J+1=17$ discrete positions. In a previous work, using optical Raman transitions coupling neighboring Zeeman sublevels of the electronic ground state, we showed that a Hall ribbon with sharp edges can be engineered.

We now report the use of this internal degree of freedom as a discretized dimension with periodic boundary conditions, used to prepare the equivalent of a Hall cylinder. In this geometry, the threading of a quantum of magnetic flux through the hole of the cylinder induces a quantized particle transport along the inifinite dimension, associated to the 1st Chern number.

Pushing the versatility of this approach forward, we also encode two synthetic dimensions in the total angular momentum of each atom, that we couple to two real physical dimensions. This effectively simulates a four-dimensional quantum Hall system with one cyclic dimension, one finite dimension with edges and two infinite dimensions. The dimensionality strongly affects the underlying physics: the topology of four-dimensional Hall systems is characterized by the 2nd Chern number which corresponds to a quantized nonlinear response.

Presenter name: Fabre, Aurélien

Nonequilibrium dynamics in a quenched ferromagnetic spinor Bose-Einstein condensate

Authors: SeungJung Huh[1]; Kyungtae Kim[2]; Junhyeok Hur[1]; Jihoon Seo[1]; Kiryang Kwon[1]; Jae-yoon Choi[1]

[1] *KAIST*

[2] *JILA*

In this poster, we will present recent experiments on a quenched ferromagnetic spinor BECs. In the first part, we present the observation of spin-momentum correlated matter-wave jets from spinor BECs [1]. Preparing a quasi-two-dimensional condensate in the $m_F = 0$ state, we quench the quadratic Zeeman energy to -2 kHz. Transversely propagating atomic beams in the $m_F = 1$ and $m_F = -1$ state ($m_F = 0$ state) are generated due to the superradiant collision process. Investigating angular correlation for each spin state, we reveal the strong correlation between spin and momentum, which suggests the possibility of being Einstein-Podolsky-Rosen (EPR) state. In the second part, we investigate the long-time relaxation dynamics after the quench [2,3]. Generated spin pairs form magnetic domains and are merged to display coarsening dynamics. We investigate correlation functions of the magnetization and observe the functions at different time collapse to a single function. Our result shows a good agreement with numerical simulation.
[1] K. Kim, J. Hur, S. Huh, S. Choi, and J.-Y. Choi, Phys. Rev. Lett. **127**, 043401 (2021)
[2] L. A. Williamson and P. B. Blakie., Phys. Rev. Lett. **116**, 025301 (2016)
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Presenter name: SeungJung Huh

Poster session / Th-9:   *Degen. gases, many-body phys. & quant. sim.*   ID98

NASA's cold atom laboratory: a multiuser facility for quantum gas research on the International Space Station

Author: Matteo Sbroscia[1]

Co-authors: David Aveline[1] ; Ethan Elliott[1] ; James Kellogg[1] ; Leah Phillips[1] ; Jim Kohel[1] ; Christian Schneider[1] ; Kamal Oudrhiri[1] ; Jason Williams[1] ; Robert Thompson[1]

[1] *JPL*

NASA's Cold Atom Laboratory (CAL) was launched to the International Space Station in 2018, where it has been conducting quantum experiments in microgravity ever since. CAL is a multiuser instrument designed to be fully operated remotely, with the possibility of astronaut-led hardware upgrades and replacements. Scientists have performed investigations ranging from BECs in bubble shaped geometries to extreme cooling protocols, all while commissioning efforts are under way to demonstrate atom interferometry and dual species BECs in space.

Presenter name: Matteo Sbroscia

Poster session / Th-10: *Degen. gases, many-body phys. & quant. sim.* ID113

Spin dynamics in optical lattices dominated by superexchange via virtual molecules

Authors: Yoo Kyung (Eunice) Lee[1]; Hanzhen Lin[1]; Wolfgang Ketterle[1]

[1] *Massachusetts Institute of Technology*

Simple, paradigmatic systems are important tools in understanding strongly correlated systems. One such system is the Bose-Hubbard model, which can be realized using atoms in optical lattices with delta-function interactions. We report the first experimental observation of two features of the Bose-Hubbard model: superexchange via virtual molecules in excited bands and off-site contact interactions. Adiabatic sweeps confirm the creation of these excited-band molecules, exemplifying a new kind of Feshbach resonance.

Presenter name: Yoo Kyung (Eunice) Lee

Poster session / Th-11: *Degen. gases, many-body phys. & quant. sim.* ID125

Big time crystals in a bouncing BEC

Authors: Arpana Singh[1]; Ali Zaheer[1]; Chamali Gunawardana[1]; Tien Tran[1]; Satoshi Tojo[2]; Krzysztof Giergel[3]; Andrei Sidorov[1]; Krzysztof Sacha[4]; Peter Hannaford[1]

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[2] *Department of Physics, Chuo University, Tokyo, Japan*

[3] *Optical Sciences Centre, Swinburne University of Technology, Melbourne, Australia, Institute of Theoretical Physics, Jagiellonian University, Krakow, Poland*

[4] *Institute of Theoretical Physics, Jagiellonian University, Krakow, Poland*

Discrete time crystals created in a Bose-Einstein condensate (BEC) bouncing resonantly on a periodically driven atom mirror can involve dramatic breaking of discrete time translation symmetry [1] with response periods up to s 100 times the driving period T [2]. This allows the creation of big time crystals having a large number of temporal lattice sites. By choosing suitable Fourier components in the periodic driving of the atom mirror, such a system enables effective potentials to be constructed in time lattices with nearly any shape, which provides a flexible platform for realising a broad range of condensed matter phenomena in the time dimension. Predicted phenomena include topologically protected edge states in time, Mott insulator states in the time dimension, and time crystals exhibiting temporal disorder, quasi-crystalline order and exotic long-range interactions [3].

Here, we report experimental progress towards creating big time crystals in a bouncing potassium-39 BEC system. The BEC is prepared in a 1064 nm crossed optical dipole trap above an oscillating 532 nm light-sheet atom mirror, which is driven with frequency corresponding to the selected s : 1 resonance for a given drop height and with amplitude adjusted to produce stable resonance islands located around periodic orbits with period sT. The BEC is then released from the optical dipole trap to fall on to the oscillating mirror under strong transverse confinement. When the particle interaction is raised above a critical value to spontaneously break the time-translation symmetry, a stable localized wave-packet evolves without tunnelling to other wave-packets, i.e., a discrete time crystal is formed.

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3. K. Sacha, Time Crystals, Springer (2020).

Presenter name: Arpana Singh

Poster session / Th-12: *Degen. gases, many-body phys. & quant. sim.* ID131

Observation of interaction-driven delocalization of the Anderson insulator in synthetic dimensions

Authors: Jun Hui See Toh[1]; Xinxin Tang[1]; Tristan Rojo[1]; Katie McCormick[1]; Carson Patterson[1]; Nicolas Williams[1]; Subhadeep Gupta[1]

[1] *University of Washington, Seattle*

The quantum kicked rotor is a paradigm system to study classical and quantum chaos. When viewed in momentum space, it is equivalent to the Anderson model of transport in the presence of disorder, featuring dynamical localization in the synthetic momentum space. We report the observation of interaction-driven delocalization in d-dimensional (d=1-4) Anderson models in the synthetic momentum space. Higher dimensions are generated by amplitude modulating the kick pulses of the quantum kicked rotor, and interactions are controlled via the transverse confinement of the 1D tubes. We show that interaction destroys dynamical localization for d=1-4, and the dynamics of the system becomes sub-diffusive. We also observed the onset of delocalization to start earlier with stronger interaction, modulation, and kick. Compared to earlier experimental studies in position space, our approach addresses interaction-driven transport in the Anderson model in great than 1 dimension and with infinitely-long range interactions realized in momentum space.

Presenter name: Jun Hui See Toh

Poster session / Th-13: *Degen. gases, many-body phys. & quant. sim.* ID137

Parameter optimization for laser slowing and magneto-optical trapping of MgF molecules via motion simulation

Authors: Dongkyu Lim[1]; Eunmi Chae[2]

[1] *Department of physics, Korea University.*

[2] *Department of physics, Korea University*

A magneto-optical trap (MOT) is the first step to take various atoms and molecules to the ultracold temperature. For molecules, because of their complex energy structure, there are too many parameters to be adjusted in the MOT and the preceding laser slowing stage. It is difficult to experimentally optimize all the parameters one by one. Motion simulation of particle can provide the optimized parameters more efficiently, and also can give us the motional trace to check if parameters are valid for MOT and laser slowing.

We optimize the parameters for MOT and laser slowing of Magnesium monofluoride (MgF) via motion simulation, to maximize the capture velocity (v_c) and the ratio of trapped molecules to the total molecules from a cold buffer-gas beam source (R_{trap}). We simulate the motion of MgF in two stages, MOT region and laser slowing region, using rate equation model. In the MOT region, we optimized various parameters of lasers and magnetic field to maximize v_c, using Bayesian optimization method. Using the optimized experimental parameters, we set a capture condition of initial positions and velocities which determines if molecules are trapped or not, when they enter the stage. In laser slowing stage, we optimize the parameters of slowing lasers to maximize R_{trap} using the capture condition of the MOT. In the poster, we further discuss the overall structure, initial conditions and optimization result of the simulation.

Presenter name: Dongkyu Lim

Poster session / Th-14:   *Degen. gases, many-body phys. & quant. sim.*   ID155

Quantum gas microscopy of triangular lattice Mott insulators

Author: Peter Schauss[1]

[1] *University of Virginia*

Frustrated quantum systems can host quasi-particles with fractional statistics and pose significant challenges to condensed matter theory due to their extensive ground state degeneracy. Here, we aim at quantum simulation of electronic systems on triangular lattice geometries using ultracold atoms in a quantum gas microscope.

We present the site-resolved imaging of fermionic lithium atoms in our novel triangular optical lattice geometry and the realization of Mott insulators in the triangular lattice. Our experiment allows for the preparation of triangular Hubbard systems of several hundred atoms and we image these systems with 98% detection fidelity. We report on our progress in characterizing triangular Hubbard systems using site-resolved density and correlation observables in the experiment and discuss comparisons of experimental data to Numerical Linked Cluster Expansion calculations as well as Quantum Monte Carlo simulations.

Our new experimental platform opens the path for studies of kinetic frustration, searches for spin-liquids and investigations of transport properties in frustrated lattices.

Presenter name: Peter Schauss

Poster session / Th-15:   *Degen. gases, many-body phys. & quant. sim.*   ID169

Can dipolar interaction shield dipolar relaxation?

Authors: Pierre Barral[1]; Michael Cantara[1]; Li Du; Alan O. Jamison[1]; Julius de Hond[1]; Wolfgang Ketterle[1]

[1] *Massachusetts Institute of Technology*

There has been a long-term effort in reducing inelastic losses in quantum gases, from dipolar relaxation in spin mixtures to reactive collisions in molecules. For the first time we show shielding between atoms via the dipolar interaction and strong confinement. This has been achieved with bosonic dysprosium and resulted in an order of magnitude suppression of dipolar relaxation. Theoretical and experimental aspects will be presented.

Presenter name: Pierre Barral

Poster session / Th-16: *Degen. gases, many-body phys. & quant. sim.* ID188

Ultracold fermions in optical superlattices

Authors: Janek Fleper[1]; Nick Klemmer[1]; Valentin Jonas[1]; Jens Samland[1]; Andrea Bergschneider[1]; Michael Köhl[1]

[1] *Physikalisches Institut, Universität Bonn*

The quantum simulation of Fermi-Hubbard models using ultracold atoms in optical lattices has been essential to deepen our understanding of condensed matter systems. With the precise tunability of the model parameters and the possibility to even change the dimensionality of the systems, it allows to investigate many-body quantum phases. In particular, probing spin correlations has been of interest in understanding high-temperature superconductivity.

Our experimental setup is based on a three-dimensional optical lattice where a vertical lattice confines the atoms in two-dimensional layers. Recently, the vertical lattice has been extended to a superlattice to implement pairs of layers coupled by interlayer tunneling. To introduce the superlattice capabilities to the two-dimensional layers, we are currently working on the implementation and stabilization of an in-plane superlattice. In the future, we are going to investigate topological systems and transport properties in time-dependent superlattices.

Presenter name: Janek Fleper

Poster session / Th-17:   *Degen. gases, many-body phys. & quant. sim.*   ID203

Preparation of the spin-Mott state: A spinful Mott insulator of repulsively bound pairs

Authors: Julius de Hond[1]; Jinggang Xiang[1]; Enid Cruz-Colón[1]; Woo Chang Chung[1]; Wenlan Chen[1]; William Cody Burton[1]; Colin J. Kennedy[1]; Wolfgang Ketterle[1]

[1] *Massachusetts Institute of Technology*

We observe and study a special ground state of bosons with two spin states in an optical lattice: the spin-Mott insulator, a state that consists of bound pairs that is insulating for both spin and charge transport. Because of the pairing gap created by the interaction anisotropy, it can be prepared with low entropy and can serve as a starting point for adiabatic state preparation. We find that the stability of the spin-Mott state depends on the pairing energy and observe two qualitatively different decay regimes.

Presenter name: Enid Cruz-Colón

Poster session / Th-18:   *Degen. gases, many-body phys. & quant. sim.*   ID222

Tomography of a number-resolving detector by reconstruction of an atomic many-body quantum state

Authors: Mareike Hetzel[1]; Luca Pezzè[2]; Cebrail Pür[1]; Martin Quensen[1]; Andreas Hüper[1]; Jiao Geng[3]; Jens Kruse[4]; Luis Santos[5]; Wolfgang Ertmer[4]; Augusto Smerzi[2]; Carsten Klempt[1]

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A tomography of many-body quantum states of indistinguishable particles is generally performed by global couplings between the involved states and a subsequent counting of the occupation numbers. While precise couplings belong to the standard toolbox, an accurate number counting presents a considerable challenge for both photonic and atomic quantum states. Here we present an application of a number-resolving atom counting for the state reconstruction of an atomic coherent spin state. We generate a coherent spin state by driving a Rabi coupling between the two hyperfine clock states of an ultracold rubidium ensemble. The result is analyzed by a number-resolving fluorescence detection setup. We characterize the fidelity of our detector and show that a negative-valued Wigner function is associated with it. The results offer an exciting perspective for the high-fidelity tomography of entangled states and can be applied for the future demonstration of Heisenberg-limited atom interferometry.

Presenter name: Mareike Hetzel

Poster session / Th-19:   *Degen. gases, many-body phys. & quant. sim.*   ID247

Probing open- and closed-channel p-wave Feshbach resonances

Authors: Colin J. Dale[1]; Denise J. M. Ahmed-Braun[2]; Kenneth G. Jackson[1]; Scott Smale[1]; Ben A. Olsen[3]; Servaas J. J. M. F. Kokkelmans[2]; Paul S. Julienne[4]; Joseph H. Thywissen[1]

[1] *University of Toronto*

[2] *Eindhoven University of Technology*

[3] *Yale-NUS College*

[4] *JQI, University of Maryland*

We study a *p*-wave Feshbach resonance in potassium-40 with a combination of spectroscopic binding energy measurements, coupled-channels calculations, and a two-channel model [1]. Using both resonant association and spin-flip association, the binding energy of bound and quasi-bound dimers is measured across a five-gauss range. Our scattering model incorporates the ramping closed-channel state, weak dipole-dipole interactions, and a low-lying *p*-wave shape resonance in the open channel. The open-channel resonance affects low energy scattering and creates nonlinearity in the binding energy near threshold, which resolves an open question [2]. We explain why in the low-energy limit a divergent contribution to the scattering volume from dipole-dipole interactions violates the *p*-wave threshold law, and how we isolate the contribution of the short-range potentials to scattering. Our improved understanding of *p*-wave scattering near this resonance enables quantitative testing of predictions for low-dimensional odd-wave gases, and lays a basis for future few- and many-body *p*-wave experiments.

[1] D. J. M. Ahmed-Braun, K. G. Jackson, S. Smale, C. J. Dale, B. A. Olsen, S. J. J. M. F. Kokkelmans, P. S. Julienne, J. H. Thywissen, Probing open- and closed-channel *p*-wave resonances, Phys. Rev. Research 3, 033269 (2021).

[2] J. P. Gaebler, J. T. Stewart, J. L. Bohn, and D. S. Jin, *p*-wave Feshbach molecules, Phys. Rev. Lett. 98, 200403 (2007).

Presenter name: Colin J. Dale

Poster session / Th-20: *Degen. gases, many-body phys. & quant. sim.* ID257

Perturbative calculation of the energy of an impurity immersed in a spin-1/2 Fermi superfluid in the Random-Phase Approximation

Authors: Arnaud Bigué[1]; Frédéric Chevy[1]; Xavier Leyronas[1]

[1] *Laboratoire de Physique de l'Ecole Normale Supérieure*

In order to investigate the low-energy physics of a system composed of an impurity immersed in a many-body medium, one may study the properties of the quasiparticle formed by the impurity dressed by excitations of the surrounding medium : the so-called polaron. This idea was first introduced in solid-state physics by Landau and Pekar in the 1950's to study the coupling of electrons to a crystalline lattice. Decades after these first theoretical studies, the development of the field of ultracold atoms provided a variety of experimental setups for the study of polaron physics : an impurity in a weakly interacting Bose-Einstein Condensate (BEC) forms a Bose polaron, whereas a Fermi polaron is obtained when the surrounding medium is a Fermi sea. By choosing the surrounding medium to be a 2-component Fermi superfluid, we can interpolate between these two types of physics along the BEC-BCS crossover.

We present a calculation of the energy of an impurity weakly coupled to a spin-1/2 fermionic superfluid based on Random-Phase Approximation. We show that it is necessary to go beyond mean-field BCS theory in order to have a proper description of the excitations of the many-body background, allowing us to cure the divergences caused by three-body effects. RPA allows us to describe the excitations of the system along the BEC-BCS crossover and to regularize the energy of the impurity. These effects should be experimentally observable, for example in the case of a small BEC immersed in a Fermi superfluid, through a measurement of the frequency shift of the oscillations of the impurity in an external potential.

Presenter name: Arnaud Bigué

Measuring the Chern number with weakly interacting spin-orbit-coupled Bose gases in optical lattices

Authors: Saubhik Sarkar[1]; Abhijeet Alase[2]; David L. Feder[2]

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[2] *Institute for Quantum Science and Technology, University of Calgary*

The quantification of topological invariants for tight-binding Hamiltonians with certain crystalline point group symmetries is well-studied, and in particular, the Chern number can be expressed in terms of the eigenvalues of the symmetry operator at the high-symmetry points of the Brillouin zone [1]. In recent years, it has become possible to utilize this relation in cold atom experiments to measure the Chern number by loading spinor BECs with spin-orbit coupling onto 2D optical lattices (e.g. Ref. [2]). Spin polarization measurements are used to quantify the topological invariant, although so far it has been limited to Chern number 1. A recent experimental proposal based on Chern insulators with additional spin-space symmetries has paved the way for extracting higher Chern number with better resolution by performing polarization measurements only at those high-symmetry points for an ideal BEC [3]. In this work, we go beyond the assumption that the BEC is noninteracting and study the effects of interactions that are weak enough not to destroy the condensation but can still be comparable or even stronger than the band gaps of the spin-orbit coupling Hamiltonian. Our framework is based on a mean-field treatment including fluctuations. Aside from quantifying the deviations in Chern number measurements from the noninteracting limit, we are able to investigate other interesting effects arising from the competition between the interactions, spin-orbit coupling, and the optical lattice potential under realistic experimental conditions.

Acknowledgments

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[2] Z. Wu, L. Zhang, W. Sun, X.-T. Xu, B.-Z. Wang, S.-C. Ji, Y. Deng, S. Chen, X.-J. Liu, and J.-W. Pan, [Science 354, 83 (2016)].
[3] A. Alase and D. L. Feder, [Phys. Rev. A 103, 053305 (2021)]

Presenter name: Saubhik Sarkar

Pattern formation in tilted optical lattices

Authors: Ludwig Mathey˙; Vijay Singh[1]; Lukas Freystatzky[2]; Henrik Zahn[2]; Marcel Kosch[2]; Luca Asteria[2]; Klaus Sengstock[2]; Christof Weitenberg[2]

[1] *University of Hamburg, University of Hannover*

[2] *University of Hamburg*

Driving a many-body system out of equilibrium induces phenomena such as the emergence and decay of transient states, which can manifest itself as pattern and domain formation. The understanding of these phenomena expands the scope of established thermodynamics into the out-of-equilibrium domain. We report our theoretical and experimental study on the out-of-equilibrium dynamics of a bosonic lattice model subjected to a strong dc field, realized as ultracold atoms in a strongly tilted optical lattice. We observe the emergence of pronounced density-wave patterns, which spontaneously break the underlying lattice symmetry. The experimental observation utilizes a single-shot imaging technique with two-dimensional single-site resolution in three-dimensional systems, which also resolves the domain structure. Our study suggests that the short-time dynamics arises from resonant pair tunneling processes within an effective description of the tilted Hubbard model. More broadly, we establish the far out-of-equilibrium regime of lattice models subjected to a strong dc field, as an exemplary and paradigmatic scenario for transient pattern formation. [1]

[1] H. P. Zahn, V. P. Singh, M. N. Kosch, L. Asteria, L. Freystatzky, K. Sengstock, L. Mathey, and C. Weitenberg, Phys. Rev. X 12, 021014 (2022)
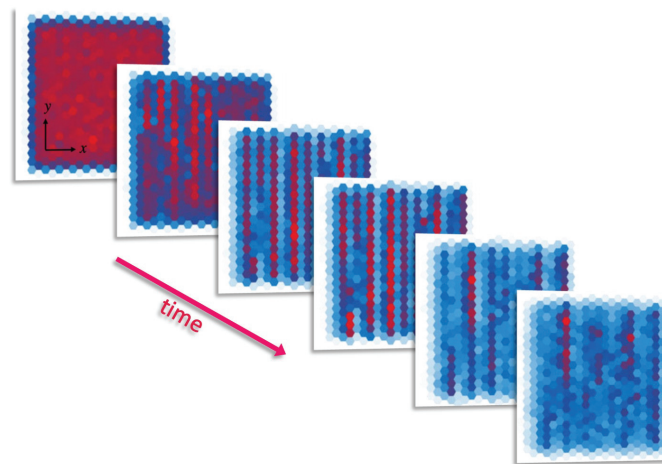
Figure 1: Spontaneous pattern formation in a tilted optical lattice

Presenter name: Ludwig Mathey

Poster session / Th-23: *Degen. gases, many-body phys. & quant. sim.* ID301

Towards programmable strontium atomic arrays with holographic metasurfaces

Authors: Weijun Yuan[1]; Aaron Holman[1]; Siwei Zhang[1]; Chun-Wei Liu[1]; Quan Gan[1]; Matthew Molinelli[1]; Xiaoyan Huang[1]; Nanfang Yu[1]; Minho Kwon[1]; Sebastian Will[1]

[1] *Columbia University*

Optical tweezer arrays combined with the rich internal structure of alkaline earth atoms enable explorations of new quantum systems for quantum optics, quantum simulation, and quantum computing. We report on our progress towards programmable arrays of strontium atoms generated with holographic metasurfaces. Innovations of our setup include: (1) Demonstration of a novel dispenser-based 2D MOT for strontium that provides a high atomic flux while being compact. (2) The development and implementation of holographic metasurfaces for the creation of high quality optical tweezer arrays with arbitrary geometries in 1D, 2D, and 3D. We have thoroughly characterized the light patterns generated by the metasurfaces and find that they efficiently produce high-quality trapping potentials. We have performed the characterization with 520 nm light, which is an unexplored magic wavelength of the strontium intercombination line. Recently, we have created an ultracold strontium gas at 1 μK via narrow line cooling. In the next step, we will trap strontium in holographic optical tweezer arrays. The scientific goals of this platform are the creation of highly entangled many-body quantum states that display subradiance, as well as applications in quantum simulation and quantum computation.

Presenter name: Yuan, Weijun

Poster session / Th-25:   *Degen. gases, many-body phys. & quant. sim.*   ID324

A resonance facilitated three-channel model for p-wave scattering

Authors: Denise Ahmed-Braun[1]; Servaas Kokkelmans[1]

[1] *Eindhoven University of Technology*

We have shown that two-channel Feshbach theory works well to describe p-wave Feshbach resonances [1], however a peculiar result of a nonintuitive molecular magnetic moment led to the realization that an additional shape resonance was part of the scattering problem and unaccounted for.

We study how two shape resonances in separate hyperfine channels in Potassium-40 interact with a Feshbach resonance. To account for all resonances, we need (at least) a three-channel model. This is theoretically and computationally highly involved.

However, as full coupled-channels calculations reveal a strong magnetic field dependence of the atom loss between the two hyperfine channels that contain the shape resonances, we approximate the coupling between the shape resonances to be purely facilitated by the Feshbach channel.

This greatly simplifies the three-channel model and allows us to retrieve the standard Breit-Wigner form of the scattering matrix with corrected values of the resonance width and resonance shift resulting from the presence of the third channel. We reveal that, contrary to the resonant two-channel model used in our previous analysis [1], the resonance-facilitated three-channel model can consistently match full coupled channels calculations with physically realistic input parameters. Hence, it captures physics beyond the reach of the standard two-channel Feshbach approach.

[1] D. J. M. Ahmed-Braun, K. G. Jackson, S. Smale, C. J. Dale, B. A. Olsen, S. J. J. M. F. Kokkelmans, P. S. Julienne, J. H. Thywissen, Probing open- and closed-channel p-wave resonances, Phys. Rev. Research 3, 033269 (2021).

Presenter name: Denise Ahmed-Braun

Poster session / Th-26: *Degen. gases, many-body phys. & quant. sim.* ID338

Interference of Bose-Einstein condensates with the Lee-Huang-Yang correction: a theoretical scheme

Authors: Che-Hsiu Hsueh[1]; Wen-Chin Wu[1]

[1] *National Taiwan Normal University*

We propose a theoretical scheme to study the Lee-Huang-Yang (LHY) quantum correction on the interference of two expanding Bose-Einstein condensates (BEC). The key is to consider a long-term expanding condensate whose wave function mimics the dynamic Gaussian wave. This enables to solve analytically the wave function at an earlier time when the LHY correction is active. Based on the GPE approach, we then perform the simulations for the interference, and a good agreement with the theory has been achieved. Our results suggest that interference might be a good candidate to identify the LHY correction in a BEC system.

Presenter name: Wen-Chin Wu

Poster session / Th-27:   *Degen. gases, many-body phys. & quant. sim.*   ID361

SU(2) hadrons on a quantum computer

Authors: Jinglei Zhang[1]; Yasar Y Atas[1]; Randy Lewis[2]; Amin Jahanpour[3]; Jan F. Haase[1]; Christine A. Muschik[1]

[1] *University of Waterloo*

[2] *York University*

[3] *Univerisity of Waterloo*

We realize, for the first time, a nonAbelian gauge theory with both gauge and matter fields on a quantum computer. This enables the observation of hadrons and the calculation of their associated masses. The SU(2) gauge group considered here represents an important first step towards ultimately studying quantum chromodynamics, the theory that describes the properties of protons, neutrons and other hadrons. Quantum computers are able to create important new opportunities for ongoing essential research on gauge theories by providing simulations that are unattainable on classical computers. Our calculations on an IBM superconducting platform utilize a variational quantum eigensolver to study both meson and baryon states, hadrons which have never been seen in a nonAbelian simulation on a quantum computer. We develop a resource-efficient approach that not only allows the implementation of a full SU(2) gauge theory on present-day quantum hardware, but further lays out the premises for future quantum simulations that will address currently unanswered questions in particle and nuclear physics.

Presenter name: Jinglei Zhang

Poster session / Th-28:   *Degen. gases, many-body phys. & quant. sim.*   ID372

Bosons in novel lattices: discontinuous quantum phase transitions and the Bose glass

Authors: Bo Song[1]; Shaurya Bhave[1]; Jr-Chiun Yu[1]; Lee Reeve[1]; Emmanuel Gottlob[1]; Georgia Nixon[1]; Ulrich Schneider[1]

[1] *University of Cambridge*

Quantum phase transitions occur at temperatures close to absolute zero and are driven by quantum fluctuations. One paradigmatic example is the change from a superfluid to a Mott insulator of ultracold bosons. This transition typically is continuous, i.e., the system undergoes a smooth change.

Using a resonantly shaken lattice, we could however turn the Mott transition into a discontinuous or first-order transition [1]. By modulating the position of the lattice, we hybridize the lowest two bands and drive a transition between a Mott insulator and a π-superfluid with a staggered order, where atoms dominantly occupy the band edge. Crucially, the transition can be discontinuous, as the nonstaggered order in the Mott insulator is incompatible with the staggered order of the π-superfluid.

Furthermore, we observe metastability and hysteresis associated with the discontinuous transition, by monitoring how fast one phase changes into another. After crossing the discontinuous phase transition, the system remains in its initial, now metastable state, instead of following the evolution of the ground state. The eventual decay from the metastable state due to quantum fluctuations would be analogous to the false vacuum decay in the early universe.

In disordered or quasiperiodic media, the propagation of matter waves will be affected by (quasi)random interferences, forming a localized state known as the Anderson insulator. In the Bose-Hubbard model, the combination of interactions and disorder can give rise to the Bose glass phase, an insulating but compressible phase without long-range order that sits between the superfluid and the Mott insulator.

We have created a two-dimensional optical quasicrystal [2] and observed Anderson localization of noninteracting bosons above a critical lattice depth [3]. The interplay of disorder and interactions significantly shifts the transition from the superfluid to the Bose glass. Our realization of this transition in the optical quasicrystal opens a new avenue to exploring intriguing transport phenomena and many-body localization in two dimensions.

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[3] Matteo Sbroscia *et al.* Observing localisation in a 2D quasicrystalline optical lattice, *Phys. Rev. Lett.* **125**, 200604 (2020).

Presenter name: Bo Song

Poster session / Th-29:   *Degen. gases, many-body phys. & quant. sim.*   ID382

Reconfiguration algorithms and low-latency feedback control system to prepare large configurations of atoms in two-dimensional arrays of optical traps

Authors: Barry Cimring[1]; Remy El Sabeh[2]; Jessica Bohm[1]; Zefei Ou[1]; Marc Bacvanski[3]; Zhiqian Ding[1]; Parth Padia[1]; Artem Zhutov[1]; Kent Ueno[1]; Anastasiia Mashko[1]; Naomi Nishimura[4]; Izzat El Hajj[2]; Amer Mouawad[2]; Alexandre Cooper-Roy[1]

[1] *Transformative Quantum Technologies, Institute for Quantum Computing, University of Waterloo, Canada*

[2] *Department of Computer Science, American University of Beirut, Lebanon*

[3] *Northeastern University, United States of America*

[4] *David R. Cheriton School of Computer Science, University of Waterloo, Canada*

We report on the design and characterization of exact and heuristic algorithms to solve atom reconfiguration problems. These algorithms can be used to prepare deterministic configurations of atoms in two-dimensional arrays of optical traps, as well as to realize quantum many-body systems with dynamic connectivity graphs and time-varying interactions. We numerically quantify the operational performance of our algorithms using realistic experimental parameters. Our results indicate that implementing the redistribution-reconfiguration (red-rec) algorithm would enable the assembly of arrays of 256 and 1024 atoms using 512 and 2048 optical traps with a success probability of 91.3(2) % and 21(1) %, respectively. Further rejecting configurations of atoms containing less atoms than a given threshold results in greater mean success probability.

We further report on the design and characterization of a low-latency reconfiguration system to perform feedback control experiments on atomic systems. The system exploits low-latency communication protocols among hardware devices and parallel processing on a CPU or a GPU to speed up the process of acquiring and processing images, generating control sequences, and synthesizing and streaming waveforms actuating active diffractive optical elements. We benchmark and optimize the computational runtime for different reconfiguration problem sizes, identifying the regime for which the GPU outperforms the CPU. This system can readily be deployed for real-time operation to actuate dynamic arrays of optical traps, realizing adaptive, variational, and error correction protocols, as well as synthesizing and streaming optimal control pulses.

Presenter name: Alexandre Cooper-Roy

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Poster session / Th-30: *Degen. gases, many-body phys. & quant. sim.* ID167

Generating and detecting topological phases with higher Chern number

Authors: Abhijeet Alase[1]; David L. Feder[1]

[1] *Institute for Quantum Science and Technology, University of Calgary*

Topological phases with broken time-reversal symmetry and Chern number $|C|>=2$ are of fundamental interest, but it remains unclear how to engineer the desired topological Hamiltonian within the paradigm of spin-orbit-coupled particles hopping only between nearest neighbours of a static lattice. We show that phases with higher Chern number arise when the spin-orbit coupling satisfies a combination of spin and spatial rotation symmetries. We leverage this result both to construct minimal two-band tight binding Hamiltonians that exhibit $|C|=2,3$ phases, and to show that the Chern number of one of the energy bands can be inferred from the particle spin polarization at the high-symmetry crystal momenta in the Brillouin zone. Using these insights, we provide a detailed experimental scheme for the specific realization of a time-reversal-breaking topological phase with $|C|=2$ for ultracold atomic gases on a triangular lattice subject to spin-orbit coupling. The Chern number can be directly measured using Zeeman spectroscopy; for fermions the spin amplitudes can be measured directly via time of flight, while for bosons this is preceded by a short Bloch oscillation. Our results provide a pathway to the realization and detection of novel topological phases with higher Chern number in ultracold atomic gases.

Presenter name: Abhijeet Alase

Virtual poster / Vir4: *Degen. gases, many-body phys. & quant. sim.* ID110

Scale-free localization induced by long-range coupling

Authors: Yi-Cheng Wang[1]; Jhih-Shih You[2]; Hsiang-Hua Jen[3]

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nonHermiticity is ubiquitous in systems that exchange energy with the environment, and these nonHermitian systems are sensitive to boundary conditions. Recent years there have seen various studies on nonHermitian skin effect, where extensive bulk eigenstates pile at open boundaries. Yet, little is known about the role of long-range coupling in a nonHermitian system. Here we study the nonHermitian skin effect in a one-dimensional lattice model with long-range couplings whose coupling range depends on the system size. We show that the nonlocality gives rise to the scale-free localization, where the localization length of eigenstate is proportional to the system size. By tuning the coupling range, the competition between the nearest-neighboring coupling and nonlocality results in a crossover in the size dependence of localization length. Our results shed light on the interplay between long-range coupling and nonHermiticity, which can be implemented and observable in atom-waveguide interfaces or optical lattices of ultracold atoms.

Presenter name: Yi-Cheng Wang

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Virtual poster / Vir6: *Degen. gases, many-body phys. & quant. sim.* ID215

Observation of universal Hall response in strongly interacting fermions

Authors: Tian Wei Zhou[1]; Giacomo Cappellini[2]; Daniele Tusi[3]; Lorenzo Franchi[4]; Jacopo Parravicini[5]; Cecile Repellin[6]; Sebastian Greschner[7]; Massimo Inguscio[8]; Thierry Giamarchi[7]; Michele Filippone[9]; Jacopo Catani[10]; Leonardo Fallani[11]

[1] *LENS - University of Florence*

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The Hall effect, originating from the motion of charged particles in magnetic fields, has deep consequences for the description of materials, extending far beyond condensed matter. Understanding such an effect in interacting systems represents a fundamental challenge, even for small magnetic fields. In a very recent work, we use an atomic quantum simulator to track the motion of ultracold fermionic ^{173}Yb atoms in two-leg ribbons threaded by artificial magnetic fields. We unveil a *universal* interaction-independent behavior above an interaction threshold, in agreement with theoretical analyses. More in detail, we monitor the real-time dynamics of the system following the instantaneous quench of a linear potential, which tilts the lattice along x and mimics the action of a longitudinal electric field Ex. We observe that the combined action of Ex and the synthetic magnetic flux triggers a longitudinal current Jx, accompanied by the Hall polarization of the system along the transverse direction. Through controllable quench dynamics, we measure the Hall response for a range of synthetic tunneling and atomic interaction strength. Our system, able to reach hard-to-compute regimes, also demonstrates the power of quantum simulation to investigate strongly correlated topological states of matter.

Presenter name: Jacopo Catani

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online poster URL:

https://doi.org/10.48550/arXiv.2205.13567

Virtual poster / Vir7: *Degen. gases, many-body phys. & quant. sim.* ID231

Finite-momentum superfluid phases of ultracold bosons in optical lattices

Authors: Kuldeep Suthar[1]; Pardeep Kaur[2]; Sandeep Gautam[2]; Dilip Angom[3]

[1] *Institute of Atomic and Molecular Sciences, Academia Sinica, Taiwan*

[2] *Indian Institute of Technology Ropar, Rupnagar 140001, Punjab, India*

[3] *Department of Physics, Manipur University, Canchipur 795003, Manipur, India*

The ultracold atoms are an excellent platform to simulate complex quantum many-body systems of condensed-matter physics. We discuss the quantum phases of a two-dimensional spin-orbit coupled bosons in an optical lattice. This system breaks the rotational symmetry in momentum-space and the condensation occurs at finite momentum. The interplay of single-particle hopping, strength of spin-orbit coupling, and interspin interaction results into finite-momentum superfluidity. At low hopping strengths, the insulating phases are destroyed and phase-twisted superfluid emerges. We further identify a phase-twisted to stripe superfluid transition as hopping strength increases. Finally, we show the role of thermal fluctuations on the stability of finite-momentum superfluids. Our findings are timely and pertinent to the recent progress on quantum gas experiments and pave a way to observe finite-momentum superfluid phases in optical lattices.

Presenter name: Dr. Kuldeep Suthar

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Virtual poster / Vir8: *Degen. gases, many-body phys. & quant. sim.* ID245

Atomic cooling scheme and ground experimental verification towards Chinese space station

Authors: Xuzong Chen[1]; Hui Li[2]; Jiacheng Yu[2]

[1] *Peking University*

[2] *Institute of Quantum Electronics, Department of Electronics*

The Cold Atom Physics Rack (CAPR) of Chinese space station will be launched at the end of 2022. The important goal of CAPR is to achieve BEC at 100pk. In order to obtain ultracold atoms in microgravity of space station, we propose a two-stage cooling scheme using all-optical trap with different waist beams. The cold atom cloud obtained by this scheme is composed of condensate and thermal atoms around condensate. The design of our two-stage cooling scheme will effectively reduce the temperature of the thermal atom cloud and the effective temperature generated by the interaction energy of the condensate. The atomic temperature of 2nk is obtained from the ground test experiment, and the corresponding temperature under the microgravity condition of the space station is theoretically predicted to be less than 100pk. Taking the advantages of ultracold temperature and long-time detection, many scientific experiments will be arranged.

Presenter name: Xuzong Chen

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Virtual poster / Vir9:   *Degen. gases, many-body phys. & quant. sim.*   ID275

A novel probe of quantum many-body correlations by path-independent ramping dynamics

Authors: Libo Liang[1]; Wei Zheng[2]; Ruixiao Yao[3]; Qi Huang[1]; Qinpei Zheng[1]; Xuzong Chen[1]; Wenlan Chen[3]; Hui Zhai[4]; Jiazhong Hu[3]

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Quantum correlations are the central features characterizing many-body physics, which become one of the most important observables in many experiments. Here we present an alternate scheme both theoretically and experimentally, probing the equilibrium correlations by ramping dynamics which can tell a strong correlated system has well-defined quasi-particle descriptions or not. By ramping a physical parameter nonadiabatically with finite speeds, we find the leading deviation of any measured observable to the adiabatic value is linearly proportional to the ramping speed, path-independent and only depending on the final states' equilibrium correlations. The slope of linearity reflects the equilibrium correlations and is significant while the system does not have a well-defined quasi-particle description. We demonstrate and experimentally prove our theory in Bose-Hubbard models with degenerate cold gas.

Experimentally, we first ramp our system from four different initial lattice depths to the same final one at 15Er (recoil energy). After each ramp, we extract our observable, the central quasi-momentum distribution in 1D by means of our developed band-mapping method. Through the four sets of measurements, we find that the strength of our observable is only linearly dependent on the ramping speed and we obtain the same slope of linearity reflecting the same equilibrium correlations for the same final state. Then we change the final lattice depths to 11, 13, 17, 19, 21Er to obtain the slopes of linearity for different final states. We find the slopes of linearity are apparently larger in quantum critical region, reflecting the significant equilibrium correlations.

Ideally, by comparing our measurements with theoretical results, we can determine the critical exponent by studying the temperature dependence of this correlation. Our scheme can be directly applied to probe correlations in other ultra-cold atomic gases systems, such as unitary Fermi gas and quantum simulation of various spin models. Our method can also be applied to other systems beyond ultra-cold atomic gases, such as trapped ions, NV centers, and condensed matter systems. As shown in the example of studying the Bose-Hubbard model, our method accesses a different aspect of quantum many-body correlation compared with many existing measurement tools. Thus, our protocol provides a new direction to study correlations in quantum matters.

Presenter name: Libo Liang

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online poster URL:

Virtual poster / Vir10: *Degen. gases, many-body phys. & quant. sim.* ID279

Simulating an exact one-dimensional transverse Ising model in an optical lattice

Authors: Ren Liao[1]; fangyu Xiong[2]; Xuzong Chen[1]

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A spinless Bose-Hubbard model in a one-dimensional (1D) double-chain tilted lattice is numerically studied at unit filling per cell. When each atom is localized in a two-site cell, the low-energy effective model gives rise to an exact textbook model of the 1D transverse Ising model via superexchange interaction. To validate the effective transverse Ising model, we calculate the energy spectrum and the nearest-neighbor correlation functions of the states in a subspace of the Bose-Hubbard model which is equivalent to the Hilbert space of a spin-1/2 magnetic model. The results show good consistency with the effective transverse Ising model, and we show that it is possible to simulate the dynamical quantum phase transition of the 1D transverse Ising model exactly with such a double-chain Bose-Hubbard model. Our results may provide some inspirations for realizing and exploring an exact 1D transverse Ising model in ultracold neutral atom systems.
Key words: transverse Ising model; Bose-Hubbard model; dynamical quantum phase transition

Presenter name: Ren Liao

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Virtual poster / Vir11: *Degen. gases, many-body phys. & quant. sim.* ID280

Dimensional crossover of quantum critical dynamics at many-body phase transitions

Authors: Qinpei Zheng[1]; Yuqing Wang[2]; Libo Liang[1]; Qi Huang[1]; Jingxin Sun[1]; Ren Liao[1]; Pengju Zhao[1]; Jiazhong Hu[2]

[1] *School of Electronics, Peking University, Beijing 100871, China*

[2] *Department of Physics and State Key Laboratory of Low Dimensional Quantum Physics, Tsinghua University, Beijing, 100084, China*

We demonstrate how dimensions of many-body systems influence the critical dynamical behaviors at quantum phase transition. We perform our experiment in a quasi-two-dimensional Bose-Hubbard model and do the improved band-mapping method to measure the quasi-momentum distribution. Based on these measurements, we obtain the components of coherent and incoherent parts in the mixture of superfluid and Mott insulators. This helps us to learn about the excitation defects due to the nonadiabaticity of quantum phase transitions. We observe a smooth crossover of critical scalings from two dimensions to three dimensions. To further quantitatively explain the phenomena, we apply quantum Monte Carlo calculations in an anisotropic Bose-Hubbard model.

Presenter name: Qinpei Zheng

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Virtual poster / Vir12:   *Degen. gases, many-body phys. & quant. sim.*   ID286

Enhanced antiferromagnetism driven by superexchange interaction in a three-component Fermi-Hubbard model

Authors: Ren Liao[1]; JIngxin Sun[1]; Pengju Zhao[1]; Shifeng Yang[1]; Hui Li[1]; Xinyi Huang[1]; Wei Xiong [1]; Xiaoji Zhou Zhou[1]; Dingping Li[1]; Xiongjun Liu[1]; Xuzong Chen[1]

[1] *Peking University*

The low-energy effective XXZ model of a three-component Fermi-Hubbard model is analyzed at a Mott-insulator regime where each lattice site is filled with either a single atom or an atom pair. We find the nearest-neighbor spin-exchange interaction can be strongly reduced with atoms paired, while the diagonal antiferromagnetic interaction remains unaffected. Therefore, the antiferromagnetism of such a three-component Fermi-Hubbard model can be stronger than that of a typical two-component Fermi-Hubbard model at the half-filling regime. And we discussed the possible realization with 6-Li atoms under a proper external magnetic field where the three-body loss rate is small. Our results may be useful for experimental observation of the long-range antiferromagnetic order of ultracold neutral fermions at low temperature. Key words: Antiferromagnetism; Fermi Hubbard model;

Presenter name: Ren Liao

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Virtual poster / Vir13:   *Degen. gases, many-body phys. & quant. sim.*   **ID289**

Decay of collective dipole spin wave in the nonlinear optics regime

Authors: lingjing Ji[1]; Yizun He[1]; Liyang Qiu[1]; Yuzhuo Wang[1]; Saijun Wu[1]

[1] *Fudan University*

Interaction of light with a dense cloud of ultracold atoms is an open-system many-body problem. Even within the linear optics regime, interesting effects beyond effective medium theory can arise from near-field interaction and multiple scatterings. On the other hand, when subjecting to strong optical excitions, the coupled quantum dynamics involves long-range dipole correlations defined in an exponentially large Hilbert space, and can become impossible to simulate by any classical computers. Therefore, comparing with experimental investigation of linear optical response, nonlinear optical response of cold atoms can be even more intriguing for uncovering emergent many-body effects in optics. In this work, we develop an experimental technique to study the dynamics of laser-cooled atomic ensembles subjected to strong resonant excitations. By temporally shifting the wavevector of the strongly excited dipole spin-wave, the colletive forward emissions are separated from the much stronger excitation pulse itself, fascilitating a precise measurement of the collective emission dynamics deeply in the nonlinear excitation regime, for the first time to our knowledge. In contrast to an exponential superradient decay in the linear regime, we find the nonlinearly excited spin waves decay much slower initially, for certain time, before the recovery of exponential decay characteristics. The measured decay curves deviate substantially from simple theoretical predictions by nonlinear couple dipoles that ignore many-body dipole correlations.

Presenter name: Ji Lingjing

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Virtual poster / Vir14:   *Degen. gases, many-body phys. & quant. sim.*   ID292

The manipulation of ultracold atoms of high orbitals in optical lattices

Authors: Xiaoji Zhou[1]; Shengjie Jin[1]; Hongmian Shui[1]; Zhongcheng Yu[1]

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Ultracold atoms in optical lattices are a powerful tool for quantum simulation, precise measurement, and quantum computation. A fundamental problem in applying this quantum system is how to manipulate the higher bands or orbitals in Bloch states effectively. Here we mainly introduce our methods for manipulating high orbital ultracold atoms in optical lattices with different configurations. Based on these methods, we load the ultracold atoms into the P and D bands of the hexagonal optical lattice and the triangular lattice, and then observe the novel quantum phases and study the dynamical evolution of the atoms in the high bands. Furthermore, we construct the atom-orbital qubit under nonadiabatic holonomic quantum control. The effective manipulation of the high orbitals provides strong support for applying ultracold atoms in the optical lattice in many fields.

The first is the shortcut method for transferring the ultracold atoms in a harmonic trap to the D band of a triangular optical lattice. The lattice potential can be expressed as $V(\vec{r}) = -V \sum_{i,j} \cos[(\vec{k}_i - \vec{k}_j) \cdot \vec{r}]$, where $\vec{k}_1 = (\sqrt{3}\pi, -\pi)/\lambda$, $\vec{k}_2 = (-\sqrt{3}\pi, -\pi)/\lambda$, $\vec{k}_3 = (0, 2\pi)/\lambda$, and V is the depth of the triangular lattice. This shortcut method is characterized by short time and high fidelity, which can directly transfer ultracold atoms from the ground state in the harmonic trap to any Bloch state, and accurately manipulate atoms of different orbitals in optical lattices. The shortcut is composed of a series of optical lattice pulse sequences. Each pulse pulse-i consists of two parts. First, the lattice is turned on for t_j^{on}, and then the interval is t_j^{off}. The time $\{t_j^{\mathrm{on}}, t_j^{\mathrm{off}}\}$ are optimized to achieve the goal of manipulating quantum states. By this method, we load Bose-Einstein condensate of 87Rb atoms into the Γ point of the first D band with zero quasimomentum in the triangular optical lattice. Then we investigate the collisional scattering channels for atoms in the excited bands of a triangular optical lattice and demonstrate a dominant scattering channel in the experiment. After some evolution time, the number of atoms scattering into the S-band induced by two-body collisions is around four times the number that scatters into the second most populated band. Our numerical calculation shows that the ss scattering channel is dominant, roughly consistent with the experimental measurement. The appearance of dominant scattering channels in a triangular optical lattice is owing to nonorthogonal lattice vectors. This work is helpful for the research on many-body systems and directional enhancement in optical lattices.

Next, we introduce the band swapping technique for loading the atoms into the second band of a hexagonal optical lattice. The key to realizing this is constructing a controllable composite optical lattice, including deep and shallow wells. In the experiment, we construct the composite hexagonal lattice by combining a triangular lattice and a honeycomb lattice, which can be expressed as $V(\vec{r}) = -V_{\epsilon'} \sum_{i,j} \cos[(\vec{k}_i - \vec{k}_j) \cdot \vec{r} + \theta_j - \theta_i] + \frac{1}{2} V_\epsilon \sum_{i,j} \cos[(\vec{k}_i - \vec{k}_j) \cdot \vec{r}]$. V_ϵ ($V_{\epsilon'}$) is the depth of the honeycomb (triangular) lattice. This lattice contains two sub-wells, denoted as A and B. At first, well A is deeper than B, and the atoms are located at the A well. By changing the phase θ, well A is shallower than B, and the atoms are pumped into the second band. After the atoms are transferred into the band maximum of the second band, the phase coherence in the state will immediately disappear. After a few milliseconds, the phase coherence reemerges, and the quantum state spontaneously chooses one orientation, giving rise to a three-state Potts nematicity.

Finally, we introduce an atom-orbital qubit using *s*- and *d*-orbitals of a one-dimensional optical lattice. We initial the qubit by the shortcut method, and the average fidelity of the initial states is 99.72(7)%. We have measured the orbital relaxation time (T_1) and the dephasing time (T_2), finding $T_1 = 4.5 \pm 0.1$ ms (milliseconds), and $T_2 = 2.1 \pm 0.1$ ms in our experiment. By programming lattice modulation, we reach universal nonadiabatic holonomic quantum gate control over the atom-orbital qubit, which exhibits noise-resilience against laser

fluctuations due to geometrical protection. We demonstrate the holonomic quantum control of Hadamard and $\pi/8$ gates, which form a universal gate-set for single-qubit rotation. The lattice modulation pulses are programmed to minimize orbital leakage error, which is the key to reaching high fidelity holonomic quantum control of atom-orbital qubit. We implement quantum process tomography (QPT) on the orbital qubit to measure the full density matrix, from which the obtained average gate fidelity is 98.36(10)%. Furthermore, we give a proposal to construct two-qubit gates, by which we can achieve universal quantum computing with the orbit qubit setup. Our work opens up wide opportunities for atom-orbital-based quantum information processing, of vital importance to programmable quantum simulations of multiorbital physics in molecules and quantum materials.

[1] Hongmian Shui, Shengjie Jin (Co-first author), Zhihan Li, Fansu Wei, Xuzong Chen, Xiaopeng Li, and Xiaoji Zhou. Atom-orbital qubit under nonadiabatic holonomic quantum control. Physical Review A 104, L060601 (2021).

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Presenter name: Xiaoji Zhou

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Virtual poster / Vir15:   *Degen. gases, many-body phys. & quant. sim.*   ID323

Many-body dynamical quantum phase transitions in cold atomic optical lattice

Authors: Qi Huang[1]; Ruixiao Yao[2]; Libo Liang[1]; Qinpei Zheng[1]; Dingping Li[3]; Wenlan Chen[4]; Xuzong Chen[1]; Jiazhong Hu[4]

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[4] *Department of Physics and State Key Laboratory of Low Dimensional Quantum Physics, Tsinghua University, and Frontier Science Center for Quantum Information, Beijing 100084, China.*

Nonequilibrium physics and many-body dynamic behavior is an important and challenging question in modern physics. We using the cold atomic inhomogeneous optical lattice system investigate dynamic quantum phase transition from superfluid to Mott insulator. We use a new method to measure the quasi-momentum distribution and define the observable physical quantities based on it. According Kibble-Zurek mechanism which is used to explain some universal scaling law in dynamic phase transitions and our observations, by obtaining the relaxation time and defect density respectively, we get two sets of critical parameters. Also, different regions with different scaling behaviors are observed by different ramp rates. These provide new possibilities for further study of the many-body and dynamic behavior of quantum phase transition.

Reference
Qi Huang *et al.* Physical Review Letters **127**, 200601 (2021)

Presenter name: Qi Huang

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Virtual poster / Vir16: *Degen. gases, many-body phys. & quant. sim.* ID326

Vortex nucleations in spinor Bose condensates induced by synthetic gauge potentials

Authors: Yu-Ju Lin[1]; Shao-Ci Wu[1]; Yuki Kawaguchi[2]; Sungkit Yip[3]; Tzu-Ken Shen[1]

[1] *Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei, Taiwan*

[2] *Department of Applied Physics, Nagoya University, Nagoya*

[3] *Institute of Physics,Academia Sinica, Taipei, Taiwan*

We investigate novel mechanisms of vortex nucleations in a spinor Bose condensate owing to synthetic azimuthal gauge potentials, which are light-induced effective rotations, both theoretically and experimentally. We identify the main mechanism of vortex nucleations as the dynamical instability of low-energy excitations associated with vortex splitting and pair creation at the center of condensate in respective internal spin components. This is unlike the vortex nucleations in scalar Bose condensates under mechanical stirring, where the vortices nucleate from the edge of the cloud due to surface mode excitations. Our experimental data has qualitative agreement with the time-dependent Gross-Pitaevskii equation (GPE) simulations including laser beam jittering noise in the experimental setup.

Presenter name: Wu, Shao-Ci

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/ Vir17: *Degen. gases, many-body phys. & quant. sim.* ID385

Quantum thermodyanmics in quenched spinor condensates

Authors: Meng-Ju Tsai[1]; Yu-Hao Yeh[1]; Xiang-Liang Pan[1]; Jun-Ho Hsieh[1]; Ming-Shien Chang[1]

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We present our recent studs contributed to quantum thermalization in an isolated system utilizing spinor condensates[1]. Under the single-mode approximation (SMA), the motional degrees of freedom of spinor condensates are frozen, and all Zeeman components share the same spatial wavefunction. Under such circumstances, the spin dynamics dominates the system's evolution, and the restricted spin degrees of freedom presents a small Hilbert space ideally suited for studying quantum thermalization[2].

Experimentally, we prepared spinor condensates under the SMA with designed spin compositions in a high magnetic field, and the spin dynamics in low fields with different field ramping speeds were followed. The experiment results were used to test the eigenstate thermalization hypothesis (ETH).

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Presenter name: Meng-Ju, Tsai

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Poster session / Vir18: *Degen. gases, many-body phys. & quant. sim.* ID55

Thermodynamic characteristics of ideal quantum gases in harmonic potentials within exact and semiclassical approaches

Authors: Alexander Peletminskii[1]; Andrii Sotnikov[1]; Elvira Bilokon[1]; Valeriia Bilokon[1]

[1] *Karazin Kharkiv National University, Akhiezer Institute for Theoretical Physics, NSC KIPT*

We theoretically examine equilibrium properties of the harmonically trapped ideal Bose and Fermi gases in the quantum degeneracy regime. We analyze thermodynamic characteristics of gases with a finite number of atoms by means of the known semiclassical approach and perform comparison with exact numerical results. For a Fermi gas, we demonstrate deviations in the Fermi energy values originating from a discrete level structure and show that these are observable only for a small number of particles. For a Bose gas, we observe characteristic softening of phase transition features, which contrasts to the semiclassical predictions and related approximations. We provide a more accurate methodology of determining corrections to the critical temperature due to finite number of particles.

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Presenter name: Elvira Bilokon

Thermodynamic properties of interacting trapped Bose gases

Authors: Edmur Martins[1]; Gustavo Telles[1]

[1] *University of Sao Paulo*

The understanding of the interplay between quantum-statistical phenomena and the atomic interactions taking place in trapped degenerate gases may yet extend far our ability to control and harness the full potential of such exquisite, dilute quantum systems. In this scenario, a key role is played by the external trap potential, which defines the spatial dissociation of the condensate and thermal fraction, at finite temperatures. The decoupled spatial spread may be clearly observed using simple techniques such as absorption imaging, allowing for detailed studies of the physical properties of the system. Many previous works already mapped the properties of condensed gases at very low temperatures ($\ll T_c$), with negligible thermal fraction. In the Thomas-Fermi regime, the general behavior of condensates is essentially set by the interplay between the external (trap) potential and the atomic interactions. At higher temperatures, yet below Tc, the thermal fraction becomes meaningful to the system, even if it is much more dilute than the condensate. In these conditions, the kinetic energy per thermal atom grow larger than the mean-field energy, though the ideal gas behavior remains mostly valid. Note that, most fundamental thermodynamical properties, such as the condensed/thermal fraction and the mean energy, are experimentally measurable. Detailed comparison of experimental results, acquired under actual laboratory conditions of finite temperature and number, with theoretical frameworks including the atomic interactions are yet very few. Moreover, to the best of our knowledge, simple analytical models, accounting for the interactions, ready to guide experimental measurements and initial analysis are still not available in the literature. We then present here an alternative theoretical framework, based on the density-of-state approach, which allows for an analytical evaluation of the thermodynamics of trapped Bose gases. In this work, we start by determining a better and more accurate density of states for an ideal trapped system, particular to the chosen spheroid geometry (oblate or prolate). We then derive two fundamental state variables of the system, the total number of atoms and the total internal energy. Next we determine other interesting quantities such as the number density, the chemical potential, the heat capacity, and the isothermal compressibility. The results are then analyzed near the temperature range of interest, running across the critical temperature. We compared our result with those presented in the literature to draw the conclusions and suggest some follow-up work.

Presenter name: Telles, Gustavo

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Poster session / Vir20:   *Degen. gases, many-body phys. & quant. sim.*   ID56

Quantum correlations in two-orbital ultracold atomic mixtures in one-dimensional optical lattices

Authors: Valeriia Bilokon[1]; Elvira Bilokon[2]; Andrii Sotnikov[2]; Agnieszka Cichy[3]; Mari Carmen Bañuls[4]

[1] *Karazin Kharkiv National University, National Science Center "Kharkiv Institute of Physics and Technology"*

[2] *Karazin Kharkiv National University, Akhiezer Institute for Theoretical Physics, NSC KIPT*

[3] *Faculty of Physics, Adam Mickiewicz University*

[4] *Max Planck Institute of Quantum Optics*

We theoretically study magnetic and orbital correlations in ultracold Fermi gases of alkaline-earth(-like) atoms in one-dimensional state-dependent optical lattices. In particular, with the calculated parameters in the two-orbital Hubbard model realized with ^{87}Sr, ^{171}Yb, and ^{173}Yb atoms, we employ exact diagonalization and matrix product state approaches. We calculate spatial correlation functions in the spin and orbital sectors and construct effective diagrams in the space of variable densities of atomic components in different orbital states. We also examine antiferro-orbital and antiferromagnetic couplings in the strong-coupling limit. For small systems with the fixed number of particles, we study the evolution of correlation functions with temperature.

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Presenter name: Valeriia Bilokon

Virtual poster / Vir21: *Degen. gases, many-body phys. & quant. sim.* ID312

Investigation of Fermi-Hubbard ladders with the quantum gas microscope

Authors: Petar Bojovic[1]; Pimonpan Sompet[1]; Sarah Hirthe[1]; Dominik Bourgund[1]; Thomas Chalopin[1]; Julian Bibo[2]; Joannis Koepsell[1]; Ruben Verresen[3]; Frank Pollmann[2]; Guillaume Salomon[1]; Christian Gross[1]; Timon Hilker[1]; Immanuel Bloch[1]

[1] *Max Planck Institute of Quantum Optics*

[2] *Department of Physics, Technical University of Munich*

[3] *Department of Physics, Harvard University*

With our ^{6}Li quantum gas microscope we are able to prepare, manipulate and image individual ultracold fermions in optical lattices. In every experimental run we have an access to full density and spin resolution [1], as well as to site-resolved potential shaping [2]. This platform has proven to be promising for the analog quantum simulation, e.g., of Fermi-Hubbard model which is believed to be the key in understanding the cuprate high-temperature superconductors. With this poster I will present the capabilities of our experiment and how we simulate and study the Fermi-Hubbard model, with a focus on our recent findings in undoped ladder systems.

In undoped ladder systems, I will show that we are able to experimentally realize the paradigmatic example of symmetry protected topological (SPT) phase – the spin-1 Haldane chain [2]. This is achieved by creating a tailored spin-1/2 ladder geometry which maps directly to the spin-1 Haldane chain [3]. We detect a finite nonlocal string correlator in the bulk and localized spin-1/2 states at the edges, which are the main characteristics of the SPT phase. The robustness of the state is confirmed by tuning the ratio of the leg to rung coupling of the ladder.

[1] J. Koepsell et al., Phys. Rev. Lett. 125, 010403 (2019)
[2] P. Sompet, S. Hirthe, D. Bourgund et al., Nature, doi: 10.1038/s41586-022-04688-z (2022)
[3] White et al., Phys. Rev. B 53, 52 (1996)

Presenter name: Petar Bojovic

online poster URL: https://cloud.physik.lmu.de/index.php/s/wLk6SDRHz7fm4Nd

Catching a particle inside a barrier

Authors: David Spierings[1]; Joseph McGowan[1]; Nick Mantella[1]; Harshil Neeraj[1]; Aephraim Steinberg[1]

[1] *University of Toronto*

Can one detect a tunneling particle inside of a barrier? Traditional quantum measurement of the position of a tunneling particle inside a barrier transfers significant energy to the particle, precluding observation of a tunneling particle while it is in the 'forbidden' region. Instead, one might probe a tunneling particle 'weakly,' so as to prevent energy transfer, as envisioned by a weak Larmor measurement, and post-selecting on the particle having been in the probed region of the barrier. We theoretically study how this weak, nondisturbing measurement can become strong upon post-selection and enhance transmission through the barrier. We discover a new timescale corresponding to the duration over which particles in the probed region are significantly disturbed, which is tempting to interpret as the time it takes for particles to escape the probed region undetected. We observe that such measurements may lead to experimentally realizable 'observationally assisted barrier penetration.'

Presenter name: Aephraim Steinberg

Micro-integrated laser and frequency reference modules for operation in quantum technology applications

Authors: Janpeter Hirsch[1]; Nora Goossen-Schmidt[1]; Sriram Hariharan[1]; Norbert Müller[1]; Max Schiemangk[1]; Christoph Tyborski[1]; Dian Zou[1]; Andreas Wicht[1]

[1] *Ferdinand-Braun-Institut (FBH)*

The Ferdinand-Braun-Institute has been developing micro-integrated, high-power, narrow-linewidth semiconductor laser sources for precision spectroscopy applications for more than ten years. Starting with hybrid-integrated diode laser chips and micro-optics on a ceramic platform, we successfully enabled Bose-Einstein condensation experiments in a drop tower [1]. As the next step we now develop, qualify, and deliver whole laser modules for applications on space-borne platforms including sounding rockets, the International Space Station and small satellites [3]. Here, we present two novel devices for operation in quantum technology applications: A hybrid micro-integrated laser module and a frequency reference module.

A robust design will enable the deployment of our latest micro-integrated diode laser modules in space applications. Specially developed control algorithms shall ensure enhanced functionality and user-friendliness. Temperature stabilization is achieved by the calculation of an effective micro-optical bench temperature through distributed temperature sensors. By that the optical resonator length and hence the optical emission frequency is stabilized. An intra-cavity pick-off will enable the generation of an error signal allowing to extend the laser's mode-hop free tuning range beyond the limit given by the free spectral range of the laser resonator.

Especially tailored to meet the requirements of laser automation in quantum technology applications, a compact and robust frequency reference module is being developed. By an intermediary stabilization of the laser to the well-designed frequency reference, laser locking to a desired atomic transition is accelerated. A sophisticated thermal stabilization concept shall ensure a frequency accuracy of 50 MHz and a tuning range of more than 20 GHz. The reference module is designed to be operated in three different modes: (i) Stabilization of a laser to the frequency reference for achieving an accelerated lock-acquisition, (ii) Operation of the frequency reference as a wavemeter and measuring the emission frequency of a free-running laser and (iii) recalibration of the frequency reference with a reference laser. In its first application the frequency reference is intended to complement the laser module by facilitating accurate control of the laser frequency in an atom interferometer application with ultra-cold potassium atoms.

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[2] Julia Pahl et al., Appl. Opt. 58, 5456-5464 (2019)
[3] Christian Kürbis et al., Appl. Opt. 59, 253-262 (2020)

Presenter name: Janpeter Hirsch

Poster session / We-30: *Misc.* ID352

Zeeman-Sisyphus deceleration of polyatomic molecules

Authors: Alexander Frenett[1]; Hiromitsu Sawaoka[1]; Abdullah Nasir[1]; Nathaniel Vilas [1]; Christian Hallas[1]; Zack Lasner[1]; Benjamin Augenbraun[1]; John Doyle[1]

[1] *Harvard University*

Polyatomic molecules can provide improvement over diatomic systems in cold chemistry, precision measurement of fundamental physics, and quantum information. Slowing these species to trappable velocities is a major limitation in realizing these applications. Over the past decade, radiative slowing methods have been successfully applied to diatomic and, recently, triatomic molecules with highly diagonal Frank-Condon factors. Alternative slowing methods are needed for molecules that are less favorable for scattering the ~10,000 photons required for radiative slowing. Here we present a superconducting-magnet-based Zeeman-Sisyphus decelerator that requires fewer than 10 photon scatters to slow molecules to velocities suitable for loading a MOT, magnetic, or electric trap. We describe the design considerations, apparatus construction, and application of the slower to both CaOH and YbOH molecular beams. We also discuss the generalizability of this slowing method to increasingly complex molecular species.

Presenter name: Alexander Frenett

Poster session / Th-31: *Misc.* ID84

Stand-alone vacuum cell for compact ultracold quantum technologies

Authors: Oliver Burrow[1]; Paul F. Griffin[1]; Aidan S. Arnold[1]; Erling Riis[1]

[1] *University of Strathclyde*

In the drive to develop cold-atom quantum technologies, compact vacuum systems are key to enabling quantum sensing for real world applications. These vacuum systems not only have to be reduced in size, weight, and power compared to their traditional counterparts, but face other challenges. Eliminating active pumping addresses both size and power, but introduces the issue of helium gas permeation as passive vacuum pumping techniques do not remove noble gases. Here we present a centilitre-scale vacuum cell, constructed from low helium permeable materials, with an integrated grating magneto-optical trap optic. A robust cold-atom demonstrator is described, loading 107 s-1 laser-cooled 87Rb, with 12 W of electrical power through a USB battery and optical power delivered by fibre. Under active vacuum pumping, with continuous Rb gas emission, a pressure equilibrium of 10^{-7} mbar is achieved. With purely passive vacuum pumping the pressure stabilises to 3×10^{-6} mbar with a 17-day time constant, and has been demonstrated to work for two years with only passive vacuum pumping. This research continues to advance and will enable a wide range of cold-atom quantum sensors.
Appl. Phys. Lett. 119, 124002 (2021); doi: 10.1063/5.0061010

Presenter name: Dr. Oliver Burrow

Poster session / Th-32: *Misc.* ID364

Direct laser cooling of YO molecules

Authors: Kameron Mehling[1]; Jun Ye[1]; Yewei Wu[1]; Justin Burau[1]; Parul Aggarwal[1]; Shiqian Ding[1]

[1] *JILA*

Ultracold molecules are poised to open many important applications, ranging from quantum information science to precision tests of fundamental physics. In the past decade, direct laser cooling of molecules has successfully achieved magneto-optical trapping, sub-Doppler cooling, and confinement in conservative optical traps. A key research direction for molecule-based quantum science requires achieving a high phase space density. We have recently demonstrated the highest phase-space density in a bulk gas of laser cooled molecules[1]. We are working on further increasing the phase space density of YO molecules by optimizing the scattering rate of the slowing scheme and MOT parameters. We will present our latest work in this direction and also discuss a scheme to utilize narrow-line cooling on an intermediate low–lying A'2Δ3/2 state, after cooling the YO molecules by gray molasses to a few microkelvin temperature.

[1] Y. Wu et al. Phys. Rev. Lett. 127, 263201 (2021)

Presenter name: Kameron Mehling

Virtual poster / Vir22:   *Misc.*   ID315

Bi-color atomic beam slower and magnetic field compensation for ultracold gases

Authors: Jianing Li[1]; Kelvin Lim[1]; Swarup Das[1]; Thomas ZanonWillette[1]; Chang Chi Kwong[1]; Shau-Yu Lan[1]; David Wilkowski[1]

[1] *Nanyang Technological University, 21 Nanyang Link, Singapore 637371, Singapore*

Since the first demonstration of laser cooling and trapping, cold and ultracold trapped atoms have played a vital role in realizing many modern advanced atomic physic experiments through a coherent control of matter-light interaction. Among various trapped cold atomic species, Strontium atoms has become one of the interesting candidates in realizing various experimental platforms from quantum sensing metrology to quantum simulation of condensed matter physic problems with ultracold fermionic and bosonic gases. In most of these applications a compact and high flux source of cold atoms is an important requirement. We design and build up a compact cold strontium-88 atomic source with a transversely loaded 2D-MOT and a bi-color hybrid slowing scheme, leading to an enhancement in the number of atoms prepared in the 3D blue MOT by a factor of 9. Also, due to the sensitivity of the strontium intercombination line transition to a few milligauss of magnetic field, we further implemented an active magnetic field control system with PID feedback. The performance of the magnetic field feedback is tested by recording the red MOT position. We show that the system is capable of suppressing the change in MOT position, for magnetic field jumps of the order of 10 mG typically experienced in the lab.

Presenter name: Jianing Li

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Poster session / Mo-30:   *Precision meas. & tests of fund. phys.*   ID27

New perspectives on quantum transition times: the tunneling flight time

Author: Tom Rivlin[1]

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Recent experimental and theoretical works have reignited long-standing debates over the time taken for certain quantum transitions, such as tunneling, to occur. This is important, as tunneling is a common quantum phenomenon in molecular systems where nonadiabatic couplings are significant, and certain simulation methods struggle to accommodate its effects. Here we propose a new type of quantum mechanical flight time, based on weak-averaging, and show the conditions under which it becomes equal to another measure known as the phase time. We compare these results to recent Larmor time experiments for tunneling, and show that the Larmor time and dwell time coincide under the same circumstances as the new flight time and the phase time. Finally, we discuss ongoing work to evaluate flight times in two-level systems with strong nonadiabatic couplings emulating certain electronic transitions, and show the effects nonadiabatic couplings have on tunneling times.

Presenter name: Tom Rivlin

High-precision mass measurements of light atomic nuclei: the helium-4 atomic mass

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Atomic masses with high precision can be determined by Penning-trap mass spectrometry. The LIONTRAP experiment is one such high-precision mass spectrometer that can achieve relative mass uncertainties of the order of 10^{12} and is dedicated to light ions. Measurements on light ions are challenging due to the relatively large ratio of kinetic energies compared to the low rest mass.

The results at LIONTRAP include the atomic mass measurements of the proton [1], the deuteron and the HD^+ molecular ion [2]. The deuteron mass was measured to a relative precision of 8.5 ppt [2]. Our results show an excellent agreement with values that were extracted from laser spectroscopy of HD^+ [3]. This comparison is currently limited by the precision of the electron's mass in atomic mass units (amu), derived from a measurement of the bound electron g-factor in $^{12}C^{5+}$ [4]. ^4He is a prime candidate for a future improvement, as it is far less sensitive to higher-order terms of quantum electrodynamics (QED) and to the charge radius of the nucleus. Currently, we have measured the atomic mass of ^4He to support such a determination of the electron mass in amu.

Furthermore, an ultra-precise measurement of the mass difference of ^3He and ^3T will provide an important crosscheck of the determination of the electron anti-neutrino mass with the KATRIN experiment [5]. Moreover, ^3He to ^{12}C mass ratio could further clarify the so-called 'puzzle of the light masses', which is an inconsistency in the values of light masses from different world-leading experiments [2]. In this contribution, the present status of the experiment will be discussed.

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Presenter name: Sangeetha Sasidharan

Poster session / Mo-32: *Precision meas. & tests of fund. phys.* ID135

Development of a deep-ultraviolet chirped pulse laser for Doppler cooling of positronium

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Positronium (Ps), a bound state of an electron and a positron, is a purely leptonic and anti-particle system. Preparing a cold gas of Ps leads to precision spectroscopy and a realization of Bose-Einstein condensation of exotic atoms. Owing to the nature of the particle-antiparticle pair, Ps has a finite lifetime of 142 ns. Therefore, developing a rapid cooling method is the key to cool Ps effectively.

Laser cooling using the 1S-2P transition is one of the most promising methods for Ps cooling. With laser cooling, Ps atoms at room temperature could ideally be cooled to the photon recoil limit of 0.6 K within one microsecond. The temperature is well below 150 K, achieved by a conventional cooling method via momentum exchange processes with a cold Ps converter[1].

It is well known that laser cooling using continuous-wave lasers can reduce the temperature of a gas of atoms to submillikelvin temperatures[2]. However, because of the finite lifetime and the small mass of Ps, a cooling laser for Ps should be a unique pulsed laser that has a broadband spectrum, a frequency chirp, and a long pulse duration of several hundred nanoseconds[3]. We designed and developed a prototypical cooling laser (Figure 1) that satisfies these requirements. We also numerically simulated its oscillation dynamics and successfully reproduced the measured temporal and spectral structures of the laser[4].

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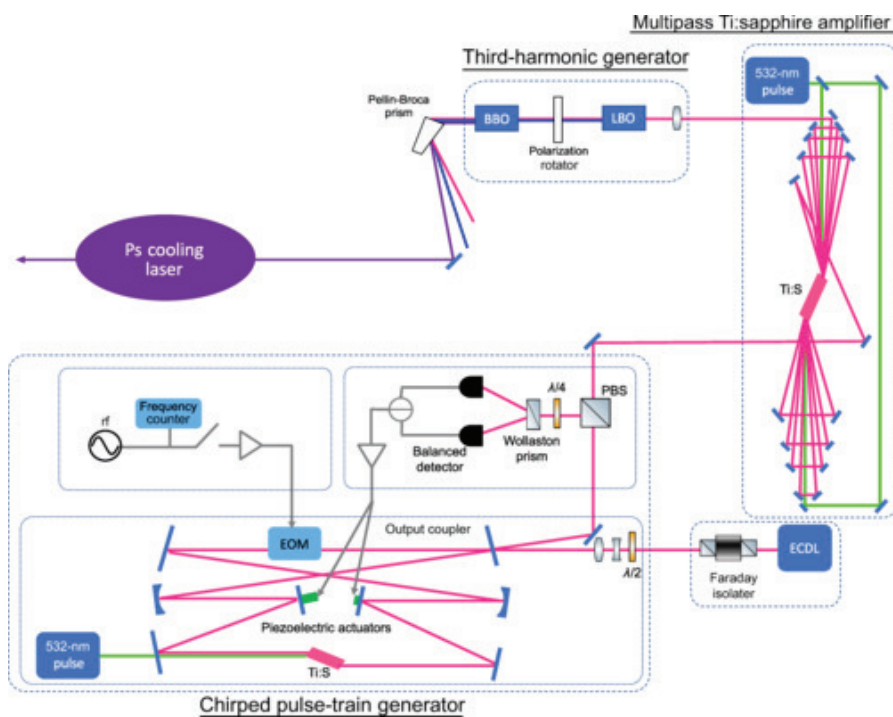
Figure 1: Schematic of the prototypical cooling laser system.

Presenter name: Tajima Yohei

Towards a compound ^{27}Al$^+$ - ^{40}Ca$^+$ and multiion ^{40}Ca$^+$ clock

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An optical atomic clock based on a single aluminum ion is holding the current world record for accuracy with a fractional frequency uncertainty below 10^{-18} [1]. This outstanding precision allows for novel applications like relativistic geodesy [2,3] on the cm level and helps to tighten the bounds for physics beyond the standard model [4]. But single ion clocks are impeded by their low signal-to-noise ratio and require therefore long averaging times. These can be significantly reduced by probing at the coherence time limit of the atom, given by the excited state lifetime. However, such second-long probe times can only be achieved with lasers offering correspondingly long coherence time.

Here we present the current status of PTB's laboratory aluminum ion clock and the experimental implementation of a multiion Ca$^+$ reference based on dynamical decoupling to extend the clock laser coherence time in the future.

We present the estimated error budget of the ^{27}Al$^+$ clock based on calibration measurements using a ^{40}Ca$^+$ ion as a sensor. This includes characterization of black body radiation, residual kinetic energy from excess micromotion as well as second order and ac Zeeman shifts caused by dc magnetic fields and magnetic fields from the trap drive, respectively. Recent upgrades of the vacuum system improved the estimated accuracy to 1.1×10^{-18}.

Improving the signal-to-noise ratio of the clock interrogation requires increasing the number of stored ions or longer interrogation times. We present a continuous dynamic decoupling scheme [5] to suppress inhomogeneous broadening by quadrupole and tensor ac Stark shifts in multiion ^{40}Ca$^+$ crystals. Simultaneous suppression of first order Zeeman shifts allows interrogation of the crystal close to the natural lifetime limit. A clock laser pre-stabilized to a multiion ^{40}Ca$^+$ reference will extend the laser coherence time and enable seconds long interrogation of ^{27}Al$^+$ in the future, thus forming a compound clock.

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Presenter name: Lennart Pelzer

Poster session / Mo-34:   *Precision meas. & tests of fund. phys.*   ID183

Next-generation strontium ion optical atomic clocks

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The performance of optical atomic clocks has improved tremendously over the last two decades. The fractional frequency uncertainties of the best optical clocks reach the 10^{-18} level and currently outperform cesium fountain clocks, the current primary frequency standards defining the SI second, by two orders of magnitude. Redefinition of the SI second based on optical clocks is expected to take place in the next decade. The criteria require that optical clocks are evaluated with fractional frequency uncertainties of 3×10^{-18} or better, and compared with other devices in remote laboratories with uncertainties comparable to their evaluated uncertainties. In recent years, the frequency and time group at the National Research Council Canada (NRC) has been developing a high-accuracy transportable optical atomic clock for direct comparisons with clocks in other National Metrology Institutes.

The optical clock at NRC is based on the 445-THz $5s\,^2S_{1/2}$ - $4d\,^2D_{5/2}$ electric quadrupole transition in ^{88}Sr$^+$. The frequency reference is a single laser-cooled ion, suspended between two endcap electrodes with a radio-frequency (RF) electric field. An optical clock based on ^{88}Sr$^+$ is well suited for the transportable system due to its simple energy-level structure, where only four lasers with easily accessible wavelengths are required for its operation. Furthermore, the systematic effects that perturb the clock transition are well understood, and can be controlled at or below the 10^{-18} level. Our transportable system is equipped with a newly-designed ion trap with improved thermal properties that is expected to reduce the blackbody radiation shift (BBRS) uncertainty by an order of magnitude compared to our existing stationary clock. It also has a compact vacuum chamber with 10 times lower background gas pressure, which is expected to reduce the collisional frequency shift (CFS) by the same factor.

With these upgrades, all the systematic effects in the transportable system are expected to be below the 10^{-18} level. For further improved performance, we have recently started to build a cryogenic ^{88}Sr$^+$ optical clock, where both the BBRS and CFS will be suppressed below the 10^{-19} level. Future comparisons between cryogenic and transportable clocks will validate the accuracy of our ensemble of ^{88}Sr$^+$ clocks.

We will present a brief overview of our ^{88}Sr$^+$ clock system, and the current status and future prospects of both the transportable and cryogenic systems.

Presenter name: Kosuke Kato

Evaluation of the blackbody radiation shift uncertainty of the NRC strontium ion clock

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At the National Research Council Canada (NRC), an optical frequency standard based on a single trapped strontium ion has been developed. The optical clock uses the 5s $^2S_{1/2}$ – 4d $^2D_{5/2}$ electric quadrupole transition of the $^{88}Sr^+$ ion at 445 THz as its reference transition. This clock transition of the $^{88}Sr^+$ ion has been recommended as one of the secondary representations of the SI second. Currently, the overall systematic uncertainty of NRC's $^{88}Sr^+$ ion clock is 1.2×10^{-17} in fractional frequency units, which is mainly limited by the blackbody radiation (BBR) shift uncertainty of 1.1×10^{-17}.

The BBR shift is caused by the interaction of the energy levels of the clock transition with the electric field of the thermal radiation at the ion position. The BBR shift uncertainty of our $^{88}Sr^+$ ion clock is mainly limited by the evaluation of the electric field caused by the thermal radiation. The other two parameters needed to determine the BBR shift, namely the polarizability and the dynamic correction of the clock transition, can either be measured or calculated accurately and their contributions to the uncertainty of the BBR shift is below 10^{-18}.

In order to evaluate the thermal electric field experienced by the $^{88}Sr^+$ ion in the optical frequency standard, we built a copy of ion trap and installed it in an offline vacuum chamber dedicated to thermal imaging measurements. A calibrated IR camera has been used to measure the temperature change of the test trap components when a drive rf voltage is applied to electrodes. To increase the accuracy of the temperature measurements using the IR camera, key trap components were painted with matte black paint to increase emissivities. The temperature data of the test trap components will be compared to a finite element simulation from which the effective thermal electric field experienced by the $^{88}Sr^+$ ion can be extracted for the evaluation of the BBR shift and its uncertainty.

It is expected that the overall uncertainty of the $^{88}Sr^+$ ion optical clock will be reduced to the $\sim 5 \times 10^{-18}$ level with the results of the current study.

Presenter name: Bin Jian

Poster session / Mo-36:   *Precision meas. & tests of fund. phys.*   ID233

Developing a high-resolution Doppler broadening spectroscopy for cold positronium

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Cooling of positronium (Ps), an electron-positron bound state, leads to important research such as precision measurements of energy intervals or realizing Bose-Einstein condensation. The current coldest limit of Ps, which was achieved by thermalization with cooled solid, is still over 100 K [1]. Laser cooling and other cooling methods are under intense research to give a breakthrough in this field. On this occasion, evaluating the temperature of cold Ps is an important task to be undertaken. Obtaining the Doppler broadening by laser spectroscopy is one of the preferred methods since it allows high-resolution measurements regarding the laser technology of today.

However, since Ps has a short lifetime of 142 ns due to the electron-positron annihilation, it is principally difficult to prepare a large number of Ps at once for observation. Thus, to conduct a high-resolution Doppler broadening spectroscopy, not only should the resolution be high, but also the excitation efficiency by the laser should be kept high enough to realize an observation with a high signal-to-noise ratio. This gives certain requirements to the frequency structure and the power of the probing laser.

To evaluate the required characteristics of the probing laser, we conducted a numerical simulation based on optical Bloch equations under laser fields whose frequency structure was realistically modeled. Based on this evaluation, we have developed a frequency-tunable UV pulsed laser with the characteristics suited for doppler spectroscopy of cold Ps. We will introduce an overview of this laser along with the experimental results to evaluate whether our pulsed laser satisfies the above requirements.

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Presenter name: Ryosuke Uozumi

Poster session / Mo-37:   *Precision meas. & tests of fund. phys.*   ID258

Symmetry-violating properties for precision measurements in diatomic molecules

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High-precision experiments to measure parity (P), and parity and time-reversal (P, T) violation using paramagnetic molecules are a promising route to look for physics beyond the Standard Model of particle physics. Using close-lying opposite-parity molecular states enhances the symmetry-violating experimental signals. This enhancement is purely relativistic and increases with the atomic number [1], making systems containing heavy atoms ideal for symmetry-violation experiments. The enhancement factor can not be measured separately and therefore electronic structure theory is needed to determine its value. This work presents the molecular enhancement for the nuclear spin-dependent P-violating anapole moment in the diatomic molecules containing lanthanum and lutetium heavy atoms. We employ the finite field approach with the relativistic 4-components coupled-cluster method in the DIRAC program [2]. In addition, we present the enhancements factor for the P, T–violating electron electric dipole moment, the P, T–violating electron-nucleus interaction, and the P, T–violating nuclear magnetic quadrupole moment. We pursue a systematic study to estimate the effect of various computational parameters, such as the basis set and electron correlation, on the calculated properties. We have found a consistent dependence of the different symmetry-violating properties on the computational parameters leading to similar uncertainties. The precision of our calculations is approximately 6% and makes the reported enhancement factors suitable for extracting the relevant fundamental properties from future measurements.

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Presenter name: Yuly Andrea Chamorro Mena

Poster session / Mo-38:   *Precision meas. & tests of fund. phys.*   ID282

Dynamic cryogenic radiation shield for sub-10^{-19} blackbody radiation shift uncertainty in optical lattice clocks

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The blackbody radiation (BBR) Stark shift currently limits the performance of many atomic frequency standards. It constitutes the largest uncancelled shift and the leading uncertainty in the most accurate optical lattice clocks [1,2]. One attempt to tackle this limitation has been to create a well-characterized BBR environment at room temperature [3]. However, the uncertainty on the atomic polarizability manifested as a dynamic correction to the BBR shift limits this strategy at the 10^{-18} fractional frequency level. An alternative approach utilizes a cryogenic radiation shield to reduce the total BBR shift and more importantly the above-mentioned BBR dynamic correction uncertainty [4,5]. However, a lingering challenge is to achieve adequate isolation from the external environment. In these attempts, the leaking room temperature BBR limits the shift evaluation uncertainty at the same 10^{-18} fractional frequency level.

Here we report on the design of a mechanically dynamic cryogenic in-vacuum radiation shield that enables controlling the BBR shift uncertainty *below* the 10^{-19} level in optical lattice clocks. While the shield accommodates ample physical and optical access during atomic state preparation, mechanical actuation of its internal structure closes all physical and nearly all optical apertures during spectroscopy. The mechanical actuation encloses the atomic sample from *virtually all* the 4 steradians of solid angle with highly emissive cryogenic surfaces and blocks the atoms' direct line of sight to the external environment. Consequently, shifts due to leaking room temperature BBR are suppressed below the 10^{-18} level. To verify the homogeneity of the cryogenic environment, the shield accommodates temperature measurement and control of all the cryogenic surfaces with direct-line-of-sight to the atoms to be within 100 mK from a mean temperature of 75 K or lower. The shield also acts as a Faraday shield and employs three mutually orthogonal electrode pairs for evaluation of stray electric fields inducing a DC Stark shift. The highly uniform BBR environment delivered by the shield at cryogenic temperatures and up to room temperature provides a controlled platform for many AMO experiments that investigate and seek to eliminate the perturbative BBR environment on their quantum systems.

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Presenter name: Youssef S. Hassan

Muonium 1S-2S spectroscopy with improved statistics

Authors: Akihiro Koda[1]; Cedric Zhang[2]; Hideaki Hara[3]; Kamioka Syusei[1]; Katsuhiko Ishida[4]; Kazuhito Suzuki[5]; Mai Yotsuzuka[5]; Masashi Otani[1]; Mitsuhiro Yoshida[1]; Naritoshi Kawamura[1]; Patrick Strasser[1]; Saeid Kamal[6]; Satoshi Uetake[3]; Shimomura Koichiro[1]; Shinsuke Yamamoto·; Sou Sugiyama[5]; Taihei Adachi[4]; Takahiko Masuda[3]; Tsutomu Mibe[1]; Wataru Saga[3]; Yajun Mao[2]; Yamazaki Takayuki[1]; Yasuhiro MIyake[1]; Yasutaka Imai[3]; Yoshimura Koji[3]; Yu Oishi·; Yuki Miyamoto[3]; Yutaka Ikedo[1]

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Our purpose is precision measurement of the 1S-2S energy interval in Muonium, which is an exotic hydrogen-like atom consisting of a positive muon and an electron. This purely leptonic system enables a precise calculation of the energy interval with the Standard Model without any concerns of the uncertainty from the charge radius of the nucleus, unlike the hydrogen-atom. This advantage motivates us to measure the precise 1S-2S energy interval in Muonium with technology of laser spectroscopy and to determine the muon mass with the highest accuracy of 10 ppb. The improvement of muon mass accuracy has an impact on verification of the Standard Model, muon g-2/EDM experiment, for example.

The energy interval accuracy has been statistically limited since 1999 [1]. However, more powerful muon beam is available now at J-PARC in Japan and we are developing new UV laser system.

We will report a recent result of Muonium 1S-2S energy interval measurement at J-PARC. The event rate in our experiment is 50 times higher than the previous experiment. This dramatic improvement gives promising prospect for higher accuracy of 1S-2S energy interval and the muon mass accuracy in the future.

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Presenter name: Shinsuke Yamamoto

Poster session / Mo-40:   *Precision meas. & tests of fund. phys.*   ID337

An optical atomic clock based on a highly charged ion

Authors: Steven King[1]; Lukas Spieß[1]; Peter Micke[1]; Alexander Wilzewski[1]; Tobias Leopold[1]; Erik Benkler[1]; Richard Lange[1]; Nils Huntemann[1]; Andrey Surzhykov[1]; Vladimir Yerokhin[1]; José R. Crespo López-Urrutia[2]; Piet O. Schmidt[1]

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Optical atomic clocks are the most precise and accurate measurement devices ever constructed, reaching fractional systematic uncertainties below one part in 10^{18} [1]. Their exceptional performance opens up a wide range of applications in fundamental science and technology. The extreme properties of highly charged ions (HCI) make them highly sensitive probes for tests of fundamental physical theories [2, 3]. Furthermore, these properties make them significantly less sensitive to some of the leading systematic perturbations that affect state-of-the-art optical clocks, making them exciting candidates for next-generation clocks [4, 2]. The technical challenges that hindered the development of such clocks have now all been overcome, starting with their extraction from a hot plasma and sympathetic cooling in a linear Paul trap [5], readout of their internal state via quantum logic spectroscopy [6], and finally the preparation of the HCI in the ground state of motion of the trap [7], which allows levels of measurement accuracy to be reached that were previously limited to singly-charged and neutral atoms. Here, we present the first operation of an atomic clock based on an HCI (Ar^{13+} in our case) and a full evaluation of systematic frequency shifts [8]. The achieved uncertainty is almost eight orders of magnitude lower than any previous frequency measurements using HCI. Measurements of some key atomic parameters confirm the theoretical predictions of the favorable properties of HCIs for use in clocks. The comparison to the $^{171}Yb^+$ E3 optical clock [9] places the frequency of this transition among the most accurately measured of all time. Furthermore, by comparing the isotope shift between $^{36}Ar^{13+}$ and $^{40}Ar^{13+}$ to improved atomic structure calculations, we were able for the first time to resolve the largely unexplored QED nuclear recoil effects. Finally, prospects for 5th force tests based on isotope shift spectroscopy of Ca^+/Ca^{14+} isotopes and the high-sensitivity search for a variation of the fine-structure constant using HCI will be presented. This demonstrates the suitability of HCI as references for high-accuracy optical clocks and to probe for physics beyond the standard model.

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Presenter name: Piet O. Schmidt

Poster session / Mo-41:   *Precision meas. & tests of fund. phys.*   ID349

Experiment and theory for a helium tune-out frequency: an independent test of quantum electrodynamics

Authors: Gordon Drake[1]; Bryce Henson[2]; Jacob Ross[2]; Kieran Thomas[2]; David Shin[2]; Sean Hodgman[2]; Yong-Hui Zhang[3]; Li-Yan Tang[3]; Aaron Bondy[1]; Andrew Truscott[2]; Carlos Kuhn[2]; Kenneth Baldwin[2]

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Quantum electrodynamics (QED) is one of the most stringently tested theories underpinning modern physics. Nevertheless, recent precision atomic spectroscopy measurements have uncovered several small discrepancies between experiment and theory. One particularly powerful experimental observable that tests QED independently of traditional energy level measurements is the *tune-out frequency*, where the dynamic polarizability vanishes and the atom does not interact with applied laser light. In our work, we measure the tune-out frequency for the $2\,^3S_1$ state of helium between transitions to the $2\,^3P_J$ and $3\,^3P_J$ manifolds and compare it with new theoretical QED calculations [1]. The experimentally determined value of 725,736,700(260) MHz differs from theory [725,736,252(9) MHz] by 1.7 times the measurement uncertainty and resolves both the QED contributions and retardation corrections. The underlying theory is formulated more generally as a zero in the forward Rayleigh scattering cross section, rather than a zero in the dynamic polarizability. Relativistic, QED, and retardation corrections are included in a nonrelativistic QED (nr-QED) approach.

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Presenter name: Gordon Drake

Poster session / Mo-42:   *Precision meas. & tests of fund. phys.*   ID360

Progress towards precision measurements in trapped poly-atomic molecules

Authors: Ashay Patel[1]; Phelan Yu[1]; Yi Zeng[1]; Arian Jadbabaie[1]; Nickolas Pilgram[1]; Chandler Conn[1]; Yuiki Takahashi[1]; Chi Zhang[1]; Timothy Steimle[2]; Nicholas Hutzler[1];   Timur Tscherbul[3]; Seth T. Rittenhouse[4]; Hossein Sadeghpour[5]

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The Standard Model as we know contains insufficient sources of charge parity (CP) violation to explain the observed baryon asymmetry of the universe (BAU). Heavy polar molecules are a sensitive, tabletop platform for precision searches of CP-violating electromagnetic moments originating from Beyond the Standard Model (BSM) physics. The polyatomic molecule YbOH is a promising platform to measure the electron electric dipole moment (eEDM); the electron localized around the Yb nucleus provides the ability to laser cool and trap the molecule, while the vibrational bending mode provides closely spaced parity doublets that allow for systematic error rejection and full alignment of the molecule in modest lab electric fields. Prerequisites for trapping YbOH molecules include developing an efficient molecular slowing scheme, identifying vibrational repump transitions, and spectroscopy on the excited states. Here we report on our progress developing a compact permanent magnet Zeeman-Sisyphus slower. We also report high-resolution frequency modulated (FM) absorption spectroscopy of the (300) stretching vibration in the electronic ground state of YbOH, and progress on excited state spectroscopy.

Presenter name: Ashay Patel

EDM[3]: Towards a measurement of the electron electric dipole moment using BaF molecules embedded in a solid Ar matrix

Authors: Z. Corriveau[1]; D. Heinrich[1]; J. Perez Garcia[1]; H.-M. Yau[1]; N. McCall[1]; G. K. Koyanagi[1]; M.C. George[1]; C.H. Storry[1]; R.L. Lambo[1]; A. Marsman[1]; M. Horbatsch[1]; R. Fournier[1]; J.T. Singh[2]; A.C. Vutha[3]; E.A. Hessels[1]

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Improved measurements of the electron electric dipole moment (eEDM) will strongly constrain the parameter space of new physics theories. Over the last decade, polar molecules have become established as the most promising systems for eEDM searches, due to the large internal electric fields experienced by an eEDM in these molecules. The sensitivity of eEDM searches is determined by the coherence time available for measuring eEDM-induced electron spin precession, as well as by the total number of molecules available over the course of a measurement. We present our progress in implementing a measurement scheme [1] that will use a large number of barium-monofluoride molecules embedded into a solid argon matrix. The large number of BaF for matrix-isolated BaF molecules is expected to lead to excellent statistical precision, and the method offers an array of reversals and controls for cleanly suppressing systematic effects to a level commensurate with the improved statistical precision.

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Presenter name: Zachary Corriveau

Experimental upgrades for improving statistical and systematic uncertainties in ACME III

Authors: Zhen Han[1]; Peiran Hu.

Co-authors: Daniel Ang [2]; David DeMille [3]; Collin Diver [4]; John Doyle [2]; Gerald Gabrielse [4]; Ayami Hiramoto [5]; Nick Hutzler [6]; Daniel Lascar [4]; Zack Lasner [2]; Siyuan Liu [4]; Takahiko Masuda [5]; Cole Meisenhelder [2]; John Mitchell [4]; Cristian Panda [7]; Noboru Sasao [5]; Satoshi Uetake [5]; Maya Watts [4]; Xing Wu [8]; Koji Yoshimura [5]

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The measurement of the electron electric dipole moment (eEDM), d_e, is a powerful probe of physics beyond the Standard Model. The current most stringent limit of $|d_e| < 1.1 \times 10^{-29}$ e $\cdot$ cm was reported by the ACME II experiment (*Nature*, **562**(2018), 355). ACME III aims to improve this experimental limit by an order of magnitude. Progress has been made in improving the statistical sensitivity. An electrostatic lens that can increase the flux of a ThO molecular beam has been built and tested. We are also upgrading our fluorescence detectors to silicon photomultipliers for higher quantum efficiency. An upgraded cryogenic buffer gas beam (CBGB) source featuring shorter cool-down time and in-situ target changing function is built for increasing the duty cycle of the experiment. Guided by our recent H $^3\Delta_1$ lifetime measurement, a longer interaction region is constructed. We also made progress toward reducing systematic errors and their uncertainty. One significant source of systematic error comes from birefringence gradients in the laser optics. We are implementing a modified measurement scheme to reduce this systematic error and taking several new measures to reduce birefringence gradients. Last, we are building and testing an upgraded magnetic shielding and field control system.

Related publications:
https://arxiv.org/pdf/2204.05906.pdf,
https://arxiv.org/pdf/2204.05904.pdf,
https://opg.optica.org/oe/fulltext.cfm?uri=oe-29-11-16914&id=451129

Presenter name: Zhen Han

Quantum sensor networks as exotic field telescopes for multimessenger astronomy

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Multimessenger astronomy, the coordinated observation of different classes of signals originating from the same astrophysical event, provides a wealth of information about astrophysical processes. So far, multimessenger astronomy has correlated signals from known fundamental forces and standard model particles like electromagnetic radiation, neutrinos and gravitational waves (GW). Many of the open questions of modern physics suggest the existence of exotic fields with light quanta (masses $\ll 1$ eV/c^2). Quantum sensor networks could be used to search for astrophysical signals predicted by beyond-standard-model theories which address these questions. Here, we show that networks of precision quantum sensors that by design are shielded from or are insensitive to conventional standard-model physics signals can be a powerful tool for multimessenger astronomy. We consider the case where high-energy astrophysical events produce intense bursts of exotic low-mass fields (ELFs), and we propose a novel model for the potential detection of an ELF signal based on general assumptions. We estimate ELF signal amplitudes, delays, rates, and distances of GW sources to which global networks of atomic magnetometers and atomic clocks could be sensitive. We find that such precision quantum sensor networks can function as ELF telescopes to detect signals from sources generating ELF bursts of sufficient intensity.

Details in Nature Astronomy **5**, 150 (2021)

Presenter name: Andrei Derevianko

Poster session / Tu-33:   *Precision meas. & tests of fund. phys.*   ID85

Atmospheric channel measurements for long-range optical time transfer and quantum state dissemination

Authors: Benjamin Stuhl[1]; William Swann[2]; Martha Bodine[2]; Holly Leopardi[1]; Tyler Wright[3]; Jean-Daniel Deschênes[4]; Emily Hannah[5]; Nathan Newbury[2]; Laura Sinclair[2]

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Free-space optical time transfer is a key enabling technology for intercontinental comparisons of optical atomic clock time scales and the eventual redefinition of the SI second. However, full realization of their potential for femtosecond-level intercomparisons requires ground-to-space (and possibly space-to-space) link operation. We present a series of long-range atmospheric channel characterizations and time transfer demonstrations, through a variety of atmospheric turbulence conditions. In addition to time transfer, our channel measurements are also relevant for long-range quantum communications, including space-to-ground quantum resource dissemination.

Presenter name: Benjamin Stuhl

Progress on the CeNTREX TlF Schiff moment search

Authors: Olivier Grasdijk[1]; David DeMille[2]; Jakob Kastelic[3]; David Kawall[4]; Steve Lamoreaux[3]; Oskari Timgren[3]; Jianhui Li[5]; Tristan Winick[4]; Yanhang Yang[6]; Tanya Zelevinsky[5]

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[5] *Columbia University*

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The The aim of CeNTREX (Cold molecule Nuclear Time-Reversal Experiment) is to search for the proton's electric dipole moment by measuring the Schiff moment it induces in the ^{205}Tl nucleus. We use the amplified energy shift from the Schiff moment that is present in the polar molecule thallium fluoride (TlF). To maximize the population of the science state, we employ rotational cooling on the cold TlF beam, which pumps lowest few rotational states into a single J=0 hyperfine level of the $^1\Sigma^+$ electronic ground state. Electrostatic focusing with a quadrupole lens will be used to efficiently direct molecules to a downstream detection region; this requires a weak-field seeking state. This is achieved by adiabatic state transfer from J=0 to J=2 with microwaves. Finally, the Schiff moment measurement requires careful nulling of magnetic fields in the interaction region. Characterization of a new magnetic shielding system is ongoing.

Presenter name: Olivier Grasdijk

Poster session / Tu-35: *Precision meas. & tests of fund. phys.* ID140

Systematic effects in eEDM searches with BaF

Authors: Alexander Boeschoten[1]; Hendrick L. Bethlem[2]; Anastasia Borschevsky[3]; Steven Hoekstra[3]; Joost W.F. van Hofslot[3]; Klaus Jungmann[3]; Virginia Marshall[3]; Thomas B. Meijknecht[3]; Maarten C. Mooij[2]; Rob G.E. Timmermans[3]; Anno Touwen[3]; Wim Ubachs[2]; Lorenz Willmann[3]

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[3] *Van Swinderen Institute, University of Groningen*

A promising way to explore physics beyond the Standard Model of particle physics is doing high-precision measurements on molecules. One such measurement is the search for the P,T-violating electric dipole moment of the electron (eEDM). In diatomic molecules with one heavy atom, the effect of the eEDM is expected to be strongly enhanced, because of small rotational splittings and an enhanced electron density near a highly charged nucleus, with currently the best limit of $d_e < 1.110^{-29}$ e cm measured in ThO [1]. In the NL-eEDM collaboration, the eEDM induced contribution to the ground state of BaF is investigated [2]. The eEDM manifests itself as an extra splitting between the magnetic substates due to the electric field, in addition to the Zeeman effect in magnetic fields. To measure the effect of a possible eEDM, a spin precession experiment is set up in well-controlled electric and magnetic fields. We use a two-photon transition to create a superposition of two hyperfine substates. In the magnetic and electric field, a phase difference between the two hyperfine states is accumulated, which has an extra contribution due to the electric field if the eEDM exists. The contributions to this phase from known-physics, in particular from the magnetic moment, require understanding of the molecular structure. The derived value for the eEDM is limited by statistics and the understanding of systematic effects.

To increase the statistical sensitivity, an intense source of ultracold BaF molecules will be used, produced in a cryogenic source. The molecules will be transversely laser cooled and decelerated with a Stark decelerator [3].

To have control over the systematics, it is crucial to understand how the eEDM signal depends on the experimental parameters, such as the magnetic field and laser intensities. For this we developed a description of the dynamics of our spin-precession experiment, based on the Optical Bloch Equations. With this tool we can calculate to which precision we need to control and measure the experimental parameters during the experiment.

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Presenter name: Boeschoten, Alexander

Low uncertainty absolute frequency measurement of the strontium ion optical clock transition

Authors: Pierre Dubé[1]; Bin Jian[1]; John E. Bernard[1]; Marina Gertsvolf[1]

[1] *NRC*

The electric quadrupole transition of the ^{88}Sr$^+$ ion at 445 THz is one of 11 recommended optical transitions that can be used as secondary representations of the SI second. Progress towards the redefinition of the SI second using an optical clock indicates that a new definition will be based on either one atomic optical transition or an ensemble of such reference transitions, selected from the recommended frequencies. One criteria that must be met before the SI second is redefined is continuity with the current definition of the SI second as realized with cesium fountain clocks, at a level of 3×10^{-16} or better.

Here, we report a new absolute frequency measurement of the ^{88}Sr$^+$ ion optical transition. The measurement campaign of the ion frequency lasted 12 days in June 2017, and provided 92 hours of comparison data with a local maser flywheel oscillator at NRC. The link between the optical standard and the SI second was completed by measuring the maser continuously during the month of June 2017 with respect to the SI second using a GPS link. The SI second is realized with primary and secondary frequency standards (PSFS) that report to the BIPM. The maser frequency (UTC(NRC)), averaged over a 30-day period, is provided in the Circular T \#354 report published by the BIPM.

The uncertainty of the absolute frequency measurement has three dominant components of comparable values (2.2 to 2.5×10^{-16}): the dead time uncertainty caused by the intermittent operation of the optical clock, the GPS link uncertainty, and the uncertainty of the realization of the SI second with the PSFS. The optical clock evaluated uncertainty of 1.2×10^{-17} is insignificant in comparison. The main improvements compared to previous measurement campaigns are a better evaluation of the dead time uncertainty based on a noise model of maser, and the use of a maser with better noise characteristics than previously available.

The frequency measurement accuracy has a fractional uncertainty of 4.2×10^{-16}. This is a factor of four better than our our previous best determination and represents a significant step towards meeting the continuity criterion with the current definition of the SI second.

Presenter name: Pierre Dubé

Poster session / Tu-37:   *Precision meas. & tests of fund. phys.*   ID194

Update of the JILA Gen. II eEDM experiment

Authors: Trevor Wright[1]; Tanya Roussy[1]; Luke Caldwell[1]; Kia Boon Ng[1]; Noah Schlossberger[1]; Sun Yool Park[1]; Anzhou Wang[1]; Benjamin Hunt[1]; Antonio Vigil[1]; Gustavo Santaella[1]; Jun Ye[1]; Eric Cornell[1]

[1] *JILA*

Increasingly precise measurements of the permanent electric dipole moment of the electron (eEDM) probe physics beyond the standard model and shed light on open questions such as the baryon asymmetry and dark matter. Our measurement of the eEDM uses a thermal cloud of HfF+ ions held in an RF trap, allowing us to leverage second-scale coherence times and the large internal electric fields present in polar molecules. In this poster I present the final stages of the second generation measurement and discuss key systematic effects in the experiment.

Presenter name: Trevor Wright

Poster session / Tu-38: *Precision meas. & tests of fund. phys.* ID210

In-beam hyperfine spectroscopy of (anti-)hydrogen for tests of CPT and Lorentz invariance

Author: Eberhard Widmann[1]

[1] *Stefan Meyer Institute Vienna*

Cold antihydrogen, the bound state of an antiproton and a positron, is an ideal laboratory to test the fundamental CPT symmetry, one of the cornerstones of the Standard Model of particle physics, by comparing its energy levels to ordinary hydrogen. Hydrogen is one of the best studied atoms experimentally, among the two best-known transitions is the ground-state hyperfine transition $_{HF}$ with a relative precision of better than 10^{-12}.

The ASACUSA collaboration has proposed a measurement of $_{HF}$ in a beam, which allows to perform the experiment in a region far away from the strong magnetic fields needed for antihydrogen creation. Substantial progress has been made to improve the temperature and density of the positron plasma [1,2], which is expected to substantially increase the rate and ground-state fraction of antihydrogen atoms and thus for a measurement of $_{HF}$. ASACUSA aims at an initial precision of 1 ppm, at which level the finite size of the antiproton becomes visible.

Initially with the aim to establish the in-beam method, ASACUSA has performed a measurement of $_{HF}$ of ordinary hydrogen using a polarized beam and the same Rabi spectroscopy setup as will be used for antihydrogen and obtained a precision of 2.7 ppb [3]. Within the Standard Model Extension (SME) framework, that describes potential Lorentz invariance and CPT violation scenarios, also measurements using ordinary atoms can be used to constrain symmetry-violating SME coefficients [4]. First experiments have been performed on the orientation dependence of an external static magnetic field for hydrogen hyperfine measurements [5], and preparations are under way to study the hyperfine structure of deuterium.

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Presenter name: Eberhard Widmann

An experiment to measure the electron's electric dipole moment using an ultracold beam of YbF molecules

Authors: Freddie Collings[1]; Rhys Jenkins[1]; Xavier Y Alauze[1]; Gen Li[1]; Simon Swarbrick[1]; Christopher Ho; Noah J Fitch[1]; Ben E Sauer[1]; Michael R Tarbutt[1]

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The standard model predicts that the electron's electric dipole moment (eEDM, d_e) is too small to measure with current technology [1]. Theories that extend the standard model, however, predict much larger values, often exceeding 10^{-29} e cm. With the current experimental upper limit set at $|d_e| < 1.1 \times 10^{-29}$ e cm, [2] we can expect that improved measurements will either discover new physics or rule out most of the remaining parameter space for popular theories beyond the standard model. Measurements of d_e are made by measuring the precession of the electron spin induced by an applied electric field. The precession angle is enhanced when the electron is bound to a heavy polar molecule. The precision can be further improved by increasing the spin precession time and the total number of molecules detected. To this end, we have produced an intense beam of laser-cooled YbF molecules [3] and built an experiment to measure d_e using this beam [4]. The laser cooling lowers the temperature below 100 μK and increases the beam brightness by at least a factor of 300, leading to a projected statistical sensitivity better than 10^{-30} e cm. Realising such high precision requires a spin precession region with exceptionally low magnetic noise. Our apparatus features ceramic electric field plates inside a glass vacuum chamber, minimising magnetic Johnson noise, a four-layer magnetic shield with a shielding factor exceeding 10^6, and an array of atomic magnetometers. The magnetic noise in the apparatus is below 50 fT/$\sqrt{\text{Hz}}$ at 1 Hz. The poster will present our progress in laser cooling YbF molecules and our characterisation and optimisation of the eEDM apparatus.

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Presenter name:　　　　Freddie Collings

Silicon-photomultiplier embedded photodetector for ACME III

Authors: Takahiko Masuda[1]; Daniel Ang[2]; David DeMille[3]; Collin Diver[4]; John Doyle[5]; Gerald Gabrielse[4]; Zhen Han[6]; Ayami Hiramoto[1]; Peiran Hu[6]; Nick Hutzler[7]; Daniel Lascar[4]; Zack Lasner[2]; Siyuan Liu[4]; Cole Meisenhelder[2]; John Mitchell[4]; Cristian Panda[8]; Noboru Sasao[1]; Satoshi Uetake[1]; Maya Watts[4]; Xing Wu[6]; Koji Yoshimura[1]

[1] *Okayama University*

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A measurement of the electron electric dipole moment (eEDM) is a powerful probe for the existence of physics beyond the Standard Model of particle physics. The ACME experiment searched for eEDM with the world's highest sensitivity using cold ThO polar molecules (Nature, **562** (2018) 355-360). One of the improvements for the next generation of the ACME experiment is using silicon photomultipliers (SiPMs) as LIF photon detectors instead of PMTs. We have developed a dedicated SiPM module and evaluated its performance. The SiPM module shows about a 2.5 times higher detection efficiency than the PMTs used in the previous ACME experiment. This reports the design and results of performance test of the SiPM module.

Presenter name: Takahiko Masuda

Poster session / Tu-41:   *Precision meas. & tests of fund. phys.*   ID305

Towards a two-photon optical clock in calcium

Authors: Shira Jackson[1]; Scott Smale[1]; Amar Vutha[1]

[1] *University of Toronto*

Two-photon transitions in neutral atoms are attractive candidates for the development of compact and portable optical clocks. Such clocks can be used to search for dark matter and dark energy, to build a gravitational wave telescope, to perform ultra-precise surveys of the earth's gravitational potential, and to serve as the foundation for the new definition of the SI second. The Doppler- and recoil-free nature of two-photon transitions eliminates the need for confinement of the atoms at ultracold temperatures. Clock precision of $\delta\nu/\nu \approx 10^{-16}/\sqrt{\tau}$ can be achieved without the need for an optical lattice or ion trap, both of which would introduce Stark shifts. Although it was historically thought that large probe laser light shifts were inevitable due to the high laser power required to drive two-photon transitions, we have developed a system of magic polarization to eliminate this shift. We report on progress towards the observation of the $4s^2\ {}^1S_0 \to 3d4s\ {}^1D_2$ two-photon clock transition at 915 nm in a cloud of freely-falling ^{40}Ca atoms.

Presenter name: Shira Jackson

Tests of King's linearity in Ca$^+$

Authors: Timothy Chang[1]; Renee DePencier Pinero[1]; Bless Bah Awazi[1]; Sonya Dutton[1]; Charlie Doret[1]

[1] *Williams College*

We report progress towards a precise measurement of the isotope shifts in the $4^2S_{1/2} \to 3^2D_{3/2}$ 732 nm electric quadrupole transition in Ca$^+$. We perform correlation spectroscopy [1,2] on two co-trapped calcium isotopes. Simultaneous excitation of both ions using frequency sidebands derived from a single laser enables cancellation of common-mode laser phase noise and reduction of systematic uncertainties from laser frequency drift or magnetic field instabilities. Such measurements have the potential to exceed Hz-level precision. When combined with our prior exploration [3] of the $4^2S_{1/2} \to 3^2D_{5/2}$ transition isotope shifts in a King Plot, these measurements can enable exacting tests of King's linearity, offering a path toward probing new physics beyond the Standard Model and providing benchmarks for ever-improving theory of atomic and nuclear structure.

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Presenter name: Timothy Chang

Electron spin resonance spectroscopy using optically trapped polyatomic molecules

Authors: Arian Jadbabaie[1]; Loic Anderegg[2]; Christian Hallas[2]; Nathaniel Vilas[2]; Paige Robichaud[2]; Andrew Winnicki[2]; John M Doyle[2]; Nicholas Hutzler[1]

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[2] *Harvard University*

Optically trapped polyatomic molecules are a promising platform for measurements of time-reversal symmetry violation due to their highly polarizable structure, co-magnetometer states, and long achievable coherence times [Kozyryev and Hutzler, PRL 119 (2017)]. For example, linear polyatomic molecules in the vibrational bending mode could be used to search for the electron's electric dipole moment (eEDM), which would cause the electron to precess in the effective electric field present in polarized molecules. Here we present microwave spectroscopy of the vibrational bending mode in optically trapped CaOH molecules, and discuss progress towards electron spin resonance spectroscopy with long coherence times. Applied to heavier molecules with otherwise identical structure, these measurements would have the potential to probe physics beyond the standard model approaching PeV energy scales.

Presenter name: Arian Jadbabaie

Progress towards measuring the nuclear magnetic quadrupole moment in YbOH molecules

Authors: Chandler Conn[1]; Yuiki Takahashi[1]; Arian Jadbabaie[1]; Nickolas Pilgram[1]; Yi Zeng[1]; Phelan Yu[1]; Ashay Patel[1]; Chi Zhang[1]; Timothy Steimle[2]; Nicholas Hutzler[1]

[1] *Caltech*

[2] *Arizona State University*

Measurements of heavy, polar molecules in the gas-phase are sensitive experimental probes of Parity (P) and Time reversal (T) violating new physics. The large internal fields and relativistic electron dynamics in these molecules amplify potential sources of P,T violating physics, such as the electron's electric dipole moment (eEDM) or a nuclear magnetic quadrupole moment (NMQM). Molecular beam measurements of an NMQM would provide a modern probe of P,T violating physics in the hadronic sector, complimentary to existing eEDM constraints on new leptonic physics. We present progress toward measuring the NMQM on the ^{173}Yb nucleus in a beam of cold ^{173}YbOH molecules. The polyatomic structure of YbOH enables full control of polarization in the vibrational bending mode, while retaining the ability to cycle photons and laser-cool. Our progress on YbOH includes: preliminary spin precession in the vibrational ground state, spectroscopy of the vibrational bending mode, demonstration of cycling in the odd isotopologues, and construction of a magnetically shielded science chamber for precision measurement.

Presenter name: Chandler Conn

Poster session / Tu-45: *Precision meas. & tests of fund. phys.* ID373

Towards a new search for hadronic CP violation using ultracold assembled ^{223}FrAg molecules

Authors: Mohit Verma[1]; Shaozhen Yang[1]; Thomas Langin[1]; David DeMille[2]

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[2] *University of Chicago & Argonne National Laboratory*

We present a new approach to search for hadronic CP violation by measuring the ^{223}Fr nuclear Schiff moment in ultracold assembled FrAg (francium silver) molecules. The ^{223}Fr nucleus is known to have octupole deformation that leads to a factor of ~300 enhancement in the size of its Schiff moment for a given strength of CP-violating hadronic interactions [1]. The observable CP-violating energy shift induced when electrons interact with the Schiff moment is further amplified (relative to the shift in Fr atoms) when ^{223}Fr is bound in a strongly ionic molecule that produces a large internal electric field. Binding Fr and Ag forms such a polar molecule [2,3]. Furthermore, both atoms have alkali-like atom structures, making them accessible to laser cooling, controllable interactions via Feshbach resonances, and optical trapping. Recent calculations have shown that the FrAg electronic structure is highly amenable to optical transfer of molecules from weakly-bound magneto-associated "Feshbach molecule" states, into the rovibronic ground state [4]. Assuming experimental parameters for molecule number, nuclear spin coherence time, and detection efficiency that have already been demonstrated in other experiments that use ultracold assembled molecules, we project a factor of 1000 improvement in underlying CP-violating physics for the first generation of an experiment with ^{223}FrAg. Work is underway to form a magneto-optic trap of silver and then study ultracold Ag-Ag scattering properties. We also present plans to laser cool francium using an offline source.

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Presenter name: Mohit Verma

Poster session / Tu-46: *Precision meas. & tests of fund. phys.* ID406

High precision eigenvalues for the Rydberg S-states of helium for principal quantum numbers $n > 10$

Authors: Lamies Sati[1]; Aaron Bondy[1]; Evan Petrimoulx[1]; Gordon Drake[1]

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In previous work, high precision eigenvalues for all states of helium up to $n = 10$ and $L = 7$ have been obtained by the use of double basis sets in Hylleraas coordinates [1]. In the present work, we show that triple basis sets using three sets of individually optimized nonlinear parameters for different distance scales yield an order of magnitude improvement in accuracy for basis sets of the same size for the Rydberg S-states states of helium. They also allow an extension of high precision calculations for the nonrelativistic energies and wave functions up to at least $n = 16$ with little loss of accuracy. An important advance in computational technique is the use of David Bailey's double-quadruple (dq) precision arithmetic (approximately 70 decimal digits) in the optimization of the nonlinear parameters in the basis set. Except for this, the wave functions have a high degree of numerical stability, and standard quadruple precision is sufficient for the evaluation of matrix elements. A comparison with the best previous calculations for $n > 10$ [2] will be presented.

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Presenter name: Lamies Sati

Poster session / We-31:   *Precision meas. & tests of fund. phys.*   ID46

Shear interferometry in microgravity with atomic ensembles in the picokelvin regime

Authors: Merle Cornelius[1]; Julia Pahl[2]; Peter Stromberger[3]; Laura Pätzold[4]; Dorthe Leopoldt[5]; Waldemar Herr[5]; Sven Herrmann[4]; Patrick Windpassinger[3]; Christian Schubert[5]; Markus Krutzik[2]; Ernst M. Rasel[5]; Claus Lämmerzahl[4]

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[3] *Johannes Gutenberg University Mainz*

[4] *University of Bremen*

[5] *Leibniz University Hannover*

Atom interferometry as a tool for precision measurements opens up a broad field of application: from testing fundamental physics to geodesy or navigation. Since the sensitivity of an atom interferometer scales quadratically with the interrogation time, operating on a microgravity platform is highly beneficial. Extended times of flight of several seconds require low expansion rates of the atomic ensemble, which can be achieved with magnetic lensing, also known as delta-kick collimation. To pave the way for space-borne atom interferometry, the QUANTUS-2 experiment was developed. This high-flux rubidium BEC machine, based on the atom chip technology, is designed to operate at the 110m high ZARM drop tower in Bremen, Germany, where microgravity times of 9.7 s can be reached.

In this contribution, a quadrupole-mode enhanced magnetic lens is presented to achieve a three-dimensional collimated BEC. The resulting atomic ensemble features an ultra-low internal 3D kinetic energy of $\frac{3}{2}k_B \cdot 38$ pK and a high signal to noise ratio even after 2 s time of flight [1]. The novel application of a Ramsey sequence as a shear interferometer consisting of two successive double Bragg beam splitter pulses enables us to investigate the divergence of the BEC and possible magnetic lens imperfections. Additionally, the spatially resolved velocity spread can be deduced based on the recorded spatial interferometry pattern. The demonstrated atom interferometry with picokelvin ensembles provides the basis for future interferometry measurements on long time scales with the aim of unprecedented precision.

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Presenter name: Merle Cornelius

Poster session / We-32:   *Precision meas. & tests of fund. phys.*   ID67

Improvements on direct-bonded copper, atom chips used for Cold-Atom Atomic Interferometry

Authors: Brian Kasch[1]; James Stickney[2]; Johnathan White[2]; Matthew Squires[1]; Rudy Kohn[2]; Spencer Olson[1]; Stacy Scramm[1]

[1] *AFRL*

[2] *SDL*

The Air Force Research Laboratory (AFRL) has been developing atom chips for use with cold-atom sensing and atom interferometry. We detail numerous advances in processing and fabrication techniques. Design improvements support tighter traps and rapid prototyping. Development of vias allow atom chips to serve as vacuum-chamber walls, decreasing current demands. Fabrication innovations that improve planarization support the integration of micro-features on single chips and chip-based assemblies.

Presenter name: Johnathan White

Scale factor corrections for point-source atom interferometer gyroscopes

Authors: Seji Kang[1]; John Kitching[2]; McGehee William[2]

[1] *Associate of the National Institute of Standards and Technology; Department of Physics, University of Colorado*

[2] *National Institute of Standards and Technology*

Point-source atom interferometry (PSI) offers a pathway for realizing compact inertial sensors with relatively low experimental complexity. Rotation sensing in PSI gyroscopes uses the velocity distribution in an expanding cold-atomic cloud to realize many parallel atom interferometers with velocity-dependent phase shifts. The scale factor relating the rotation rate to the observed atomic population fringes depends on the spatial distribution of atoms at the beginning of the atom interferometry sequence. For magneto-optical trap-based PSI gyroscopes, these size-dependent corrections to the scale factor are significant and scale factor errors contribute to both the accuracy and long-term stability of PSI-based rotation measurements. For Gaussian atomic density profiles, scale factors can be analytically corrected using the magnification ratio between initial and final gas sizes. Here, we present a method to correct scale factor for arbitrary initial cloud shapes and sizes, and we comment on the limitations to long-term gyroscope stability due to cloud size stability.

Presenter name: Seji Kang

Quasi-continuous superradiance on the kHz clock transition of 88Sr

Authors: Sofus Laguna Kristensen[1]; Eliot Bohr[1]; Jörg Helge Müller[1]

[1] *Niels Bohr Institute*

Lasing in the superradiant or "bad cavity" regime has attracted interest in the optical clock community as it offers an alternative to conventional lasers limited by the thermal noise fluctuations of reference cavities. In our experiment, we investigate pulsed lasing on the 7.5 kHz clock transition of ^{88}Sr atoms in an optical cavity. We continuously repump the lasing to achieve pulse durations on the ms scale, compared to a pulse length of a few μs using a single population inversion pulse. To observe the narrowing of the spectral line, we constructed an ultra-stable reference cavity system in order to characterize the spectral properties of the emission. Lastly, we experimentally investigate the prospect of using superradiant pulses as a readout of a Ramsey interferometer sequence. This scheme has the advantage of a fast, nondestructive measurement with increased sensitivity, which would be beneficial to the performance of optical atomic clocks.

Presenter name: Sofus Laguna Kristensen

Ancillary transitions in ^{171}Yb$^+$ ion clocks for shift evaluation and tests of fundamental physics

Authors: Melina Filzinger[1]; Richard Lange[1]; Martin Steinel[1]; Burghard Lipphardt[1]; Ekkehard Peik[1]; Yuriy Bidasyuk˙; Anton Peshkov[1]; Andrey Surzhykov[1]; Nils Huntemann[1]

[1] *Physikalisch-Technische Bundesanstalt*

^{171}Yb$^+$ ions feature two optical clock transitions: an electric quadrupole (E2) transition at 436 nm and an electric octupole (E3) transition at 467 nm. These two transitions have very different properties due to the different electronic structure of their excited states. In particular, they have a large differential sensitivity to the fine structure constant α, so that tight limits on possible variations can be obtained by comparing their frequencies at various positions in spacetime [1].

Of the two transitions, the E3 transition (^{2}S$_{1/2}$, F=0 $-$ ^{2}F$_{7/2}$, F=3) is particularly suitable for precision spectroscopy: Its excited state features a yearslong natural lifetime [2], so that coherent interrogation times are not limited by the spontaneous decay. Additionally, the excited state sensitivity to external electric and magnetic fields is almost equal to that of the ground state, resulting in a weak differential dependence for the transition. This permits high accuracy in the realization of the unperturbed E3 transition frequency [3].

The E2 transition (^{2}S$_{1/2}$, F=0 $-$ ^{2}D$_{5/2}$, F=2), on the other hand, features a larger sensitivity to external fields, which makes it a suitable ancillary transition: Residual perturbing fields are investigated on a magnified scale and can improve the knowledge of the unperturbed E3 transition frequency when relative sensitivities are known [4]. However, the E2 transition coherent interrogation is limited to about 40 ms by the relatively short lifetime of its excited state.

Additional ancillary transitions without this limitation are provided between the F=3 and F=4 hyperfine states of the long-lived ^{2}F$_{7/2}$ state and their Zeeman manifolds (in a static external magnetic field). We drive these transitions using microwave radiation at about 3.6 GHz to investigate magnetic field and tensor frequency shifts. Microwave spectroscopy is not limited by ion heating and finite laser coherence, which makes it a useful tool to resolve small frequency shifts within a short measurement time. We obtain coherent interrogation times exceeding 5 s, allowing us to resolve mHz shifts within hours. Dynamical decoupling pulse sequences can be used to coherently average the energy of $\pm m_F$ Zeeman pairs. This suppresses the linear Zeeman shift and associated energy fluctuations while retaining sensitivity to frequency shifts depending on m_F^2, including possible shifts due to violations of local Lorentz invariance.

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Presenter name: Melina Filzinger

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Poster session / We-36: *Precision meas. & tests of fund. phys.* ID163

Ultra-high vacuum chamber development for a Sr optical lattice clock with a Laguerre-Gaussian trapping geometry

Authors: Miguel Angel Cifuentes Marin[1]; Jérôme Lodewyck[2]; Rodolphe Letargat[2]; Haosen Shang[2]; Yannick Foucault[2]

[1] *SYRTE - Observatoire de Paris*

[2] *LNE-SYRTE, Observatoire de Paris*

Strontium optical lattice clocks (OLC) are a promising instrument for applications ranging from the redefinition of the second in the international system to geodesy and fundamental physics, for instance, dark matter detection, variation of fundamental constants, or general relativity tests. LNE-SYRTE, Observatoire de Paris operates two Sr OLCs with a systematic uncertainty on the order of 10^{-17}, mostly limited by the inhomogeneous thermal distribution of the vacuum chamber inducing black body radiation (BBR) shift, but also by cold collisions between the atoms trapped in each site of the optical lattice. Aiming to improve the characterization of systematic effects in optical lattice clocks below 10^{-18}, we propose the implementation of Laguerre-Gaussian modes (LG_{pl}) to shape a multisite trap in the 1D optical lattice of a Sr OLC. Hence reducing the density of atoms, while preserving the advantages of 1D lattices such as amplified power and spatial purity of the modes, unlike 3D optical lattices or tweezers. Quantitatively, the trapping potential in an LG_{0l} mode is given by:

$$U_{0l}(r,\varphi,z) = -U_0 e^{\frac{-2r^2}{w^2(z)}} \cos^2\left[kz - \psi_l(z)\right] \left(\frac{2r^2}{w^2(z)}\right)^{|l|} \cos^2(l\varphi)$$

where $U_0 = \alpha_d I_0$, with α_d the atomic polarizability and I_0 the intra-cavity of the trapping light.

In this work, using a liquid crystal on silicon spatial light modulator (SLM), we demonstrate the generation of LG_{0l} modes with l up to 4, and the injection of these modes into an optical cavity placed in a new copper vacuum chamber. A Pound-Drever-Hall (PDH) scheme is then used to lock the cavity length to the $LG_{0l=0,1,2,3,4}$ modes. Trapping depths up to $39E_r$ for an LG_{04} were obtained, a priori making it possible to implement LG lattices within the clock sequence.

In addition, for limiting conductive and radiative exchanges between the experimental system and the laboratory, the thermal design of the new setup comprises an Ultra-High Vacuum (UHV) chamber that is also placed in a primary vacuum environment. The new thermal conditions will allow better control and determination of the contribution of the BBR to the clock transition $^1S_0 - ^3P_0$ at a fractional uncertainty below 10^{-18}.

Presenter name: Miguel Angel Cifuentes Marin

Poster session / We-37: *Precision meas. & tests of fund. phys.* ID195

Atomic mass ratios of the proton, deuteron, triton and helium-3

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The Florida State University cryogenic Penning ion trap has previously produced the most precise values of the masses of heavier atoms required for several important atomic physics applications [1]. These include Rb and Cs for atom-interferometric measurement of h/m for the fine structure constant, and isotopes of Sr and Yb for King plot analyses. More recently we have focused on mass ratios between isotopes of hydrogen and helium. The relative masses of the proton, deuteron, triton and helion are fundamental constants impacting several areas of physics. In particular, a high-precision value for the mass difference between tritium and helium-3 is important for testing systematics in the ongoing KATRIN neutrino mass experiment, while the deuteron/proton mass ratio is important for interpreting the results of recent high-precision laser and terahertz spectroscopy of the HD^+ molecular ion, leading to an improved value of the electron/proton mass ratio or, alternatively, limits on beyond-standard-model nucleon-nucleon interactions [2]. We achieve high precision by measuring the cyclotron frequency ratio of a pair of ions simultaneously trapped in a single Penning trap. For most of our measurements we alternate each ion between the center of the trap, where its cyclotron frequency is measured, and a large cyclotron "parking" orbit. Our previous measurements on mass-3 ions, besides providing the important Q-value for KATRIN, revealed significant errors in previously accepted values for the masses of p, d and h. In the case of measurements of H_2^+ against D^+, we achieved sufficient resolution to distinguish different vibrational levels of H_2^+ by their difference in mass, and also to observe vibrational Stark quenching [3]. We then placed an H_2^+ and D^+ in a coupled magnetron orbit and measured their cyclotron frequencies simultaneously [4]. This suppressed the effect of variation in the magnetic field by several orders of magnitude. It also reduced uncertainty related to measurement of the ions' axial frequencies. Using this technique we partly resolved H_2^+ rotational energy through the change in mass. This resulted in a value for the deuteron/proton mass ratio at 5 ppt and the first proton atomic mass at 10 ppt.

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Presenter name: Edmund Myers

Upgrading the transportable optical lattice clock at PTB

Authors: Chetan Vishwakarma[1]; Ingo Nosske[1]; Tim Luecke[1]; Sofia Herbers[1]; Christian Lisdat[1]

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After laboratory optical atomic clocks have reached fractional frequency uncertainties in the 10^{-18} regime, it is an ongoing task to miniaturize these complex clocks and make them transportable and in-field deployable, without compromising their performance. This effort is primarily motivated by promising prospects in geodesy. Together with accurate frequency transfer via fiber links, these clocks can measure gravitational potential differences in the 0.1 m^2/s^2 regime (corresponding to 'cm' height differences on Earth's surface) with high spatial and temporal resolution. Thus, they could be used to establish an accurate height reference system. At PTB, we have been operating a transportable optical clock based on neutral strontium atoms in a 1-D optical lattice. This clock previously had been to international measurement campaigns in Modane, Turin, Paris, and Munich.

Here we present the progress in the development of our new transportable clock, to achieve a lower uncertainty and better instability. These upgrades come in the form of a new physics package employing a single-beam pyramid MOT for the first and second stages of cooling, better stray magnetic field shielding, a lower background pressure in the science chamber and a temperature shield for better thermal uniformity during the clock interrogation phase. These changes along with the use of a new transportable cavity (instability: 1.6×10^{-16}) operating at the subharmonic of the clock transition are expected to push the fractional frequency uncertainty to the low 10^{-18} regime.

Presenter name: Chetan Vishwakarma

Poster session / We-39:   *Precision meas. & tests of fund. phys.*   ID242

Towards implanting radioactive polar molecules in a noble gas matrix for fundamental symmetry tests

Authors: Nicholas Nusgart[1]; Jochen Ballof[1]; Peyton Lelain[1]; Jaideep Singh[1]

[1] *Michigan State University*

Nuclear Schiff moments (NSMs) present a powerful probe into new physics through their connection to CP-symmetry violation. We are investigating the application of molecular matrix methods to NSM searches of radioactive isotopes, particularly radium-225, which has an enhanced Schiff moment resulting from its octupole deformations. These methods involve trapping polar molecules in a noble gas matrix, which is predicted to lock their orientation relative to the lattice vectors. In this contribution, we focus on the portion of the FRIB EDM[3] instrument, currently in the design stage, that will create and implant the polar molecules in the substrate. The instrument's beamline starts with a spray-based ion source that will be used to efficiently ionize aqueous harvested radioisotopes. The spray will be collected by a dual ion funnel which will perform initial filtering of background ions. Then the ions will be analyzed by mass-to-charge ratio using a quadrupole mass filter, and then be neutralized in a charge-exchange cell. Finally, the molecules will be co-deposited along with a noble gas matrix. We will report on the design of this high-efficiency molecular beam source and the progress of its construction.

Presenter name: Nicholas Nusgart

Poster session / We-40:   *Precision meas. & tests of fund. phys.*   ID272

Nuclear T-violation search using octupolar nuclei in a crystal

Authors: Harish Ramachandran[1]; Amar Vutha[1]

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The matter-antimatter asymmetry of the universe suggests that new sources of time-reversal symmetry (T) violation lurk at energy scales beyond the reach of colliders. New particles or T-violating interactions coupled to nucleons can lead to nuclear Schiff moments or magnetic quadrupole moments, which result in measurable energy differences between the spin states of nuclei inside electrically polarized atoms.

Nuclei with the highest intrinsic sensitivity to T-violation (octupolar nuclei) are often short-lived radioactive isotopes. Further, obtaining large atomic polarization typically requires the use of heavy polar molecules that are challenging to cool and trap. Therefore, demanding both enhancement factors – large intrinsic T-violation sensitivity and large atomic polarization – usually leads to significant experimental complexity and limited choices for feasible nuclear/molecular candidates. We present a way to evade these constraints and access both the enhancement factors using stable nuclei in a solid.

Our approach uses ^{153}Eu doped into a crystal, which realizes a large ensemble of octupolar nuclei within strongly polarized atomic ions. This system offers a simple but powerful means to hunt for T-violating physics at PeV-scale energies. We will discuss the details of our approach and our progress towards a pathfinder experiment.

Presenter name: Harish Ramachandran

Poster session / **We-41:**   *Precision meas. & tests of fund. phys.*   ID294

An eEDM sensitive experiment using BaF molecules

Authors: Virginia Marshall[1]; Hendrick L. Bethlem[2]; Alexander Boeschoten[1]; Anastasia Borschevsky[1]; Steven Hoekstra[1]; Joost W.F. van Hofslot[1]; Klaus Jungmann[1]; Thomas B. Meijknecht[1]; Maarten C. Mooij[2]; Rob G.E. Timmermans[1]; Anno Touwen[1]; Wim Ubachs[2]; Lorenz Willmann[1]

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[2] *LaserLab, VU, Amsterdam*

Searches limiting the value of the permanent electric dipole moment on the electron (eEDM) are a sensitive probe of the Standard Model of particle physics and its extensions. Such searches have been performed in a number of different atoms and molecules, which resulted in the best current limit on the eEDM of $|d_e| < 1.1 \times 10^{-29}$ e cm [1]. Our experiment has been setup with a BaF supersonic beam with velocities of ≈ 600 m/s. The sensitivity towards an eEDM requires a phase sensitive spin precession measurement in well-known E- and B-fields (10 kV/cm, 10 nT resp.) [2]. The superposition state of the $|F = 0, m_F = |1\rangle$ magnetic substates in the $X\,^2\Sigma^+(\nu = 0, N = 0)$ ground state of BaF is created and read out solely by pulsed laser field interactions. The resulting spin precession signal depends on laser field parameters such as intensity, polarization and frequency detuning. We experimentally investigated the dependence on these parameters which are indispensable for quantification of possible systematic biases that could arise on the eEDM limit extracted limit. We aim to complete an initial measurement stage at a sensitivity level 10^{-28} e cm within this year.

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Presenter name: Virginia Marshall

Poster session / We-42:   *Precision meas. & tests of fund. phys.*   ID306

Very long baseline atom interferometry for tests of fundamental physics

Authors: Dorothee Tell[1]; Vishu Gupta[2]; Ali Lezeik[1]; Christian Meiners[1]; Henning Albers[1]; Klaus H. Zipfel[1]; Christian Schubert[3]; Ernst M. Rasel[1]; Dennis Schlippert[1]

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Atom interferometry is based on the measurement of phase differences in coherent matter waves. As such, it is an ideal technique for measuring inertial forces caused by e.g. acceleration and rotation. The precision of the measurements is provided by the standing light wave imprinting its position-dependent phase onto the matter waves and therefore acting as a fine-spaced ruler.

Being based on single atoms in superposition states, atom interferometry based sensors can perform nonclassical measurements and new perspectives for tests of fundamental physics. They have the ability to probe the limits of quantum physics and general relativity, though this requires highly precise and well-controlled devices.

Here we report on the commissioning of the Very Long Baseline Atom Interferometry (VL-BAI) facility in the Hannover Institute of Technology. It will be composed of a 10.5 m high magnetically shielded free-fall baseline, two atomic source chambers featuring Bose-condensed rubidium and ytterbium, as well as a high-performance seismic attenuation system. This allows for a variety of tests of fundamental physics in a well-controlled environment [1-3].

Besides presenting the current status of the facility, we discuss its prospects for fundamental physics measurements. These include quantum clock interferometry for gravitational redshift tests [4] and differential dual-species interferometers for tests of the universality of free fall [5], but also tests of macroscopicity and fundamental decoherence by separation of superposition states on the meter scale [6].

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Presenter name: Dorothee Tell

Poster session / We-43:   *Precision meas. & tests of fund. phys.*   ID343

Pathway to magneto-optical trapping of SrOH to probe for Dark Matter and EDMs

Authors: Annika Lunstad[1]; Zack Lasner[1]; Hana Lampson[1]; John Doyle[1]

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The complex structure of polyatomic molecules offers powerful features that can be exploited for applications in quantum simulation and precision measurement. One of these features is a plethora of ro-vibrational states. In the linear triatomic molecule SrOH, two vibrational states have a near-degeneracy that can be probed with microwaves (in contrast to typical vibrational splittings of ~ 10 THz). Because the energies of these states depend differently on the proton-to-electron mass ratio, μ, a microwave resonance between them is highly sensitive to changes in μ over time. We report on high-resolution vibrational branching ratio measurements of four excited vibronic states. We are now able to design a laser-cooling scheme with over 10,000 photon scatters before loss to an unaddressed vibrational state, more than enough to form a MOT and load an optical trap. Only 8 lasers are required for this scheme, fewer than for any other known polyatomic molecule cooling cycle. We describe progress towards laser cooling of SrOH and a high-sensitivity measurement of μ variation using ultracold SrOH molecules.

Presenter name: Annika Lunstad

Poster session / We-44:   *Precision meas. & tests of fund. phys.*   ID355

Prospects for constraints on nanometer-range nonNewtonian gravity with a state-of-the-art molecular clock

Authors: Kon H. Leung[1]; Brandon Iritani[1]; Emily Tiberi[1]; Mateusz Borkowski[2]; Tanya Zelevinsky[1]

[1] *Columbia University*

[2] *Columbia University and University of Amsterdam*

Ultracold molecules are a powerful platform for metrology, precision measurements and searches for new, beyond-the-Standard-Model physics. In particular, Sr_2, thanks to its simple structure, insensitivity to external fields and narrow optical transitions, provides an excellent testbed for the search for new interactions. Here, we present a detailed characterisation of our $^{88}Sr_2$ molecular clock for a vibrational transition spanning the entire depth of the ground state potential. We control systematic shifts at the 10^{-14} level and perform absolute frequency measurements at the 10^{-13} level, limited by GPS-based time transfer infrastructure. We discuss prospects to use strontium isotopologues to place improved constraints on new mass-dependent forces, including possible pathways toward the production of ultracold $^{86}Sr_2$ and $^{84}Sr_2$ dimers and spectroscopy of clock lines in these species.

Presenter name: Emily Tiberi

Poster session / We-45:   *Precision meas. & tests of fund. phys.*   ID368

Barium-monofluoride within an argon solid: calculations to support the EDMcubed scheme for measuring the electron electric dipole moment

Authors: G. K. Koyanagi[1]; R. L. Lambo[1]; A. Ragyanszki[1]; R. Fournier[1]; M. Horbatsch[1]; E. A. Hessels[1]

[1] *York University*

The EDMcubed collaboration is working towards a measurement of the electric dipole moment of the electron (eEDM) using barium-monofluoride (BaF) embedded in an argon solid. The large numbers of embedded BaF in this measurement scheme [1] gives the potential for a very precise eEDM measurement. In this work, we present precise relativistic electronic structure calculations (all-electron, with an extrapolation to a complete basis set) of the BaF-Ar tri-atomic system, for a wide range of BaF-Ar separations and angles. The resulting BaF-Ar potential can be parameterized and used to model a BaF molecule embedded into an Ar solid to determine the structure of the local environment around the BaF molecule.

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Presenter name: E. A. Hessels

A transportable Yb optical lattice clock

Authors: Robert Fasano[1]; Wesley Brand[1]; Tobias Bothwell[2]; Yun-Jhih Chen[3]; Richard Fox[2]; Andrew Ludlow[1]

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[2] *National Institute of Standards and Technology*

[3] *JPL*

Optical lattice clocks have demonstrated fractional uncertainty and instability at the 10^{-18} level and beyond. At this performance level, such systems become useful for applications including tests of general relativity, searches for dark matter, time-resolved measurements of geophysical phenomena such as Earth tides, and remote comparisons between distant metrological institutes. However, these systems typically span one or more rooms and are staffed by several experts during clock operation. We present a transportable Yb optical lattice clock which occupies only approximately 1000L and seeks to achieve high autonomous uptime through a suite of advanced controls systems. Preliminary comparisons against a laboratory clock demonstrate an instability near 10^{-17} at 1000 seconds. Several key systematics for transportable operation have been analyzed at the 10^{-18} uncertainty level, and a full uncertainty budget will be completed in 2023. We highlight several upcoming applications including a possible test of general relativity on a >4000 m mountain summit using two-way optical time and frequency transfer to compare with laboratory clocks at NIST.

Presenter name: Robert Fasano

Poster session / Th-33: *Precision meas. & tests of fund. phys.* ID53

Towards the development of an optical lattice clock using bosonic isotopes of mercury

Authors: Clara Zyskind[1]; Manuel Andia[1]; Changlei Guo[1]; Sébastien Bize[1]

[1] *LNE-SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université*

Optical clocks have now reached accuracies close to 1 x 10^{-18} [1]. Thanks to their extremely low uncertainties, they are used as tools for various applications, such as chronometric geodesy, tests of General Relativity, search for physics beyond the Standard Model or redefinition of the SI second [3].

Mercury has not been much investigated in cold atoms or quantum gas experiments, and the properties of its various stable isotopes are still to be explored. Moreover, optical lattice clocks based on mercury are studied because of certain advantages over other neutral atoms. In particular, the mercury clock transition $^1S_0$ - $^3P_0$ has a low sensitivity to black-body radiation (BBR), that is to say the energy level shift due to the thermal radiation of an environment at a non zero temperature. Its sensitivity to BBR is 16 times lower than ytterbium and 30 times lower than strontium, two of the most successful clock species. It also has a high saturation vapor pressure favorable to implement a 2D magneto-optical trap as an efficient source of pre-cooled atoms. The mercury clock transition has a relatively high sensitivity to a putative variation of the fine structure constant [4], and hence allows to constrain theories aiming to unify gravity with other interactions and to search for dark matter. Working with mercury implies using UV-transitions which is one of the main experimental challenges. Developments of optical lattice clocks using mercury have been focusing so far on the ^{199}Hg fermionic isotope [5][6].

The clock transition $^1S_0$ - $^3P_0$ of ^{199}Hg is naturally allowed thanks to the hyperfine mixing due to the 1/2 nuclear spin of ^{199}Hg. But the lifetime of the state $^3P_0$ is becoming smaller than the longer probing time allowed by the new generation of ultrastable lasers, so it is a limiting factor to fully exploit the potential of these novel technology lasers. Instead in bosonic isotopes with a zero nuclear spin, the $^3P_0$ state has hypothetically an unlimited lifetime. The $^1S_0$ - $^3P_0$ transition can be induced with an external magnetic field by a quenching scheme, and thereby giving the possibility to adapt the strength of this coupling to the probe laser characteristics [7]. ^{174}Yb was studied with this method [8][9]. ^{88}Sr clocks also based on this approach were also studied [10] and have shown promising accuracy [11].

In this poster, we will describe the laser cooling methods used, which open the way to study collisional properties. We will describe the optical lattice clock at SYRTE and we will report the achievement made so far on the ^{199}Hg isotope (stability, accuracy budget, comparisons). We will mention limitations of our current setup and explain the scheme, the expectations and the future steps for making a clock using bosonic isotopes of mercury.

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Presenter name: Zyskind, Clara

Poster session / Th-34: *Precision meas. & tests of fund. phys.* ID78

Measurements of np - 2s transitions in the hydrogen atom

Authors: Simon Scheidegger[1]; Joseph Anton Agner[1]; Hansjürg Schmutz[1]; Frédéric Merkt[1]

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Precision experiments in the hydrogen atom have a long tradition and extensive studies of transitions between low lying $n \leq 12$ states were carried out [1-6]. These measurements can be used to determine values of the Rydberg constant and the proton charge radius. We present a new experimental approach to perform measurements of transition frequencies between the metastable 2s ^{2}S$_{1/2}(F = 0, 1)$ state of H and highly excited np-Rydberg states with principal quantum number $n \geq 23$.

We generate the hydrogen atoms by dissociating H_2 in a dielectric barrier discharge located at the orifice of a pulsed cryogenic valve. The hydrogen atoms are entrained in the supersonic expansion of H_2. The atoms are photoexcited to a specific hyperfine level of the metastable 2s ^{2}S$_{1/2}$ state by a home-built frequency-tripled Fourier-transform-limited pulsed titanium-sapphire laser (pulse length 40 ns). They enter a magnetically shielded region in which transitions to np Rydberg states are induced by a narrow-band frequency-doubled continuous-wave titanium-sapphire laser, which is phase locked to an optically stabilized frequency comb and referenced over a fiber network to a SI traceable primary frequency standard [7]. The highly excited Rydberg states are detected by pulsed-field ionization. We will report progress on our efforts to minimize uncertainties from stray electric fields and Doppler shifts and to obtain spectral lines with a FWHM below 10 MHz.

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Presenter name: Simon Scheidegger

Poster session / Th-35:   *Precision meas. & tests of fund. phys.*   ID90

Multiloop atomic Sagnac interferometry

Authors: Sven Abend[1]; Christian Schubert[2]; Matthias Gersemann[1]; Ernst M. Rasel[1]

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Inertial sensors based on matter-wave interference show great potential for navigation, geodesy, or fundamental physics. Similar to the Sagnac effect, their sensitivity to rotations increases with the space-time area enclosed by the interferometer. In the case of light interferometers, the latter can be enlarged by forming multiple fibre loops. However, the equivalent for matter-wave interferometers remains an experimental challenge. This contribution presents a concept for a multiloop atom interferometer with a scalable area formed by multiple light pulses. It exploits ultra-cold atomic ensembles combined with symmetric beam splitting and a relaunch mechanism. Due to its scalability it offers the perspective of reaching unprecedented sensitivities for rotations in compact sensor head setups.

Presenter name: Sven Abend

High-precision measurements of atomic structure in Lead and other multivalence atomic systems

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We have undertaken a series of measurements of atomic properties of group III and IV systems to test ongoing *ab initio* atomic structure calculations. These multivalence systems have relevance to tests of symmetry violation and other fundamental physics searches. Prior work involved measurements of polarizability, isotope shifts, and hyperfine structure in various excited states of the three-valence thallium and indium systems.

Recently, we have focused on the four-valence Pb system where significantly improved atomic structure calculations [1] have been completed for an atomic system in which two different precise atomic parity nonconservation experiments were performed two decades ago. Unlike alkali systems, relatively few atomic benchmark measurements exist in Pb at a level of accuracy necessary to test and guide refinement of the theory. In 2019, we completed the first measurement of the forbidden Pb $(6s^2 6p^2)$ $^3P_0$ - $^3P_2$ E2 transition amplitude at 939 nm, finding excellent agreement with the *ab initio* value computed by the Safronova group at the 1% level of accuracy. The experimental method employed the same high-precision polarimetry technique used to measure parity nonconserving optical rotation. This technique, which uses crossed polarizers and a Faraday modulation / lock-in detection technique, yields μRadian precision, allowing measurement of very weak atomic transitions via detection of milliradian-sized Faraday rotation using small DC magneticfields applied to the sample.

We are currently pursuing several new Pb atomic structure measurements using this same Faraday polarimetry method. These include measurements of transition isotope shifts and hyperfine splittings in these forbidden transitions using isotopically-enriched vapor cells, as well as measurements of electric dipole amplitudes for transitions originating in thermally-excited levels with populations of order 10^{-5} of the ground-state population.

Additionally we plan to measure, for the first time, excited-state polarizabilities in Pb, using the same atomic beam apparatus and high-voltage field-plate system used in our lab for prior measurements in indium and thallium. Here, a molybdenum crucible containing 300 g of lead is heated to above 1000 °C to create a dense, collimated atomic beam. The sensitive Faraday polarimetry method will be used to perform transverse spectroscopy in the presence of this beam and static electric fields up to 20 kV/cm will create Stark shifts in the 368 nm $(6s^2 6p^2)$ $^3P_1$ - $(6s^2 6p7s)^3P_0$ E1 transition. The predicted Stark shift is roughly half the expected Doppler-narrowed line width, and we expect to see Faraday rotation signals of order 100 μRadians, which should be easily measurable using our polarimetry technique, providing a new, exacting test of the atomic theory predictions.

Current results will be presented.

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Presenter name: Protik Majumder

Poster session / Th-37: *Precision meas. & tests of fund. phys.* ID144

An experiment to measure the electron's electric dipole moment using trapped ultracold molecules

Authors: Andrew D White[1]; Stefan Popa[1]; Jorge Mellado Munoz[1]; Jongseok Lim[1]; Xavier Y Alauze[1]; Chi Zhang[1]; Noah J Fitch[1]; Ben E Sauer[1]; Michael R Tarbutt[1]

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The large asymmetry between matter and antimatter in the Universe is a mystery. The formation of this extra matter requires charge parity (CP) violation beyond that contained in the standard model, and therefore points towards new physics [1]. The electron's electric dipole moment (eEDM) is sensitive to this new physics. Precision measurement of the eEDM tests physics beyond the Standard Model and will expand our understanding of the fundamental principles of nature. We aim to improve the precision of the eEDM measurement by 3 orders of magnitude using an array of ultracold ytterbium monofluoride (YbF) molecules held in an optical lattice, measuring an eEDM on the order of 10^{-32} e cm [2].

We produce a beam of YbF using a two stage cryogenic buffer gas source cooled to 2 K. In this source, YbF is formed by laser ablation of an ytterbium target in the presence of sulphur hexafluoride (SF6), and is then entrained in a flow of cold helium gas. We plan to decelerate these molecules using laser slowing, capture them in a magneto-optical trap, cool them to a few microkelvin and then load them into an optical lattice where spin coherence times of several seconds seem feasible. We will present the progress made towards generating a slow beam, initial laser slowing experiments and our plans for the future.

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Presenter name: Andrew D White

Poster session / Th-38:   *Precision meas. & tests of fund. phys.*   ID177

Two-beam self-oscillating OPM for low-drift high-precision DC magnetometry

Authors: Aurelien Chopinaud[1]; Stuart Ingleby[1]

Co-authors: Marcin Mrozowski [1]; Carolyn O'Dwyer [1]; Paul F. Griffin [1]; Erling Riis [1]

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Finite-field optical magnetometry offers practical advantages in geophysics, surveying and navigation due to the sensitivity and accuracy achievable with alkali double-resonance techniques. In this sensor scheme, resonant modulation at the Larmor frequency is applied to the alkali spins in order to drive the resonant response and maximise signal contrast [1,2]. Homodyne detection also offers a path to noise reduction in scalable electronic systems. In order to develop operating modes and readout schemes we have built a shielded laboratory magnetometer system using anti-relaxation-coated 133Cs cells [3]. We will run this system as a self-oscillating spin maser as a platform for development of low-drift high-precision DC magnetometry, including study of spin dynamics and limiting noise sources.

We present developments of a two-beam optically pumped alkali magnetometer for investigation of stable Cramer-Rao-lower-bound limited magnetometry, spin-noise limited off-resonant detection of spin maser precession and long-timescale shielded optical magnetometry. We discuss potential future development of this system as a network node for new physics searches [4].

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Presenter name: Aurélien Chopinaud

Update of the JILA gen. III eEDM experiment

Authors: Kia Boon Ng[1]; Noah Schlossberger[1]; Sun Yool Park[1]; Anzhou Wang[1]; Benjamin Hunt[1]; Tanya Roussy[1]; Trevor Wright[1]; Antonio Vigil[1]; Gustavo Santaella[1]; Luke Caldwell[1]; Jun Ye[1]; Eric Cornell[1]

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The Standard Model of particle physics is one of the most successful models that we use to describe the universe, yet it is known to be incomplete. Substantial efforts on the theoretical front introduce new physics through extensions of the Standard Model, and these new physics models make predictions on the value of the electric dipole moment of the electron (eEDM). Measurements of (or improved limit on) the eEDM places constraints on these new theories. The eEDM experiments at JILA take advantage of the long trapping time of ions to tap the long coherence times of the eEDM-sensitive states in our molecular ions of choice: HfF^+ and ThF^+. The ongoing experiment using HfF^+ is an upgraded version of our 2017 experiment [1], using a bigger trap for more ions, amongst other improvements for better statistics. The upcoming experiment using ThF^+ has wrapped up spectroscopy of the molecule [2,3,4], and we are now setting up a prototype experiment to demonstrate much longer coherence times than HfF^+, promised to us by the eEDM-sensitive ground state in ThF^+ [2,4]. Herein, we provide a teaser on the demonstration of long coherence times in ThF^+.

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Presenter name: Kia Boon Ng

Poster session / Th-40: *Precision meas. & tests of fund. phys.* ID225

eEDM-sensitive molecules trapped in neon ice

Authors: Samuel Li[1]; Eman Shayeb[1]; Amar Vutha[1]

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Improved searches for the electron electric dipole moment (eEDM) require large numbers of polar molecules with long spin coherence times. We report trapping of BaF molecules in cryogenic neon ice, with trap lifetimes exceeding two weeks. Laser-induced fluorescence measurements indicate that the molecules are only weakly perturbed compared to previous studies on atoms in inert solids. Our results open a path to optical spin polarization and precession measurements in BaF:Ne, aimed at developing an improved eEDM search experiment.

Presenter name: Samuel Li

Poster session / Th-41:   *Precision meas. & tests of fund. phys.*   ID249

Optical clocks with trapped ^{40}Ca$^+$ and ^{27}Al$^+$ ions

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The search for more precise and accurate frequency standards has played a key role in the development of basic science, precision measurements and technical applications. Nowadays, optical clocks with trapped ions are achieving uncertainties in the low 10^{-18} range and below. One of our group's focuses is centered on the implementation of optical clocks with trapped ^{40}Ca$^+$ and ^{27}Al$^+$.

Since its first measurement in 2009 by our group, the absolute frequency of the $4s\ ^2S_{1/2} \leftrightarrow 3d\ ^2D_{5/2}$ $^{40}Ca^+$ clock transition has been reported 4 more times. However, the first two of these published results (between 2009 and 2012) disagree with the latter two (between 2013 and 2017). We present the results of a new campaign to measure the absolute frequency of $^{40}Ca^+$ clock transition with respect to the coordinated universal time UTC at PTB by means of a GNSS link using the Precise Point Positioning (PPP) technique. After evaluation of the systematic shifts, the transition frequency is measured to be (411 042 129 776 401.3$\pm$0.6) Hz with a fractional uncertainty of 1.4×10^{-15}.

To investigate the optical transitions on the ^{27}Al$^+$, we implement Quantum Logic Spectroscopy (QLS). QLS consists of the combined implementation of an auxiliary "logic" ion, which is stored together with a "spectroscopy" ion. The "logic" ion is used to cool down the initially hot "spectroscopy" ion via their Coulomb interaction and additionally allows the preparation and detection of the internal state of the "spectroscopy" ion. We performed QLS for a measurement of the $^1S_0 \leftrightarrow\ ^3P_1$ intercombination transition in ^{27}Al$^+$. Ramsey spectroscopy is used for probing the transition in ^{27}Al$^+$ and the $4s\ ^2S_{1/2} \leftrightarrow 3d\ ^2D_{5/2}$ clock transition in $^{40}Ca^+$ in interleaved measurements. By using the precisely measured frequency of the clock transition in $^{40}Ca^+$ as a frequency reference we determine the frequency of the intercombination line to be 1 122 842 857 334 736(93) Hz and the Landé g-factor of the excited state to be 0.428132(2) [1]. We have also probed the $^1S_0 \leftrightarrow\ ^3P_0$ ^{27}Al$^+$ clock transition with a probe-time-limited width of 1 kHz. Efforts to obtain spectrally narrower lines are mostly hampered by the formation of molecular ions by reaction of the Al+ with H2 background gas molecules. Molecular ion formation limits the time that we can uninterruptedly probe the clock transition to about 15 minutes, which in combination with long Al$^+$ reloading times, prevent us from investigating the clock transition more thoroughly.

Our latest project focuses on the development of three different experimental techniques to investigate trapped-ion kinetics due to background-gas collisions. Background gas collisions can perturb the frequency of atomic clocks. The energy imparted during collision events affects the motional state distribution, which consequently has an effect on the time-dilation, also known as second-order Doppler shift. In Additional to this shift, any interaction during the collision can perturb the phase of the atomic superposition. The three techniques together detect a range in energy due to collisions spanning 7 orders of magnitude. The first technique uses a composite sequence of optical transitions in Ca$^+$ to accurately transfer information about its motional state, allowing the detection of collisions that impart a kinetic energy between 10^{-3} K to 10^{-1} K. The second technique is based on the detection of collisions that cause a reordering of a mixed-species ion pair and covers a range from 10^{-1} K to 10 K. The third technique is based on the characterization of the re-cooling dynamics of a single calcium ion after a collision and covers a range from 10 K to 10^4 K. The experimental characterization of trapped-ion kinetics due to background-gas collisions through such a broad range opens the door to a deeper understanding of the background-gas composition and its effect on trapped ion experiments.

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Presenter name: Milena Guevara Bertsch

Poster session / Th-42: *Precision meas. & tests of fund. phys.* ID277

Towards relativistic geodesy with a transportable aluminum ion quantum logic optical clock

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In relativistic geodesy, frequencies of distant optical clocks are compared to measure the relativistic redshift and thereby the geodetic height difference between the clocks. To obtain a height resolution of on the order of 1 cm, clocks with a fractional frequency uncertainty of 10-18 are required.

Here, we present a joint effort between PTB and DLR-SI to build a transportable aluminum ion clock. In contrast to other species, the aluminum clock transition is very insensitive to blackbody radiation. The linear and quadratic Zeeman shifts are small, and the electric quadrupole shift is negligible. These favorable features led to the first optical clock with an estimated systematic uncertainty below 10^{-18} [1]. However, a co-trapped so-called logic ion is required for sympathetic cooling and state readout via quantum logic spectroscopy [2].

The transportable clock setup benefits from our experience gained during development of a similar laboratory clock apparatus with a preliminary estimated apparatus-related systematic fractional frequency uncertainty of 1.9×10^{-18} [3]. Other key-components are a segmented multilayer trap made of AlN substrates [4], a transportable reference cavity for the clock laser [5], and a single-pass fourth harmonic generation unit for the clock laser that facilitates an uninterrupted phase stabilization of the fundamental laser.

We present preliminary characterization results of the reference cavity and the FHG unit as key building blocks of the clock laser. Moreover, we present potential applications of such clocks for geodetic measurement campaigns.

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Presenter name: Stephan Hannig

Continuous cold strontium atoms through a cavity as a frequency standard

Authors: Julian Robinson-Tait[1]; Eliot Bohr[1]; Sofus Kristensen[1]; Joerg Helge Mueller[1]

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The state-of-the-art optical atomic clocks rely on trapping, cooling and readout at the same point in space and the cooling stages are separated in time; however, they suffer from finite dead-time between measurements leading to additional noise, and complicated control sequences. The next generation of optical clocks should be continuous with inherently zero dead-time and steady-state operation which simplifies control.

We plan to demonstrate this with a continuous beam of neutral strontium-88 that is cooled and compressed by a sequence of laser cooling stages separated in space. The continuous beam emerges from a Zeeman slower with a speed around $30\,\mathrm{ms}^{-1}$ and enters an angled 2D MOT which will act to (1.) cool and compress the atomic beam transversely (2.) deflect the atomic beam into a cavity region that is protected from harmful stray light (3.) focus the atomic beam in 1 axis to overlap with the mode volume of a linear cavity. With this continuous, compressed, cooled and dense fluxed of atoms through the cavity, we plan to perform spectroscopy on the $7.6\,\mathrm{kHz}$ wide inter-combination line with a cavity enhanced scheme called NICE-OHMS that is immune to cavity noise (to first order), and then characterize the experiment's performance as a frequency standard.

Presenter name: Julian Robinson-Tait

Poster session / Th-44:   *Precision meas. & tests of fund. phys.*   ID347

AION: An atom interferometer observatory and network

Authors: Tiffany Harte[1]; Chung Chuan Hsu[1]; Zach Eyler[1]; Brian Bostwick[1]; Kimberly Tkalčec[1]; Ulrich Schneider[1]

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Atom interferometers are sensitive to the signatures of gravitational waves, ultra-light dark matter and other fundamental physics phenomena. The development of this new class of quantum detector will complement traditional detection methods and extend measurement capabilities.

The Atom Interferometer Observatory and Network (AION) [1] is a planned series of atom interferometers operating on the strontium clock transition in a gradiometer configuration. The baseline of terrestrial devices, corresponding to the separation between interferometers in the differential measurement, will increase from 10 m to 1 km. Current work focusses on developing the cold atom technologies to support the detection goals, including transport and cooling of the atom clouds, state preparation and large momentum transfer techniques, and design of the 10 m device. This poster outlines the scientific goals, experimental implementation and recent progress of the AION detector with a focus on the work on atom transport and cooling being carried out at the University of Cambridge.

This poster is presented on behalf of the AION consortium.

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Presenter name: Tiffany Harte

Towards a cw superradiant laser: Continuous strong coupling and transport of 88Sr atoms in a ring cavity

Authors: Vera M Schäfer[1]; Julia R K Cline[1]; Zhijing Niu[1]; Dylan J Young[1]; Eric Song[1]; James K Thompson[1]

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Superradiant lasers are a promising path towards realizing a narrow-linewidth, high-precision and high-bandwidth active frequency reference [1]. They shift the phase memory from the optical cavity, which is subject to technical and thermal vibration noise, to an ultra-narrow optical atomic transition of an ensemble of cold atoms trapped inside the cavity. Our previous demonstration of pulsed superradiance on the mHz transition in ^{87}Sr [2,3] achieved a fractional Allan deviation of $6.7 \cdot 10^{-16}$ at 1s of averaging. Moving towards continuous-wave superradiance promises to further improve the short-term frequency stability by orders of magnitude. A key challenge in realizing a cw superradiant laser is the continuous supply of cold atoms into a cavity, while staying in the collective strong coupling regime.

We demonstrate continuous loading of cold ^{88}Sr atoms into a ring cavity, after several stages of laser cooling and slowing. We characterize controlled transport of the atoms within the ring cavity using an intracavity travelling wave optical lattice, and demonstrate continuous strong collective atom-cavity coupling through continuous measurement of the vacuum Rabi splitting. We further present ongoing work on characterising apparent continuous collective light emission of the atoms on the 7.5kHz transition in ^{88}Sr.

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Presenter name: Vera Schäfer

Poster session / Th-46: *Precision meas. & tests of fund. phys.* ID370

Deflection of barium-monofluoride molecules

Authors: A. Marsman[1]; M. Horbatsch[1]; D. Heinrich[1]; N. McCall[1]; J. Perez Garcia[1]; H.-M. Yau[1]; R. L. Lambo[1]; G. K. Koyanagi[1]; M. C. George[1]; C. H. Storry[1]; Z. Corriveau[1]; J. T. Singh[2]; A. C. Vutha[3]; E. A. Hessels[1]

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Density-matrix simulations of an optical scheme for producing a large optical force on barium-monofluoride (BaF) molecules are presented. The scheme uses short laser pulses to induce excitation to the A Pi 1/2 state, with pulses from counter-propagating laser beams causing stimulated emission back to the ground electronic state. A magnetic field is used to remove degeneracies to avoid dark states. The calculated force is an order of magnitude larger than the maximum force possible with CW laser schemes. Additionally, because the molecules spend little time in the excited state, spontaneous decay is minimized, reducing or eliminating the need for re-pump lasers from other states (e.g., other ground vibrational states). Methods for electrostatic deflection of BaF will also be presented. The EDMcubed scheme [1] for measuring the electron electric dipole moment using BaF embedded in an Ar solid requires a BaF deflection to separate BaF from other products produced in a buffer-gas laser-ablation source.

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Presenter name: Daniel Heinrich

Poster session / Th-47:   *Precision meas. & tests of fund. phys.*   ID381

Measuring the $n = 2$ triplet P fine structure of atomic helium using frequency-offset separated oscillatory fields (FOSOF)

Authors: T. D. G. Skinner[1]; F. Heydarizadmotlagh[1]; K. Kato[1]; M. C. George[1]; E. A. Hessels[1]

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The n=2 triplet P fine structure of atomic helium is being measured using microwave transitions. The method [1] of Frequency-Offset Separated Oscillatory Fields (FOSOF) is used to perform the measurements. The measurement of the J=1-to-J=2 interval has been completed [2], with a measurement uncertainty of only 25 Hz. The measurement of the 29.6-GHz J=0-to-J=1 interval is now being performed. These measurements, together with sufficiently precise theoretical predictions for the intervals (see [3] for the current state-of-the-art calculations) can be used to determine a value for the fine-structure constant and to test for possible physics beyond the standard model.

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Presenter name: T. D. G. Skinner

Direct frequency comb spectroscopy with two atom species for comb laser frequency stabilization

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1. Introduction

To convert a femtosecond laser into a frequency-comb laser, it is frequently essential to use a costly atomic clock [1] to stabilize the repetition rate (f rep) and sophisticated nonlinear optics to lock the offset frequency (f ceo). In this report, we demonstrate that the mode frequencies of a comb laser can be directly referenced to two stepwise two-photon transitions (STPTs) in cesium and rubidium using just one 6-cm cesium-rubidium mixed cell and no extra clocks, revealing a new approach for comb laser frequency stabilization. The related spectra are based on a novel scheme for reducing the residual Doppler background in direct comb laser spectroscopy. For showing the possibilities of being a comb clocks, we investigate all potential error causes to demonstrate that our comb laser is capable of serving as a time-keeping equipment in the 778 nm to 822 nm wavelength range. The ultra-high spectral resolution (5 kHz) of our direct comb laser spectroscopy reveals some new and intriguing physics, such as the two-pathway interfered dip in rubidium spectra; the abnormal light shift and collision shift compared to what was observed by CW laser; a narrower linewidth despite the presence of broadening intermediate states; and the zero influence of the laser bandwidth, in contrast to the "strong-influence" conclusion in the direct two-photon transition experiment [2].

2. Experimental setup and result

Fig. 1 (a) depicts the schematic diagram of our experimental arrangement. The spectra concurrently resolved by our comb laser are shown in Fig. 1 (b). The two STPTs as the frequency references are line 7 in rubidium and line 8' in cesium, which are 5S1/2(F=1)>5P3/2(F=2)>5D5/2(F=3) and 6S1/2(F=3)>6P3/2(F=3)>8S1/2(F=3), respectively. To generate Doppler-free spectra, a piezoelectric transducer (PZT) in fig. 1 (a) was utilized to constantly change the overlapping condition of the laser beam, allowing only the fluorescence arising from the overlapped counter-propagating pulses to be amplitude modulated. In Fig. 1 (c), When compared to the CW laser experiment [3] (black line), the AC Stark shift of Rb line 7 (green line) indicates a completely different direction of detuning, although the slope of the comb laser light shift (red line) in Cs line 8' is close to that of the CW laser [4]. In addition, the authors of reference [2] report a new error source in comb laser spectroscopy frequency accuracy; that is, the laser bandwidth or shaped pulses influence the atomic transition center as well as the linewidth in their comb-DTPT (direct two-photon transition) spectrum, whereas we did not find any such frequency shift in our STPT spectra, within our experimental resolution.

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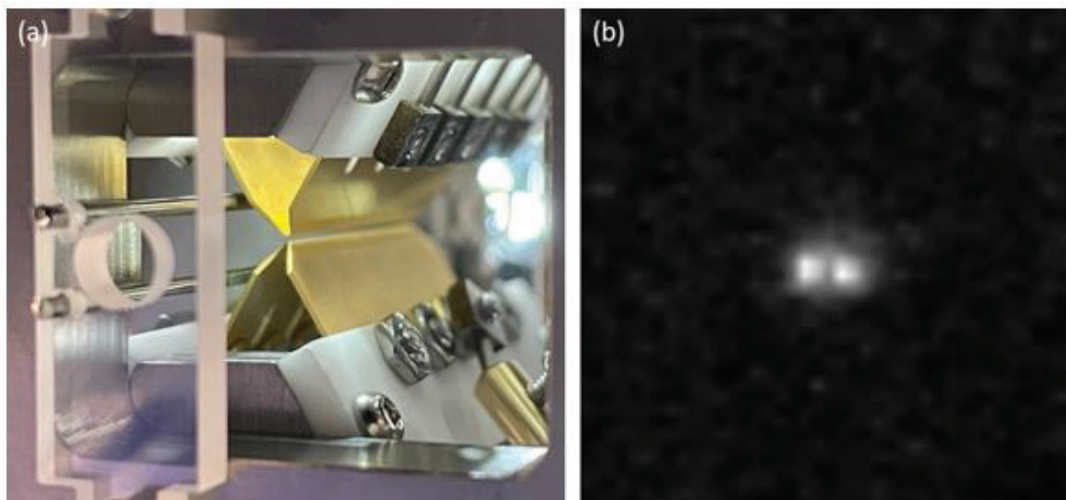
Figure 1: (a) Simplified block diagram of the experimental setup; IF: interference filter. (b) shows the original residual Doppler background and the effect of demodulation. (c) AC stark shifts of Rb and Cs two-photon transitions resolved by comb laser and CW laser.

Presenter name: Liu, Tze-Wei

Poster session / Th-49:   *Precision meas. & tests of fund. phys.*   ID79

Precision measurement of the electron orbital g-factor and the search for new physics

Author: Ayodeji Awobode[1]

[1] *University of Massachusetts Boston*

High precision measurements of the electron spin and orbital g-factors complement very well, the atomic/molecular experiments which test for parity, search for a permanent electric dipole moment, and investigate QED. In this talk, experimental evidence will be presented to show that the electron orbital g-factor is significantly anomalous. A search for an anomaly in the electron g-factors, particularly the spin g-factor, has provided stringent tests of QED (and therefore the Standard Model). However, it is currently assumed that the electron orbital g-factor is unaffected by the radiative interactions, though the anomaly $(g-2)$ in the spin g-factor, is attributed to radiative corrections. It will be shown, both by experimental data and theoretical calculations, that the orbital g-factor is affected by radiative corrections. Furthermore, it is currently assumed, without the benefit of sufficient experimental investigations, that the electron has a uniform mass-to-charge distribution like a classical point particle, hence its orbital g-factor must be exactly equal to one, i.e, $g_L = 1$. However, determinations from the measurement of the ratio of g_J values in In, Ga, Na, Ar, Ne and He, indicate that the anomaly in the electron orbital g-factor is of the order of 10^{-3} to 10^{-4} to very high precision, and that the electron may not be a simple point particle. Alternatively, this could indicate the presence of hitherto unknown interactions. Thus, high-precision measurements of the electron g-orbital factors, will constitute also be a useful guide in the search for new physics beyond the Standard Model, while also providing a low-energy means of elucidating the nature or structure of the electron.

Presenter name: Ayodeji Awobode

Virtual poster / Vir23: *Precision meas. & tests of fund. phys.* ID189

A new mass-energy test of the equivalence principle using ^{85}Rb-^{87}Rb atom interferometer

Authors: Lin Zhou[1]; Chuan He[1]; Si-Tong Yan[1]; Xi Chen[1]; Dong-Feng Gao[1]; Wei-Tao Duan[1]; Yu-Hang Ji[1]; Run-Dong Xu[1]; Biao Tang[1]; Chao Zhou[1]; Sachin Barthwal[2]; Qi Wang[1]; Zhuo Hou[1]; Zong-Yuan Xiong[1]; Yuan-Zhong Zhang[3]; Min Liu[1]; Wei-Tou Ni[1]; Jin Wang[1]; Ming-Sheng Zhan[1]

[1] *State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences, Wuhan 430071, China*

[2] *Light and Matter Physics, Raman Research Institute, Sadashivanagar, Bangalore 560080, India*

[3] *Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China*

The mass tests of equivalence principle (EP) with atoms have been performed using ^{85}Rb-^{87}Rb, ^{87}Rb-^{39}K, and ^{88}Sr-^{87}Sr atom pairs [1–7]. Beyond-mass tests have been investigated using different quantum properties, including quantum statistics [8], spin [9,10], superposition [11], and internal energy [1,10,11]. An entanglement test [12] was also proposed. All of these quantum tests use either a mass pair in a certain internal state or a state pair in a single mass. A joint test of two attributes, such as mass and internal energy, would provide more information than the single attribute test. However, such two-parameter test experiments are usually not easy because we need to specify and fix the attributes during the experiment.

Here, we use rubidium isotope atoms with specified mass and internal energy to carry out a joint mass-energy test of the EP. We correct the Coriolis error by compensating the rotation of Raman laser's mirror [13], improve the four-wave double-diffraction Raman transition method (4WDR) we proposed before to select atoms with a certain mass and angular momentum state, and form a dual-species atom interferometer. By using the extended 4WDR to ^{85}Rb and ^{87}Rb atoms with different angular momenta, we measure their differential gravitational acceleration, and we determine the value of the Eötvös parameter, η, which measures the strength of the violation of EP [14]. The Eötvös parameters of the four paired combinations ^{85}Rb$|F = 2\rangle$–^{87}Rb$|F = 1\rangle$, ^{85}Rb$|F = 2\rangle$–^{87}Rb$|F = 2\rangle$, ^{85}Rb$|F = 3\rangle$–^{87}Rb$|F = 1\rangle$, and ^{85}Rb$|F = 3\rangle$–^{87}Rb$|F = 2\rangle$ were measured to be $\eta_1 = (1.5 \pm 3.2) \times 10^{-10}$, $\eta_2 = (0.6 \pm 3.7) \times 10^{-10}$, $\eta_3 = (2.5 \pm 4.1) \times 10^{-10}$, and $\eta_4 = (2.7 \pm 3.6) \times 10^{-10}$, respectively. The violation parameter of mass is constrained to $\eta_0 = (0.8 \pm 1.4) \times 10^{-10}$, and that of internal energy to $\eta_E = (0.0 \pm 0.4) \times 10^{-10}$ per reduced energy ratio a ($a = h\nu_0/mc^2$ [2], and $\nu_0 = 1$ GHz). This work opens a door for joint tests of two attributes beyond the traditional pure mass or energy tests of EP with quantum systems.

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Presenter name: Jin Wang

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Virtual poster / Vir24:   *Precision meas. & tests of fund. phys.*   ID271

Quantum nondemolition measurement on spin precession of laser-trapped ^{171}Yb atoms

Authors: Yang Yang⋅; Tao Zheng⋅; Chang-Ling Zou⋅; Tian Xia⋅; Zheng-Tian Lu⋅

Quantum nondemolition (QND) measurement enhances the detection efficiency and measurement fidelity, and is highly desired for its applications in precision measurements and quantum information processing. We propose and demonstrate a QND scheme for the spin state of laser-trapped atoms, allowing the atoms in each spin state to be probed repeatedly. On ^{171}Yb atoms held in an optical dipole trap, a spin-selective cycling transition is produced by introducing an ancillary laser. We measure the phase of spin precession of the ^{171}Yb atoms in a 20-mG bias magnetic field. The QND approach reduces the measurement noise by $\sim$19 dB, to a level of 2.4 dB below the atom shot noise.

Presenter name: Yang Yang

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Surprising results found in testing for the continuous spectrum of X-rays predicted to accompany the photoejection of an atomic inner-shell electron

Authors: Carl Franck[1]; Philip Jacobson[1]; Arthur Campello[1]

[1] *Cornell University*

R. Pratt et al. have called attention to the unsettled observational status for the radiation (intraatomic bremsstrahlung, IAB) expected upon the photoejection of inner shell electrons. We tested for such radiation in the 3 to 7 keV band produced by photoelectrons from the K shell of a copper target upon absorption of an incident 46 keV photon. Exploiting a prediction for the major background process: ordinary bremsstrahlung due to the encounter of the photoelectron with atoms other than that of its point of origin, we conclude that for our thinnest (40 nm) targets within statistical limits we observe no IAB radiation. In this manner, contemporary theory is ruled out by over 5 sigmas. Assuming no particular secondary process the intensity of observed IAB radiation is 4 sigmas below expectations. We conclude that in contrast to the sister nuclear process of internal bremsstrahlung observed upon beta decay, our understanding of intraatomic bremsstrahlung remains lacking.

Presenter name: Carl Franck

Poster session / Mo-45:   *Quant. info.: gates, sensing, commun. & Thermo.*   ID52

Rabi vector magnetometry implemented with hot alkali vapor

Authors: Christopher Kiehl[1]; Tobias Thiele[1]; Thanmay Sunil Menon[1]; Svenja Knappe[2]; Cindy Regal[3]

[1] *JILA, University of Colorado Boulder*

[2] *University of Colorado Boulder, FieldLine Inc.*

[3] *JILA, NIST, University of Colorado Boulder*

Optically-pumped magnetometers (OPMs) are widely used for their scalar sensitivity, accuracy, and compact sensor packages, but require additional mechanical references for vector magnetometry. These mechanical references, such as a coil system, often limit the vector accuracy due to machining tolerances and drifts. Current approaches to improve vector accuracy are calibrations that involve physical rotations of the magnetometer system at the expense of increasing the complexity of the physical apparatus. In this poster we demonstrate Rabi magnetometry as a novel approach to vector sensing with an OPM that utilizes a microwave polarization ellipse (MPE) as an accurate 3D reference.

The working principle of the Rabi magnetometer is to extract the orientation of a DC magnetic field relative to the MPE from Rabi rates driven coherently on a set of hyperfine transitions by a microwave field. Importantly, we calibrate systematics such as coil system and MPE drifts, pressure shifts, and Stark shifts from an accumulation of Rabi frequencies driven at various microwave detunings. Our measurements take place in a heated microfabricated vapor cell embedded within a microwave cavity; a platform with much greater sensitivity than a previous proof-of-concept experiment with cold atoms [1]. Depending on the direction of the DC magnetic field, we extract Rabi rates by either directly measuring Rabi oscillations or by fitting to sidebands in the Larmor free-induction-decay (FID) spectrum due to microwave dressing. Here we utilize the Faraday effect of a far-detuned probe beam to nondestructively sense atomic spin. With a full theoretical model, we understand the coherence of these Rabi oscillations to be dominated by spin-exchange collisions in a regime where current theoretical studies of hyperfine coherence that assume static atomic populations are not accurate.

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Presenter name: Christopher Kiehl

Poster session / Mo-46:   *Quant. info.: gates, sensing, commun. & Thermo.*   ID72

Measurement-only phase transitions in 2D via noncommuting two qubit measurements

Authors: Vaibhav Sharma[1]; Erich Mueller[1]; Chao-Ming Jian[1]

[1] *Cornell University*

Motivated by the extensive studies of measurement-only entanglement phase transitions in 1D, we implement a simple model of random noncommuting two qubit XX and ZZ measurements in 2D. We tune the probability of measuring XX and ZZ on horizontal and vertical bonds and use long range spin correlations as the order parameter. We find that when the system has subsystem symmetries, we get a second order phase transition and a critical point with logarithmic violation of area law. Without the subsystem symmetries, the transition immediately turns into a crossover. We also find points where long range spin correlation along rows and columns show a discontinuous phase transition. We also draw connections of this model to the error correcting Bacon-shor code.

Presenter name: Vaibhav Sharma

Poster session / Mo-47:   *Quant. info.: gates, sensing, commun. & Thermo.*   ID117

Novel quantum control methods in a rubidium-87 Bose-Einstein condensate

Authors: Logan W. Cooke[1]; Joseph Lindon[1]; Arina Tashchilina[1]; Mason Protter[1]; Nicholas Milson[1]; Tian Ooi[1]; Taras Hrushevskyi[1]; Lindsay J. LeBlanc[1]

[1] *University of Alberta*

Ultracold neutral atoms are an excellent test-bed for novel quantum control techniques due to their stability, and efficient coupling to fields in the radio, microwave, and optical regimes. Various control protocols which could be used in quantum information processing (QIP) may first be investigated in ultracold atoms to prove their efficacy before being generalized to other more established systems. In this spirit we present two different novel control protocols. First we demonstrate holonomic single-qubit gates, which are conventionally performed via the adiabatic evolution of a degenerate manifold of states through a path in parameter space; this yields a nonAbelian geometric phase which couples the states in a way that depends only on the path taken. In this study, we eliminate the explicit need for degeneracy through Floquet engineering, where the atomic spin Hamiltonian is periodically modulated in time. We characterize the nonAbelian character of the geometric phase through a gauge-invariant parameter, the Wilson loop. Next, we demonstrate a decomposition of SU(3) including a resonant dual-tone operator which synthesizes coupling between two disconnected qutrit levels. For many conventional systems where the third coupling is not possible this technique provides a potential workaround. A decomposition of SU(3) using this operator is tested against conventional methods by performing a Walsh-Hadamard gate and performing maximum likelihood tomography on the resulting states. In both protocols we demonstrate novel methods for precision quantum control essential in advancing QIP techniques which can be readily adapted to trapped ions, superconducting qubits, and other quantum computing platforms.

Presenter name: Joseph Lindon

Poster session / Mo-48: *Quant. info.: gates, sensing, commun. & Thermo.* ID152

Measurement-Based Quantum Machine Learning

Authors: Polina Feldmann[1]; Luis Mantilla Calderón[1]; Robert Raussendorf[1]; Dmytro Bondarenko[1]

[1] *University of British Columbia*

Quantum machine learning (QML)—machine learning on quantum computers—is a rapidly developing, promising application of near-term quantum devices. Most present hardware implements the unitary circuit model of quantum computation. However, recently also measurement-based quantum computation (MBQC) has become technologically relevant, and progress is made towards MBQC with atomic systems. So far, measurement-based QML (MB-QML) has almost not been considered. We introduce a general framework for MB-QML on classical and quantum data. Specifically, we propose a universal building block to construct ansätze for unitaries, measurements, and channels, and discuss how to constrain these ansätze. Our algorithm successfully learns unitaries and classifies quantum states for small systems, proving robust to noise. This work lays the foundation for QML on MBQC devices.

Presenter name: Polina Feldmann

Poster session / Mo-49:   *Quant. info.: gates, sensing, commun. & Thermo.*   ID191

Integrability, ultracold matter and quantum sensing

Authors: Daniel Schneider Grun[1]; Karin Wittmann Wilsmann[2]; Leandro Hayato Ymai[3]; Arlei Prestes Tonel[3]; Jon Links[4]; Angela Foerster[2]

[1] *University of Alberta*

[2] *Universidade Federal do Rio Grande do Sul*

[3] *Universidade Federal do Pampa*

[4] *University of Queensland*

The development of novel quantum technologies ultimately depends on the ability to generate nonclassical states. In this regard, the so-called "NOON states" - "all or nothing" superpositions - have been shown to enable interferometry at the "Heisenberg sensitivity" (with a scaling that is limited by nature itself). Much effort has been made to generate such states on several platforms, with the main limitation being the number of occupied modes in each subspace. Here, we propose the use of integrability to circumvent this issue. Considering a system of interacting dipolar atoms hopping along the edges of a square plaquette, we introduce two different protocols for the generation of NOON states with scalable mode occupation. An experimental realization based on optical superlattices is proposed, which would allow for the realization of the integrable regime in the system.

Presenter name: Daniel Schneider Grun

Detection of Berezinskii-Kosterlitz-Thouless transition via generative adversarial networks

Authors: Daniele Contessi[1]; Elisa Ricci[2]; Alessio Recati[1]; Matteo Rizzi[3]

[1] *University of Trento*

[2] *University of Trento & Fondazione Bruno Kessler [FBK]*

[3] *Forschungszentrum Jülich [FZ Jülich] & University of Cologne [UoC]*

The detection of phase transitions in quantum many-body systems with lowest possible prior knowledge of their details is among the most rousing goals of the flourishing application of machine-learning techniques to physical questions. Here, we train a Generative Adversarial Network (GAN) with the Entanglement Spectrum of a system bipartition, as extracted by means of Matrix Product States ansätze. We are able to identify gapless-to-gapped phase transitions in different one-dimensional models by looking at the machine inability to reconstruct outsider data with respect to the training set. We foresee that GAN-based methods will become instrumental in anomaly detection schemes applied to the determination of phase-diagrams.

Presenter name: Daniele Contessi

New applications and current limitations of Rydberg sensors

Authors: Paul Kunz˙; David Meyer[1]; Joshua Hill[1]; Kevin Cox[1]; Brielle Anderson[2]; Donald Fahey[1]

[1] *US Army Research Laboratory*

[2] *American University*

Electric field sensors based on warm vapors of atoms excited to Rydberg states have distinguishing features that offer new application possibilities. A single sensor can operate over a wide spectrum of frequencies, from DC to THz, with a consistent instantaneous baseband bandwidth of approximately 10MHz. The sensor head containing the vapor is highly transparent and can also be small relative to the electric field wavelengths, enabling accurate measurements with sub-wavelength spatial resolution. Presently Rydberg sensors rely on the spectroscopic method of electromagnetically induced transparency (EIT) for preparing and probing the atoms, and though simple and effective, this places limits on the sensitivity and instantaneous bandwidth of the sensor. We numerically and experimentally investigate this limit for Doppler-broadened optically thick samples, and show the optimal EIT parameter regime. We further present recent results on new applications, such as a Rydberg-backend spectrum analyzer with field sensitivity of -145dBm/Hz and dynamic range >80 dB.

Presenter name: Paul Kunz

Poster session / Mo-52:   *Quant. info.: gates, sensing, commun. & Thermo.*   ID308

Simulating gauge theories in $1 + 1$ d with bosonic quantum circuits

Authors: Eleanor Crane[.]; Teague Tomesh[1]; Kevin Smith[2]; Lena Funke[3]; Stefan Kuhn[4]; Michael Demarco[3]; Isaac Chuang[3]; Nathan Wiebe[5]; Steven Girvin[2]

[1] *Princeton*

[2] *Yale*

[3] *MIT*

[4] *Cyprus*

[5] *University of Toronto*

Quantum simulations of lattice gauge theories in qubits require a truncation of the infinite dimensional Hilbert space. This alters the behavior of the model. However, recent progress in the control of bosonic qubits, which naturally host a large dimensional Hilbert space, points the way to efficient simulation of lattice gauge theories in $1+1$d that generalizes well to higher dimensions. We consider novel and realistic implementations of these models in circuit QED, in two different experimental regimes. We analyze the phase diagrams with matrix product state simulations and implement a variational quantum eigensolver in Bosonic Qiskit - our extension of Qiskit to bosonic circuits - to obtain the ground states. Furthermore, we compare the complexity of simulating lattice gauge theories with qubit and circuit QED architectures, finding that the latter provides orders of magnitude higher efficiency. Our results may be generalized to higher dimensions and nonabelian field theories.

Presenter name: Eleanor Crane

Poster session / Tu-47: *Quant. info.: gates, sensing, commun. & Thermo.* ID21

Fabrication of atomic vapor cell for atomic sensors

Authors: Sin Hyuk Yim[1]; Sangkyung Lee[1]; Ji Hoon Yoon[1]; Min Woo Kim[1]; Dongkyu Kim[1]; Kyu Min Shim[1]

[1] *Agency for Defense Development*

Corresponding Author: seamouse@add.re.kr

We present detailed procedure and experimental setup to fabricate atomic vapor cell for atomic sensor application. A cell is 7.5 mm cubic with pyrex. The inner surfaces of the cell are coated with Aluminium Oxide. The cell is cleaned with distilled water, ethanol, and methanol respectively. The cell is baked in air at 550 degrees Celsius. The cell, then, is attached to high vacuum chamber with specially designed adapter. Rubidium atoms from the hot ampoule in vapor form are collected in a cold glass cell. After that, we put 129Xe, 131Xe, nitrogen, and hydrogen gases into the cell for atom spin gyroscope. For atomic magnetometers, we put nitrogen into the cell.We will cover the performance of the atomic spin gyroscope and atomic magnetic field sensor using our cell in detail in the poster.

Presenter name: Yim, Sin Hyuk

Poster session / Tu-48:   *Quant. info.: gates, sensing, commun. & Thermo.*   ID58

A performance bound for quantum thermal machines

Authors: Matthew Gerry[1]; Dvira Segal[1]

[1] *University of Toronto*

Out-of-equilibrium atomic systems may be used to develop quantum thermal machines which operate continuously at steady state. At such small scales, the energy currents characterizing work and heat exchange with thermal reservoirs exhibit fluctuations large enough to play a significant role in evaluating machine performance. I introduce here a novel set of bounds on the performance of steady-state quantum thermal machines which involve the fluctuations in their input and output energy currents. Namely, the ratio of a machine's output to input fluctuations is bounded from below by the square of its efficiency, and from above by the square of the relevant Carnot bound. This leads to a tighter-than-Carnot bound on the efficiency itself. I will describe a model-independent proof of these results for systems near equilibrium. I will also discuss efforts to extend these results to the far-from-equilibrium regime, in the context of the quantum absorption refrigerator: a paradigmatic model for a thermal machine which can be realized using atomic systems.

Presenter name: Matthew Gerry

Poster session / Tu-49: *Quant. info.: gates, sensing, commun. & Thermo.* ID95

Connecting quantum information scrambling with entanglement-enhanced metrology

Authors: Simone Colombo[1]; Zeyang Li[1]; Chi Shu[2]; Enrique Mendez[1]; Gustavo Velez[1]; Saul Pilatowsky Cameo[1]; Roman Schmied·; Soonwon Choi[1]; Mikhail Lukin[2]; Edwin Pedrozo-Penafiel[1]; Vladan Vuletic[1]

[1] *MIT*

[2] *Harvard University*

Understanding how and at which speed information spreads in a quantum many-body system is a fundamental and intriguing question of quantum information science. Quantum metrology harnesses quantum entanglement for enhancing the precision of atomic sensors beyond the standard quantum limit. What do these apparently different fields of quantum mechanics have in common? We experimentally show that these are actually two sides of the same coin. On the one side, the direct experimental observation of quantum information spread, called "quantum information scrambling", is a difficult task. An emerging tool to witness scrambling are the out-of-the-time-ordered correlators (OTOCs). OTOCs require the system to evolve backward in time after the encoding of a small portion of quantum information. On the other side, in quantum metrology, collective entangled states are characterized by their quantum Fisher information (QFI) which quantifies the sensitivity of the state to a certain perturbation.

In this work, we experimentally investigate quantum information scrambling and entanglement-enhanced metrology in a Lipkin-Meshkov-Glick (LMG) model. We show that these two fields are comparable and, in particular, we demonstrate that QFI and OTOC are equivalent.

The LMG model, as well as its time-reversal, is implemented in a cavity QED system with ultracold ytterbium atoms. The cavity field mediates an effective all-to-all interaction within the atoms, while an external RF field induces a collective rotation of atoms. Moreover, we work in the regime of the LMG model where entanglement (or quantum information scrambling) occurs exponentially fast.

Presenter name: Simone Colombo

Poster session / Tu-50: *Quant. info.: gates, sensing, commun. & Thermo.* ID139

Experimental quantum control on IBM quantum system

Authors: Ivo Mihov[1]; Nikolay Vitanov[1]

[1] *Quantum Optics and Quantum Information group, Sofia University "Sv. Kliment Ohridski"*

In resonance, pulse shapes have no effect on the population transfer; nevertheless, they affect the resonance response curves of the qubit. In this work, the experimental response curves of various pulse shapes were validated against the theoretical predictions. Furthermore, the effects of symmetrical cropping of the Lorentzian function at different heights were examined, using one of the open-access back-end IBM quantum processors.

Presenter name: Ivo Mihov

Multimode microwave-to-optical conversion in warm 87-Rb atoms

Author: Benjamin D. Smith[1]

Co-authors: Andal Narayanan [2]; Bahar Babaei [1]; Lindsay J. LeBlanc [1]

[1] *University of Alberta*

[2] *Raman Research Institute*

The ability to convert quantum signals between the microwave and optical domains is an important tool in quantum information processing. Here, we use a room-temperature ensemble of ^{87}Rb atoms inside a microwave cavity to generate an optical signal whose frequency is the sum of an optical pump and a hyperfine microwave control field, using hybrid sum-frequency generation [1]. By using a multimode microwave control field, the generated optical field carries the same multiple-frequency character, which can be as broad as the 300-kHz cavity linewidth and tunable across the 0.5-GHz Doppler spectrum. This process, which leverages electromagnetically-induced transparency between the two optical fields, results in a "slow-light" time delay of the converted field, where the delay time depends on the power of the microwave control field [2].

Using these techniques, our gaseous atomic system acts in analogy to an electro-optic modulator, which, with its capacity to operate under ultra-low pumping powers, makes it a promising platform for quantum frequency processing [3] across several orders of magnitude in the frequency domain.
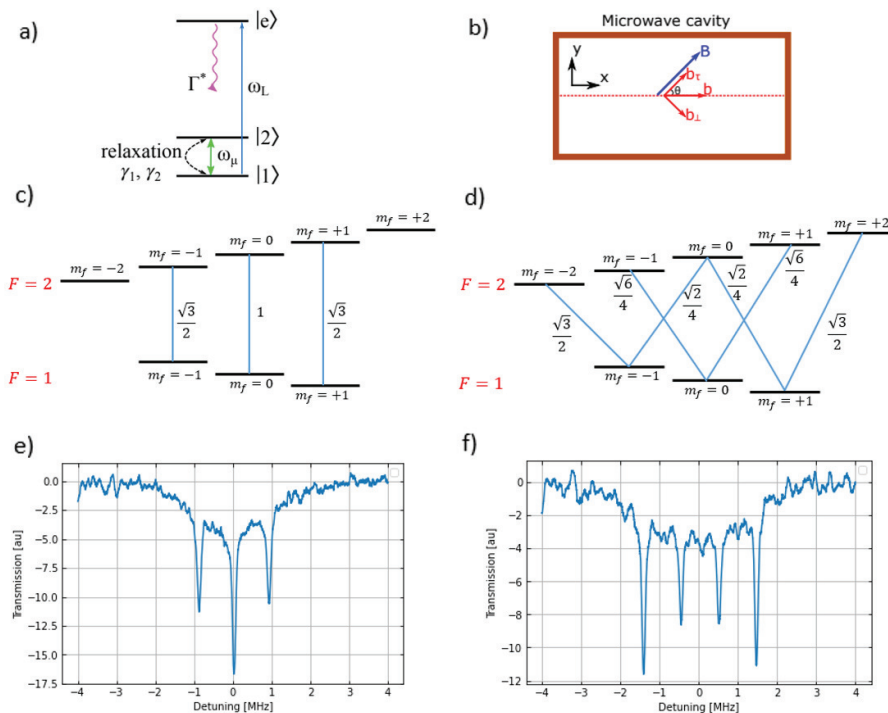
Figure 1. (a) In the nonlinear sum-frequency generation process, microwave frequency ω_μ and optical frequency ω_c combine to produce an optical frequency at $\omega_p = \omega_\mu + \omega_c$. (b) Diagram of the experimental setup. Microwave signal generator (SG), spectrum analyzer (SA), acousto-optic modulator (AOM), external cavity diode laser (EDCL), photodiode (PD), quarter waveplate (QWP), amplifier (AMP).

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Presenter name: Benjamin D. Smith

Poster session / Tu-52:   *Quant. info.: gates, sensing, commun. & Thermo.*   ID227

Enriching the quantum toolbox of ultracold molecules with Rydberg atoms

Authors: Conner Williams[1]; Kenneth Wang[2]; Lewis Picard[2]; Norman Yao[3]; Kang-Kuen Ni[4]

[1] *Harvard University*

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[3] *Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA, Department of Physics, UC Berkeley, Berkeley, California 94720, USA*

[4] *Department of Chemistry and Chemical Biology, Harvard University, Cambridge, Massachusetts 02138, USA, Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*

Assembly of rovibrational ground-state NaCs molecules in an optical tweezer array will allow for high-fidelity quantum computation and the exploration of rich dipolar exchange Hamiltonians. Currently, these systems are limited by a minimum tweezer separation, which sets a hard cap on the interaction strength and increases the characteristic time for interesting physics. Further, readout requires re-separation into the component atoms, which is destructive and error-prone. We propose a hybrid array of optically-trapped molecules and atoms to solve these problems. By leveraging the large dipole moment of resonant Cesium Rydberg levels, we can increase the effective molecular coupling and achieve fast high-fidelity gates. The atoms can then be used as auxiliary qubits for entanglement and projective measurement, giving us a path towards nondestructive molecular readout. A near-term implementation of this scheme in our molecular qubit array can carry out 300ns entangling gates with potential gate and readout fidelities higher than 99.9%.

Presenter name: Conner Williams

A simplified cold Sr experiment for cavity-based quantum simulation

Authors: Matthieu Bertrand; Torben Pöpplau; Lucas Beguin; Jan-Philipp Bureik; Romain Long; Jakob Reichel

Laboratoire Kastler Brossel

We have developed a relatively simple and compact Sr experiment designed for cavity QED with Sr atoms in a miniature ring resonator. The vacuum setup has a total length of 40cm including oven, Zeeman slower and glass cell, and routinely produces 2×10^7 87Sr atoms in the MOT with an oven temperature of 440°C. The slower does not require magnetic coils on its own as it exploits the far field of appropriately designed MOT coils, further reducing complexity and power consumption. The laser system uses master-slave architecture throughout and does not require SHG or other high-power lasers. We also present first results on the optical properties of a miniature ring cavity with laser-machined mirrors that will be used in this experiment.

Presenter name: Jakob Reichel

Poster session / Tu-54:   *Quant. info.: gates, sensing, commun. & Thermo.*   ID332

A transportable cold atom accelerometer for inertial navigation

Authors: H G Sewell[1]; S Shi[1]; K He[1]; T Krastev[1]; A Kaushik[1]; J A Thom[2]; E A Hinds[1]; J P Cotter[1]

[1] *The Centre for Cold Matter*

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Many sectors of society and the economy are now heavily reliant on Global Navigation Satellite Systems (GNSS). However, GNSS has several underlying vulnerabilities and cannot be used under- water or underground. In these situations, Inertial Navigation Systems (INSs) can act as a reliable alternative. These self-contained devices reconstruct the trajectory of a vehicle being tracked by measuring its acceleration and rotation rate. A complete INS combines measurements from three orthogonal accelerometers and three orthogonal gyroscopes. Together with knowledge of the vehicle's starting position, its current location can be calculated, without the need for an external reference. Conventional systems use high precision classical sensors, however long-term performance is currently limited by scale factor and bias drifts.

With their high-accuracy and long-term stability, cold atom interferometers have the potential to substantially improve long-range inertial navigation. At Imperial College, we are developing such systems for use in quantum enhanced INSs. Clouds of rubidium-87 atoms are cooled to ultra-cold temperatures then split, reflected, and recombined using stimulated Raman transitions to make an atom interferometer for inertial sensing.

Here, we describe our recent work developing a ruggedised quantum accelerometer for navigation. Our new system contains the laser for cooling and trapping atoms and driving Raman transitions, a science chamber for atom interferometry, and all the electronics and control systems, packaged into a transportable system for deployment outside the laboratory.

Presenter name: Henry Sewell

Poster session / We-47:   *Quant. info.: gates, sensing, commun. & Thermo.*   ID36

Atomic magnetometry with Kalman filters

Authors: Klaudia Dilcher[1]; Júlia Amorós Binefa[1]; Jan Kołodyński[1]

[1] *QOT - Centre for Quantum Optical Technologies, University of Warsaw, Poland*

Information inference from noisy systems is a focus of interest of various research and engineering disciplines. In 1960, Rudolf E. Kalman published a paper on an optimal filtering technique for systems described by linear dynamics and measurement models whose noise statistics is Gaussian [1]. In particular, this so-called Kalman Filter constitutes a way to construct an estimator that allows one to optimally extract the signal encoded in the system dynamics while minimizing the average mean-squared-error, despite the dynamics and measurement all undergoing uncontrolled independent stochastic fluctuations. In opposition to previously known algorithms, Kalman Filters do not require a full history of all previous steps. Because of this, the technique can be used for real-time data analysis.

In this work, we applied the described methods for magnetic field inference from an atomic sensor with optical read-out. Such sensors are widely used in magnetometry both within and beyond the classical limit, achieving precision comparable to cryogenic methods. The linear Kalman Filter has been applied to such systems before [2, 3]. The usability of this technique is very limited though, as the magnetic field obeys a highly nonlinear dynamics in most regimes. This suggests that using the Extended Kalman Filter, as well as other nonlinear Kalman Filtering techniques, can greatly improve the estimator beyond the linear regime. In this work, we simulate an output of such a sensor and show that in fact the magnetic field can be successfully estimated in real-time with the nonlinear methods.

[1] R. E. Kalman, A New Approach to Linear Filtering and Prediction Problems, Journal of Basic Engineering, vol.81, 1960.
[2] Ricardo Jiménez-Martínez et al. Signal Tracking Beyond the Time Resolution of an Atomic Sensor by Kalman Filtering, PRL, vol. 120, 2018
[3] Jia Kong et al. Measurement-induced, spatially-extended entanglement in a hot, strongly-interacting atomic system, Nature Communications vol. 11, Article number: 2415, 2020.

Presenter name: Klaudia Dilcher

Poster session / We-48:   *Quant. info.: gates, sensing, commun. & Thermo.*   ID62

B-field self-cancelling devices for atomic sensors

Authors: Minwoo Kim[1]; Sangkyung Lee[1]; Sin Hyuk Yim[1]; Ji Hoon Yoon[1]; Dongkyu Kim[1]; Kyu Min Shim[1]

[1] *Agency for Defense Development*

A fair number of atomic sensors require a homogeneous B-field for long-lasting Larmor oscillation of atoms. On the other hand, various electronics used in the experiments emit magnetic fields, destroying the homogeneity of the deliberately homogeneous B-field. We demonstrate a DBR laser-TEC packaging and a heater which self-cancel their emitted B-field by antiparallel current configurations. These devices can be realized inexpensively without employing MEMS technology. The effect of the self-cancellation is demonstated by a direct measurement and also a LIA signal noise comparison for the heater employed in an atomic magnetometer system.

Presenter name: Minwoo Kim

Blueprint for a scalable, modular, fault-tolerant quantum computer based on state-of-the-art Rydberg atom arrays and optical cavities

Authors: Josiah Sinclair[1]; Joshua Ramette[1]; Dolev Bluvstein[2]; Alyssa Rudelis[1]; Beili Hu[1]; Edita Bytyqi[1]; Vladan Vuletic[1]

[1] *MIT*

[2] *Harvard*

We propose a scalable, modular, fault-tolerant architecture for quantum computing based on Rydberg arrays and Rydberg compatible optical cavities. While previous modular architectures have focused on very small modules containing 2-5 qubits, our architecture consists of large modules containing thousands of physical qubits, which form surface code patches that are linked together by optical cavity photonic interconnects. While the low fidelity of Bell pairs generated via photonic interconnects has been a major challenge for all previously proposed modular architectures, our approach is uniquely immune to Bell pair infidelity because communication errors only occur along one edge of the code. Numerical simulations indicate a threshold for communication errors of about 10%. Moreover, because no distillation is required, in contrast to previous schemes, local gate requirements remain around 1%. These relaxed communication requirements enable the fault-tolerant connection of currently available Rydberg arrays of many atoms using only modest quality Bell pairs. We give quantitative performance estimates showing that a single optical cavity of modest quality allows Bell pair distribution fast enough to realize 10 kHz surface code cycles — much faster than current coherence times — as well as sufficiently fast syndrome readout and atom reloading.

Presenter name: Josiah Sinclair

Poster session / We-50:   *Quant. info.: gates, sensing, commun. & Thermo.*   ID141

Quantum optimization of maximum independent set using Rydberg atom arrays

Authors: Sepehr Ebadi˙; Alexander Keesling[1]; Madelyn Cain˙; Tout Wang˙; Harry Levine˙; Dolev Bluvstein˙; Giulia Semeghini˙; Ahmed Omran˙; Jin-Guo Liu˙; Rhine Samajdar˙; Xiu-Zhe Luo˙; Beatrice Nash˙; Xun Gao˙; Boaz Barak˙; Edward Farhi˙; Subir Sachdev˙; Nathan Gemelke˙; Leo Zhou˙; Soonwon Choi˙; Hannes Pichler˙; Sheng-Tao Wang˙; Markus Greiner˙; Vladan Vuletic˙; Mikhail Lukin˙

[1] *Quera Computing*

Realizing quantum speedup for solving practically relevant, computationally hard problems is a central challenge in quantum information science. Using Rydberg atom arrays composed of up to 289 coupled qubits in two spatial dimensions, we experimentally investigate quantum optimization algorithms for solving the Maximum Independent Set problem. We use a hardware-efficient encoding associated with Rydberg blockade, realize closed-loop optimization to test several variational algorithms, and subsequently apply them to systematically explore a class of nonplanar graphs with programmable connectivity. We find that the problem's hardness is controlled by the solution degeneracy and the number of local minima, and experimentally benchmark the quantum algorithm's performance against optimized classical simulated annealing. On the hardest instances, we observe a superlinear quantum speedup in finding exact solutions for sufficiently long evolution times beyond the shallow-circuit-depth regime, and analyze its origins.

Presenter name: Sepehr Ebadi

Arrays of cold Rydberg atoms for electromagnetic fields sensing

Authors: Alexis Bonnin[1]; Romain Duverger; Cédric Blanchard; Nassim Zahzam; Yannick Bidel; Alexandre Bresson; Sylvain Schwartz

[1] *ONERA DPHY*

We aim to develop a new kind of electromagnetic field sensor by combining the high metrological performance accessible thanks to the exaggerated Rydberg states properties with the high degree of control and tunability offered by cold atomic ensembles trapped in arrays of optical tweezers. We plan to probe EM-fields over a wide frequency range from few 100s of MHz to few THz, given by the frequency difference between neighboring Rydberg states, with a target sensitivity of about 10 mV/cm/Hz$^{1/2}$ and with a spatial resolution down to few tens of μm, corresponding to the distance between two optical tweezers. We also intend to study the possibility to perform spectral analysis by making each atomic ensemble sensitive to a specific frequency. In the poster, I will present the principle of operation of the sensor, the current experimental status together with some envisioned applications, and possible ways of improvements.

Presenter name: Alexis Bonnin

Poster session / We-52: *Quant. info.: gates, sensing, commun. & Thermo.* ID199

Engineering multimode entanglement among atomic ensembles

Authors: Philipp Kunkel[1]; Eric S. Cooper[1]; Avikar Periwal[1]; Monika Schleier-Smith[1]

[1] *Stanford University*

Interactions form the basis for the experimental generation of entanglement between quantum objects. Using all-to-all interactions, numerous experiments with atomic ensembles have generated quantum states which provide a higher precision in sensing protocols compared to unentangled states. However, many envisioned applications in quantum sensing and computation require greater control over the spatial entanglement structure and, thus, the effective graph of interactions. In our experiment, we use an optical cavity together with local spin rotations to mediate programmable long-range interactions within a 1D array of atomic ensembles. Driving the cavity with light induces all-to-all interactions between the spin-1 atoms, creating atom pairs and quantum correlations within a single spatially extended mode of the collective transversal spin. In this case, we measure spin-nematic squeezing and verify the generation of entanglement between spatially separated ensembles by quantifying the correlations in two noncommuting observables. By employing local spin rotations we selectively couple different spatial modes to the cavity and thus control the structure of the generated quantum correlations. This capability allows for tailoring the entanglement structure to a specific quantum enhanced task such as distributed quantum sensing and measurement-based quantum computation.

Presenter name: Philipp Kunkel

Training quantum denoisers

Author: Dmytro Bondarenko[1]

Co-authors: Polina Feldmann [1]; Robert Salzmann [2]; Tobias Osborne [3]; Kerstin Beer [3]; Daniel Scheiermann [3]; Ramona Wolf [4]; Terry Farrelly [5]; Jannik Eggert [3]; Robert Raussendorf [1]; Viktoria-Sophie Schmiesing [3]; Luis Mantilla [1]

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[5] *University of Queensland*

State preparation often suffers from various sources of device-dependant noise. It is hard to characterise and let alone mitigate the noise. Machine learning can be used to automate the denoising task. Quantum computers are the ultimate machines to process quantum signals. As such, we propose to use machine learning on quantum computers to denoise quantum data.

For this, we design a flexible family of trainable variational circuits that are capable of implementing arbitrary quantum channels. Due to the resemblance to their classical counterparts, we call these circuits quantum neutral networks (QNNs). We show that QNNs use the data efficiently and can be trained on imperfect devices even when part of the training data is corrupted.

We proceed to design QNN architectures that are tailored to cancel various types of noise. We show how quantum autoencoders can significantly reduce shot-to-shot noise. This is achieved without access to supervisory data and autoencoders can be trained once to denoise different highly entangled states. Then we turn our attention to extrapolation of parameters like temperature. We show how to train QNNs to produce states that are colder than any state seen during training. Finally, we develop recurrent QNNs for processing that requires memory. We use recurrent QNNs to design quantum bandwidth filters—a task greatly complicated by the no-cloning theorem. For recurrent networks, we further economize resources by combining quantum and classical processing.

Quantum denoisers offer a practical application of quantum computers to the experimental preparation of entangled states. This technology is particularly suited to an apparatus that already carries a highly-tunable quantum control system on board, such as quantum logic.

Based on: Nat. Commun. **11**, 808; Phys. Rev. Lett. **124**, 130502; PhD thesis: https://doi.org/10.15488/11050 and some work in progress.

Presenter name: Dmytro Bondarenko

Poster session / We-54: *Quant. info.: gates, sensing, commun. & Thermo.* ID322

Scalable cryogenic experiment for trapped-ion quantum computing with long ion strings

Authors: Roland Matt[1]; Robin Oswald[2]; Luca Huber[2]; Kaizhao Wang[2]; Jeremy Flannery[2]; Jonathan Home[2]

[1] *TIQI, ETH Zurich*

[2] *ETH Zurich, Trapped Ion Quantum Information Group, Switzerland*

We present experimental work performed in a cryogenic apparatus exploiting a segmented ion trap architecture for the implementation of quantum algorithms [1]. The quantum register consists of a linear string of 40Ca+ ions which are individually controlled by tightly focused laser beams perpendicular to the crystal axis. Light is delivered by a waveguide array allowing to individually feed each ion with a separately controlled laser beam.

High-fidelity gate operations require both a stable qubit system and precise control over optical fields. In order to control multiple ions in parallel, we have developed a scalable single ion addressing system based on an array of waveguides matched to the ion positions, making the optical addressing system compact and robust against mechanical noise. What is more, this single ion addressing capability will mitigate the need for ion transport operations and allow for parallel qubit manipulations thereby simplifying the overall computation. In order to improve qubit coherence times we have implemented a set of superconducting coils in a "self-shielding" configuration, which enables the suppression of magnetic field fluctuations at all frequencies down to DC [2]. Ion imaging is performed using a camera with low pixel count with state-detection via FPGA-based image processing. This should allow low-latency readout of many ions in parallel, which is essential for implementing fast feedback required for error-correction. Design considerations and experimental progress will be presented.

[1] Decaroli, C., Matt, R., Oswald, R., Axline, C., Ernzer, M., Flannery, J., Ragg, S. and Home, J.P., 2021. Design, fabrication and characterization of a micro-fabricated stacked-wafer segmented ion trap with two X-junctions. Quantum Science and Technology, 6(4), p.044001.

[2] Gabrielse, G. and Tan, J., 1988. Self-shielding superconducting solenoid systems. Journal of Applied Physics, 63(10), pp.5143-5148.

Presenter name: Roland Matt

Poster session / We-55: *Quant. info.: gates, sensing, commun. & Thermo.* ID335

A cold atom gyroscope for inertial navigation

Authors: A. Kaushik[1]; N. Bilton[1]; S. de Silva[1]; T. Krastev[1]; K. He[1]; H. G. Sewell[1]; S. Shi[1]; J. P. Cotter[1]; E. A. Hinds[1]

[1] *Imperial College London*

Many sectors of society and the economy are now heavily reliant on Global Navigation Satellite Systems (GNSS). However, GNSS has several intrinsic vulnerabilities and cannot be used underwater or underground. In these situations, Inertial Navigation Systems (INSs) can act as a reliable alternative. These self-contained devices reconstruct the trajectory of a vehicle being tracked by measuring its acceleration and rotation rate. A complete INS combines measurements from three orthogonal accelerometers and three orthogonal gyroscopes. Together with knowledge of the vehicle's starting position, its current location can be calculated, without the need for an external reference. Conventional systems use high precision classical sensors, however long-term performance is currently limited by scale factor and bias drifts.

At Imperial College we are developing cold atom interferometers for inertial sensing. Their high-accuracy and long-term stability mean they offer the potential for improved long-range navigation in the near future. Clouds of rubidium-87 atoms are cooled to ultra cold temperatures then split, reflected, and recombined using stimulated Raman transitions to make an atom interferometer. Here, we describe our recent work to extend the operation of our laboratory, two-axis accelerometer into a rotation sensor. By launching the atom cloud using a moving molasses, we are able to measure rotations about three perpendicular axes.

Presenter name: A. Kaushik

Programmable interactions and emergent geometry in a 1D array of atomic ensembles

Authors: Avikar Periwal[1]; Eric S. Cooper[2]; Philipp Kunkel[.]; Monika Schleier-Smith[2]

[1] *Stanford Universty*

[2] *Stanford University*

Control over the structure of interactions is essential for developing flexible quantum protocols. We couple an array of atomic ensembles to a driven optical cavity, creating an XY model. Using a magnetic field gradient and modulating the cavity field enables us to prune the naturally all-to-all connectivity of cavity-mediated interactions. We confirm these coupling graphs by direct measurements of two-point correlation functions. From the correlation measurements, we infer the structure and Euclidean embedding of the equivalent Hamiltonian with only local interactions. Example geometries include a Moebius ladder and a cylinder with sign-changing interactions.

This control of interactions can be leveraged to study a wide range of physical systems, including quantum gravity and quantum computation. We simulate spin systems relating quantum mechanics and gravity, inspired by a discretized formulation of the AdS/CFT correspondence. We show that the states generated by the cavity dynamics map to low-energy states of the programmed XY model. Finding the ground state of the XY Hamiltonian is an NP-hard problem, and these highly-programmable interactions open avenues towards spin-glass physics and physically-encoded computation.

Presenter name: Avikar Periwal

Poster session / Th-50:   *Quant. info.: gates, sensing, commun. & Thermo.*   ID69

Noisy atomic magnetometry in real time

Authors: Julia Amoros-Binefa[1]; Jan Kolodynski[1]

[1] *University of Warsaw*

Continuously monitored atomic spin-ensembles allow, in principle, for real-time sensing of external magnetic fields beyond classical limits. Within the Linear-Gaussian regime, thanks to the phenomenon of measurement-induced spin-squeezing, they attain a quantum-enhanced scaling of sensitivity both as a function of time, t, and the number of atoms involved, N. In our work, we rigorously study how such conclusions based on Kalman filtering methods change when inevitable imperfections are taken into account: in the form of collective noise, as well as stochastic fluctuations of the field in time. We prove that even an infinitesimal amount of noise disallows the error to be arbitrarily diminished by simply increasing N, and forces it to eventually follow a classical-like behavior in t. However, we also demonstrate that, "thanks" to the presence of noise, in most regimes the model based on a homodyne-like continuous measurement actually achieves the ultimate sensitivity allowed by the decoherence, yielding then the optimal quantum-enhancement. We are able to do so by constructing a noise-induced lower bound on the error that stems from a general method of classically simulating a noisy quantum evolution, during which the stochastic parameter to be estimated—here, the magnetic field—is encoded. The method naturally extends to schemes beyond the linear-Gaussian regime, in particular, also to ones involving feedback or active control.

Presenter name: Julia Amoros-Binefa

Poster session / Th-51:　　　*Quant. info.: gates, sensing, commun. & Thermo.*　　　ID115

Characterization of high-fidelity Raman qubits

Authors: Stancho Stanchev ; Nikolay Vitanov

In quantum information and computation, very high fidelity of gate operations is required. Measuring tiny gate errors with high accuracy is a difficult task, which is traditionally done by randomized benchmarking.

In this work we present a new method which allows to determine the gate errors of Raman qubits, in which the qubit states are coupled in a Raman transition via another state, thereby forming a three-state chainwise-connected system. The method is based on the repetition of the same gate sufficiently many times and thereby amplifying the tiny error to easily measurable sufficiently large values.

In order to deduce the gate error from the amplified error, analytic connections between the single-gate and multigate propagators are derived for three-state Raman systems with two types of symmetries:
Majorana and Morris-Shore. We extend these connections to arbitrary dimensions which paves the path toward tomography of qudits.

Presenter name:　　　　　Stancho G. Stanchev

Poster session / Th-52:   *Quant. info.: gates, sensing, commun. & Thermo.*   ID149

Scalable qubit arrays for quantum computation and simulation

Authors: Elliot Diamond-Hitchcock[1]; Jonathan Bass[1]; Nicholas Spong[1]; Boyko Nikolov[1]; Jonathan Pritchard[1]

[1] *University of Strathclyde*

Quantum computation offers a revolutionary approach to how information is processed, offering new applications in material design, quantum chemistry and speed up of real-world optimisation problems, however a large number of qubits are required to obtain quantum advantage over classical hardware. Neutral atoms are an excellent candidate for practical quantum computing, enabling large numbers of identical qubits to be cooled and trapped, overcoming major barriers to scaling experienced by competing architectures [1]. A crucial ingredient for quantum computing is the ability to perform controlled two-qubit gate operations, for which the strong, long-range dipole-dipole interaction between Rydberg atoms can be exploited to implement deterministic gate operations between atoms within a radius of $R < 10$ m.

We present progress towards a new experimental platform for quantum computation at the University of Strathclyde based on reconfigurable atom arrays of Cs atoms, demonstrating loading arrays of > 100 qubits as the first step to creating a scalable architecture for quantum computing. We show high-fidelity control and excitation of single qubits to highly excited Rydberg states and exploit the strong long-range dipole-dipole interactions between Rydberg atoms to generate a 2D array of Bell state pairs. These results pave the way to two qubit and multiqubit gate operations using twophoton adiabatic rapid passage [2].

[1] M. Saffman, T. Walker, and K. Mølmer, Rev. Mod. Phys. **82**, 2313 (2010).
[2] G. Pelegrí, A.J. Daley, and J.D. Pritchard, High-fidelity multiqubit Rydberg gates via two-photon adiabatic rapid passage, arXiv:2112.13025 (2021).

Presenter name: Elliot Diamond-Hitchcock

Poster session / Th-53:   *Quant. info.: gates, sensing, commun. & Thermo.*   ID180

Spin-wave quantum computing with atoms in a single-mode cavity

Authors: David Meyer[1]; Kevin Cox[1]; Przemyslaw Bienias[2]; Donald Fahey[1]; Paul Kunz[1]; Alexey Gorshkov[2]

[1] *US Army Research Laboratory*

[2] *University of Maryland - College Park*

We present a method for network-capable quantum computing that relies on holographic spin-wave excitations stored collectively in ensembles of qubits. This construction relies on an orthogonal basis of spin waves in a one-dimensional array and is capable of high-fidelity universal linear controllability using only phase shifts, applied in both momentum and position spaces. Neither single-site addressability nor high single-qubit cooperativity is required, and the spin waves can be read out with high efficiency into a single cavity mode for quantum computing and networking applications. We also propose an experimental implementation using a lambda-scheme in a rubidium-atom system to establish linear quantum processing and calculate the expected experimental operational fidelities due to fundamental and technical errors. In this experimental implementation, we show that efficient methods to achieve linear controllability in both a single-ensemble and dual-ensemble configuration is possible. Finally, we show a potential application of the spin-wave processor for continuous-variable quantum information processing and present a scheme to generate large dual-rail cluster states useful for deterministic computing.

Presenter name: David Meyer

Poster session / Th-54:   *Quant. info.: gates, sensing, commun. & Thermo.*   ID206

Entangling gates between bosonic qubits in trapped ions

Authors: Martin Wagener[1]; Stephan Welte[1]; Moritz Fontboté Schmidt[1]; Ralf Berner[1]; Edgar Brucke[1]; Matteo Marinelli[1]; Ilia Sergachev[1]; Paul Röggla[1]; Ivan Rojkov[1]; Florentin Reiter[1]; Daniel Kienzler[1]; Jonathan Home[1]

[1] *Institut fuer Quantenelektronik, ETH Zuerich*

Encoding quantum information in a harmonic oscillator offers a resource efficient method for quantum error correction, compared to the use of multiple two-level systems. The Gottesman-Kitaev-Preskill (GKP) encoding [1] is particularly promising and has recently been realized in both trapped ions [2, 3] and superconducting microwave cavities [4].

State preparation, readout, single qubit rotations and error correction have been achieved in both of these architectures. I will describe work towards logical entangling gates between two GKP qubits prepared in the motional modes of two atomic ions trapped in close proximity. The modes are coupled via the Coulomb interaction, which approximates a beam splitter. Combined with single mode squeezing operations this beam splitter interaction can realize universal entangling gates between the two GKP states [5]. In theoretical work, we have investigated this gate for experimentally realistic parameters and finite energy GKP states. In parallel, we are developing an apparatus for these experiments, including fabrication of a suitable ion trap and design and implementation of optical addressing with tightly focused laser beams.

[1] Daniel Gottesman, Alexei Kitaev and John Preskill, Physical Review A **64**, 012310 (2001)
[2] Christa Flühmann et al., Nature **566**, 368-372 (2019)
[3] Brennan de Neeve et al., Nature Physics **18**, 296-300 (2022)
[4] Philippe Campagne-Ibarcq et al., Nature **584**, 368-372 (2020)
[5] Ilan Tzitrin et al., Physical Review A **101**, 032315 (2020)

Presenter name: Martin Wagener

Towards a single-atom array strongly coupled to an optical microcavity for multiparticle entanglement

Authors: Pierre-Antoine Bourdel[1]; Constance Poulain[1]; Jakob Reichel[1]; Romain Long[1]

[1] *Laboratoire Kastler Brossel*

Photon-mediated interactions between atoms coupled to an optical cavity are emerging as a powerful tool for engineering entangled states and many-body Hamiltonians. However, single-atom addressing and readout is not available in most of these systems.

Leveraging recent development in atom-tweezer arrays, we will present our current effort to combine the strong coupling regime at the single atom level offered by optical fiber Fabry-Perot microcavities with the versatile manipulation and control of single atoms enabled by optical tweezers.

We demonstrate Rubidium single-atom trapping in the tweezers, we map the cavity mode by measuring the cavity transmission of a moving single tweezer-trapped atom and we measure single-atom Rabi splitting characteristic of the strong coupling regime. We will also discuss current developments towards multitweezers operation and targeting the deterministic loading of the tweezer array in the cavity.

Upon completion, this experimental platform opens up new possibilities for creating, measuring, and utilizing novel types of multiparticle entangled states, such as the generation of spatially delocalized entangled states for multiparameter quantum-enhanced sensing [1].

It opens also the way to new type of quantum simulation where the cavity field creates an effective all-to-all interaction. Such a quantum simulator will allow exploring the transport in disordered spin systems and conductivity in recently discovered, vacuum-enhanced new materials [2, 3, 4] as well as the dynamics of quantum information transport [5].

[1] M. Gessner et al., Phys. Rev. Lett. 121, 130503 (2019)
[2] E. Orgiu et al, Nature Materials **14**, 1123 (2015)
[3] J. Schachenmayer et al, PRL **114**, 196403 (2015)
[4] J. Dubail et al., Phys. Rev. A **105**, 023714 (2022)
[5] G. Bentsen et al., Phys. Rev. Lett. **123**, 130601 (2019)

Presenter name: Romain Long

Experimental realization of classic gates on trapped-ion qubits

Authors: Martin van Mourik[.]; Elias Zapusek[1]; Pavel Hrmo[2]; Lukas Gerster[3]; Florentin Reiter[4]; Rainer Blatt[5]; Thomas Monz[6]; Philipp Schindler[3]

[1] *Institute for Quantum Electronics, ETH Zurich*

[2] *Trapped Ion Quantum Information Group, ETH Zürich*

[3] *Institute for experimental physics, University of Innsbruck*

[4] *Institut fuer Quantenelektronik, ETH Zuerich*

[5] *Institute for quantum optics and quantum information, Österreichische Akademie der Wissenschaften*

[6] *Alpine Quantum Technologies, Innsbruck*

The past decade has seen astounding progress in the field of digital quantum computation (QC). Traditionally, QC circuits consist of a set of coherent qubit operations, quantum gates, that are by definition unitary and therefore reversible. Parallel to the familiar use of quantum gates, a new paradigm of quantum information theory is emerging in which hybrid quantum-classic algorithms are proposed for tasks such as quantum simulation, machine learning, and optimization. For example, the simulation of open quantum systems will require an expansion of the current circuit toolbox, to include nonunitary operations. We present an experimental demonstration of a method of realizing controlled nonunitary operations, and use this tool to demonstrate two classic gates with ionic qubits: the OR and NOR operation. The state of one of the two qubits displays the output of the logical operations, and is dependent on the initial state of the two.

We apply the gates using two $^{40}\mathrm{Ca}^+$ ions, trapped in a cryogenic segmented surface trap, as information carriers. The state is encoded in two of the ions' Zeeman sublevels, and is manipulated with optical light-fields. The gates employ engineered resonance through dressed state splitting, based on methods introduced in [1]: resonant excitation of a two-qubit system transfers information about the two qubit state's parity to a motional Fock state. Sympathetic cooling of a second co-trapped ion species, $^{80}\mathrm{Sr}^+$, dissipatively removes the motional quanta, making the process nonunitary. We achieve an 87% population fidelity of the OR gate, and an 81% population fidelity of the NOR gate. The main sources of error in our experiments are limits in ground-state cooling of the ion crystal and a nonnegligible increase in the motional mode occupation during the experimental sequences.

These experiments are a stepping stone towards an envisioned alternate scheme of quantum error correction (QEC). Conventional proposed QEC schemes rely on classical measurement and feedback to make decisions on whether to apply correction operations or not. Dissipation through engineered resonance prospectively has these decision making processes and correction operations built-in through the conditional state transfer mechanism.

[1] Reiter, F., Sørensen, A.S., Zoller, P. et al. Dissipative quantum error correction and application to quantum sensing with trapped ions. Nat. Comm. **8**, 1822 (2017).

Presenter name: Martin van Mourik

Virtual poster / Vir26: *Quant. info.: gates, sensing, commun. & Thermo.* ID94

Nonorthogonal encoding and decoding of Hadamard codes in cascaded entangled photons

Authors: Nai-Yu Tsai[1]; Hsiang-Hua Jen[2]

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[2] *Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei 10617, Taiwan*

In the quantum network, a biphoton source can be utilized to transmit Hadamard codes with high coincidence rates. It is the strong correlation in the biphoton state that facilitates the encoding and decoding task. We propose to multiplex the biphoton state from the cascade emissions of cold atomic ensembles under the four-wave mixing condition, and use this effective biphoton state to fulfill the encoding and decoding task of Hadamard codes. Using this highly correlated biphoton source with frequency entanglement, we obtain the coincidence rates and quantify the performance by calculating their contrasts. In this biphoton state, we explore various ways to encode and decode the weight and phase degrees of freedom in multiplexing to identify the best performance. In addition, nonorthogonal codes are introduced to manifest a better performance in the task of encoding and decoding. We find that these codes can enlarge the number of code lengths and promise a high-capacity quantum communication of Hadamard codes, useful in quantum error correction application.

Presenter name: Tsai, Nai-Yu

online poster URL:

Virtual poster / Vir27:   *Quant. info.: gates, sensing, commun. & Thermo.*   ID108

Almost indistinguishable single photons via multiplexing cascaded biphotons with cavity modulation and phase compensation

Authors: T. H. Chang[1]; Y.-E. Wong[2]; H. H. Jen[1]

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The frequency-correlated biphotons are an excellent resource for long-distance quantum communication. They can be generated from the diamond-type atomic level structures under four-wave mixing in an alkali metal atomic ensemble. The signal photon from the upper transition has low-loss telecom bandwidth useful in a fiber-based quantum network, while the idler photon from the lower transition can be stored locally as a collective spin wave. In contrast to the highly entangled biphotons, an almost indistinguishable single photons with low frequency entanglement are the building blocks in photonic quantum simulation or computation. In this poster we theoretically investigate the frequency entanglement of the biphoton and propose two approaches to remove their mutual correlations in frequency spaces. First, we generate a more symmetric and narrower biphoton spectrum by multiplexing atomic ensembles with phase compensation using optical cavity. The entanglement entropy S of the biphoton reduces to 0.006, which is 200 times smaller than the one without multiplexing and corresponds to the purity of single photon as 0.999. In the other approach, we symmetrically pump two atomic ensembles under nondiscrimination detectors, which leads to a moderately reduced S ~ 0.3.

Presenter name: T. H. Chang

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Virtual poster / Vir28:   *Quant. info.: gates, sensing, commun. & Thermo.*   ID168

Defect-free arbitrary-geometry assembly of mixed-species atom arrays

Authors: Cheng Sheng[1]; Jia-Yi Hou[1]; Xiao-Dong He[1]; Kun-Peng Wang[1]; Rui-Jun Guo[2]; Jun Zhuang[1]; Bahtiyar Mamat[1]; Peng Xu[1]; Min Liu[1]; Jin Wang[1]; Ming-Sheng Zhan[1]

[1] *Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences, Wuhan 430071, China*

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Optically trapped mixed-species single atom array with arbitrary geometry is an attractive and promising platform for various applications, because tunable quantum system with multiple components provides extra degrees of freedom for experimental control. Here, we report the first demonstration of two-dimensional 6×4 dual-species atom assembly with a filling fraction of 0.88 (0.89) for ^{85}Rb (^{87}Rb) atoms[1]. This mixed-species atomic synthesis is achieved via rearranging initially randomly distributed atoms by a sorting algorithm (heuristic heteronuclear algorithm) which is designed for bottom-up atom assembly with both user-defined geometries and two-species atom number ratios. Combined with our previous work on heteronuclear entanglement [2],high-fidelity single atom operations [3],balanced coherence times of heteronuclear atomic qubits [4] and the full control of the internal and external degrees of heteronuclear atoms [5], we have build a fully tunable hybrid-atom system with scalable advantages which is a good starting point for high-fidelity quantum logic, many-body quantum simulation and single molecule array formation.

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[2] Yong Zeng, et al. Entangling Two Individual Atoms of Different Isotopes via Rydberg Blockade,*Phys. Rev. Lett.* **119**, 160502 (2017).
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[5] Xiaodong He, et al. Coherently forming a single molecule in an optical trap *Science* **370**, 331(2020).

Presenter name: Xu,Peng

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Virtual poster / Vir29: *Quant. info.: gates, sensing, commun. & Thermo.* ID178

Generation of bottle beam array by spatial light modulator for atom-based quantum computing

Authors: Ya-Fen Hsiao[1]; Tsai-Ni Wang[1]; Ying-Cheng Chen[1]

[1] *Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei, Taiwan*

We develop a two-dimensional bottle beam array for laser trapping atoms in the ground and Rydberg states. A dipole-trap laser beam is diffracted by a phase spatial light modulator imprinted with a phase pattern to generate a 6 by 6 array of the bottled beam. The beam arrays are then focused by an aspheric lens and imaged by a CCD camera. The distance between two nearest-neighbour atoms is 396 μm, and the diameter of the ring of intensity peak for each trapping site is 82 μm. The average similarity of the intensity distribution between the measured trapping sites and the numerical calculation is 86%. This trap system opens appealing applications in quantum information processing and simulation based on Rydberg atoms.

Presenter name: Ya-Fen Hsiao

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Virtual poster / Vir30:   *Quant. info.: gates, sensing, commun. & Thermo.*   ID241

Gaussian-packet assisted holography for single-shot atomic spectroscopic imaging

Authors: Huang Xing[1]; Yuzhuo Wang.; Jian Zhao.; Saijun Wu[1]

[1] *Fudan University*

Precise imaging is instrumental to ultracold atomic technology both for precision measurements and for quantum simulation of many-body physics. Comparing with regular imaging techniques, holographic imaging based on phase-retrieval extends the measurement observables from real to complex numbers and therefore supports single-shot spectroscopic measurements even in presence of atomic column density uncertainty. The holographic technique also enables high spatial resolution without limiting the depth of view. Furthermore, by encoding local atomic optical response into delocalized interference fringes in the far field, the camera pixels are more efficiently exploited to support a measurement dynamic range beyond those typically achievable in absorption images. So far, the highly desirable features listed above are rarely exploited in atomic physic. Among various factors that prevent accurate implementation of holographic techniques to cold atoms is the fact that cold atomic samples are usually thermal and tend to be spatially "featureless", invalidating a class of phase-retrieval algorithms in other fields based on edge-detections. We note that when the atomic samples are subjected to plane or spherical wave illuminations, the coherent forward emission by the smooth and localized samples are naturally decomposed into Gaussian modes. We exploit this feature and develop a systematic Gaussian-packet method to resolve the optical response of cold atomic ensembles. Based on the new method, we demonstrate "complex" spectroscopic imaging of atomic ensemble capable of simultaneously resolving atomic column density and spatial-dependent light shift, both near the photon shot noise limit. We also investigate the potential of the new method for imaging atomic samples with high optical depth where regular absorption images would lead to poor statistics.

Presenter name: Xing Huang

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Virtual poster / Vir31: *Quant. info.: gates, sensing, commun. & Thermo.* ID244

Delay-line based adiabatic spin-dependent kicks on a hyperfine manifold

Authors: Liyang Qiu ; Jiangyong Hu[1]; Saijun Wu

1

Significant aspects of advanced quantum technology today rely on rapid Raman control of atomic hyperfine matterwaves. Unfortunately, efficient Raman excitations are usually accompanied by uncompensated dynamic phases and coherent spin-leakages, preventing accurate and repetitive transfer of recoil momentum to large samples. We provide systematic study to demonstrate that the limitations can be substantially overcame by dynamically programming an adiabatic pulse sequence.

Experimentally, counter-propagating frequency-chirped pulses are programmed on an optical delay line to parallelly drive five $\Delta m = 0$ hyperfine Raman transitions of ^{85}Rb atoms for spin-dependent kick (SDK) within $\tau = 40ns$, with an $f_{SDK} 97.6\%$ inferred fidelity. Aided by numerical modeling, we demonstrate that by alternating the chirps of successive pulses in a balanced fashion, accumulation of nonadiabatic errors including the spin-leakages can be managed, while the dynamic phases can be robustly cancelled. Operating on a phase-stable delay line, the method supports precise, fast, and flexible control of spinor matterwave with efficient Raman excitations.

Presenter name: Hu, Jiangyong

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Virtual poster / Vir32:   *Quant. info.: gates, sensing, commun. & Thermo.*   ID302

Progress on a portable, high-stability atom-interferometer gyroscope for dynamic rotation measurements

Authors: Honghui Chen[1]; Zhanwei Yao[2]; Zexi Lu[2]; Yinfei Mao[2]; Sibin Lu[2]; Min Jiang[2]; Shaokang Li[2]; Runbing Li[2]; Jin Wang[2]; Mingsheng Zhan[2]

1   *Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences, Wuhan 430071, China*

2   *Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences, Wuhan 430071, China*

Abstract: The atom-interferometer gyroscope has been proven to be a promising tool for high-precision rotation measurements, and it will have important applications in fields of fundamental physics, geophysics, and inertia navigation. Here, we present the recent progress of our atom-interferometer gyroscope. First, with a compact atom-interferometer gyroscope, we demonstrated the rotation sensitive property in a dynamic rotating frame [1]. Then, to improve the sensitivity, we applied three pairs of separated Raman beams to build dual large-area interference loops, and developed a self-calibrated method of atomic trajectories in dual atomic interference loops to suppress the common noise [2]. Finally, we realize a portable, large-area dual-atom-interferometer gyroscope with a long-term stability of 9.5×10^{-10} rad/s [3]. The device is compact and portable, and it was transported to Beijing from Wuhan over 1200 km. Benefit from the compact laser system and physical chamber, our atom-interferometer gyroscope reveals a high stability and a robust property even after a long-distance transport, and it demonstrates an excellent performance in two locations.

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Presenter name: Zhanwei Yao

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Poster session / Mo-53:   *Quant. optics & hybrid quant. sys.*   ID16

Generation of photons from vacuum in cavity via time-modulation of a qubit invisible to the field

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[1] *University of Brasilia*

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Dynamical Casimir effect (DCE) designates a plethora of phenomena characterized by generation of photons (or quanta of some other field) from vacuum due to time-dependent variations of the geometry (dimensions) or material properties (e.g., the dielectric constant or conductivity) of some macroscopic system. The circuit QED architecture is a handy platform for the implementation of DCE and its analogues, since both the cavity's and artificial atoms' properties can be rapidly modulated by external magnetic field. In particular, the generation of photons and light-matter entangled states from the initial vacuum state can take place for a resonant time-modulation of the atomic transition frequency or the atom-field coupling strength, when the atom is directly coupled to the field via the dipole interaction (as described by the Quantum Rabi Model). In this case, one can think of the atom as a microscopic constituent of the intracavity medium. Here we propose a scheme for the generation of photons from vacuum due to the time-modulation of some quantum system that is "invisible" to the field, namely, some artificial 2-level atom (nonstationary qubit) that is indirectly coupled to the field via some ancilla quantum subsystem. We consider the simplest case when the ancilla is a stationary qubit, coupled via the dipole interaction both to the cavity field and the nonstationary qubit, but our results can be easily generalized to more complex atoms. We find that a small number of photons can be generated from the system ground state under resonant modulations even when the nonstationary qubit is far detuned from both the ancilla and the cavity. Moreover, for specific relations between the natural frequencies of the three subsystems the photon generation rate can be strongly enhanced due to the anti-crossings in the energy levels of the bare Hamiltonian, when the system is driven to a triparite entangled state. We attest our approximate analytic results by numeric simulations and show that the photon generation from vacuum persists even in the presence of common dissipation mechanisms. Thus, our scheme could find applications in the engineering of effective interactions and entangled states in hybrid cavity QED systems, when the nonstationary qubit is designed to undergo fast large-amplitude modulations, while the cavity field is coupled to another stationary atom.

Presenter name: Alexandre Dodonov

Poster session / Mo-54:   *Quant. optics & hybrid quant. sys.*   ID35

Collective radiative dynamics of an ensemble of cold atoms coupled to an optical waveguide

Authors: Riccardo Pennetta[1]; Martin Blaha[1]; Aisling Johnson[1]; Daniel Lechner[1]; Philipp Schneeweiss[1]; Jürgen Volz[1]; Arno Rauschenbeutel[1]

[1] *Humboldt University Berlin*

We experimentally and theoretically investigate collective effects in a one-dimensional array of cold atoms coupled to a single-mode optical nanofiber [1]. Our analysis unveils the microscopic (i.e., atom per atom) dynamics of the system, showing that collective interactions gradually build-up along the atomic chain in the direction of propagation of the excitation light pulses. Our theoretical results are supported by time-resolved measurements of the light transmitted and reflected by the atomic ensemble.

In particular, when the excitation pulse is switched off on a time scale much shorter than the atomic lifetime, a superradiant decay is observed in the forward direction, while no speed-up of the decay rate is measured in the backward direction. For longer time scales, our measurements reveal the evolution of the ensemble from the superradiant state to a set of states that are fully subradiant with respect to the fiber mode [2]. Notably, our theoretical model identifies this phenomenon as a key feature of the time evolution of one-dimensional systems prepared in a timed Dicke state. This complex dynamics can be accurately described with a simple analytical expression.

Our results highlight the unique opportunities offered by nanophotonic cold atom systems for the experimental investigation of collective light-matter interaction.

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Presenter name: Riccardo Pennetta

Interferometry on the clock transition in Sr-87 with entangled atoms in momentum state superpositions

Authors: Joep Assendelft[1]; Leonardo Salvi[1]; Gabriele Rosi[1]; Gunjan Verma[1]; Enlong Wang[1]; Guglielmo Tino[1]

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I will present our activity on the realisation of atom interferometry with an optical clock transition beyond the standard quantum limit (SQL) with strontium atoms. An interferometer can be injected with entangled atoms to improve its phase resolution $\Delta\phi$, where the entanglement is created between momentum state superpositions by performing cavity-enhanced quantum nondemolition (QND) measurements [1]. Our method will improve the scaling in phase resolution $\Delta\phi$ with atom number N surpassing the SQL of $\Delta\phi \sim N^{-1/2}$ for uncorrelated atoms. An interferometer using a similar method for entanglement creation has recently been demonstrated for a small atom number N and a short interrogation time T using rubidium atoms [2].

Atom interferometry can be used to study fundamental physics, like testing the equivalence principle or determining the gravitational constant G. It can furthermore be used in Earth observation sciences and in future space applications. To reach small phase resolutions $\Delta\phi$ interferometers need large-momentum transfer, a large atom number N and a long interrogation time T. However, many applications are limited by the size, weight and power consumption of the instrument, this is especially true for space applications. An interferometer implementing QND measurements can therefore be reduced in size, weight and power consumption compared to interferometers using uncorrelated atoms. Furthermore, when using squeezing a given precision is reached after a smaller averaging time, which improves the sensor bandwidth.

We plan to create an atom interferometer on the clock transition $^1S_0 \leftrightarrow {}^3P_0$ in strontium-87 [3] and inject it with entangled atoms using QND measurements. We realised a narrow-linewidth clock laser system at 698 nm to drive the clock transition. We are working on a homodyne detection system to perform the QND measurements. A momentum state superposition will be created between $\left| {}^1S_0, p = 0 \right\rangle$ and $\left| {}^3P_0, p = \hbar k \right\rangle$ using single-photon transitions at 698 nm, with $\hbar k$ the momentum of a single photon. The QND measurements will be performed by probing the wave packets detuned from the $^1S_0 \leftrightarrow {}^3P_1$ transition at 689 nm when they cross the focus of the high-finesse experimental cavity. Squeezing will be induced by measuring the populations in the prepared superposition. At the end of the interferometer sequence the population difference will be read out with increased sensitivity. This method can be used with other atomic species where a narrow transition is available or can be created.

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Presenter name: Joep Assendelft

Rapid quantum squeezing by jumping the harmonic oscillator frequency

Authors: Mingjie Xin[1]; Wui Seng Leong[1]; Shau-Yu Lan[1]

[1] *Nanyang Technology University*

Quantum sensing and quantum information processing use quantum advantages such as squeezed states that encode a quantity of interest with higher precision and generate quantum correlations to outperform classical methods. In harmonic oscillators, the rate of generating squeezing is set by a quantum speed limit. Therefore, the degree to which a quantum advantage can be used in practice is limited by the time needed to create the state relative to the rate of unavoidable decoherence. Alternatively, a sudden change of harmonic oscillator's frequency projects a ground state into a squeezed state which can circumvent the time constraint. Here, we create squeezed states of atomic motion by sudden changes of the harmonic oscillation frequency of atoms in an optical lattice. Building on this protocol, we demonstrate rapid quantum amplification of a displacement operator that could be used for detecting motion. Our results can speed up quantum gates and enable quantum sensing and quantum information processing in noisy environments.

Reference: Mingjie Xin, Wui Seng Leong, Zilong Chen, Yu Wang, and Shau-Yu Lan. Phys. Rev. Lett.127,183602(2021).

Presenter name: Xin, Mingjie

Poster session / Mo-57: *Quant. optics & hybrid quant. sys.* ID123

Development towards a hybrid quantum repeater

Authors: Katie McDonnell[1]; Rubayet Al Maruf[1]; Paul Anderson[1]; Sai Sreesh Venuturumilli[1]; Nikolay Videnov[1]; Yujia Yuan[1]; Dan Dalacu[2]; Philip J. Poole[2]; Michael Reimer[1]; Michal Bajcsy[1]

[1] *University of Waterloo*

[2] *National Research Council of Canada*

We describe our progress in developing a proof-of-principle hybrid quantum repeater based on laser-cooled caesium ensembles and a semiconductor quantum dot. The atoms here can be used as a quantum memory or as a nonlinear medium whilst the quantum dot can be used as a bright source of entangled photon pairs. The laser cooled atoms are loaded inside a hollow-core fiber to achieve an optical depth $\sim$1000. This has the potential to enable strong interactions with photons emitted by the quantum dot, which have bandwidth of $\sim$1 GHz and can be tuned to match the cesium D_1 line. The atoms confined in the hollow-core fiber can be used to store single photons from the quantum dot and to realize single-photon wavelength conversions for quantum key distribution (QKD) via ground-to-satellite or telecom-fiber links.

Presenter name: Katie McDonnell

Poster session / Mo-58:   *Quant. optics & hybrid quant. sys.*   ID204

Can a photon cause atoms to be excited for a negative amount of time? (experimental progress)

Authors: Daniela Angulo Murcillo[1]; Kyle Thompson[1]; Vida-Michelle Nixon[1]; Andy Jiao[1]; Aephraim Steinberg[1]

[1] *University of Toronto*

If a resonant photon traverses a medium and is transmitted on the far side, does it excite any atoms along the way? Previous work (PRX Quantum 3, 010314) provides evidence that it does. Since this work was limited to measurements using only broadband pulses of light, it cannot distinguish between recent theories that make strikingly different predictions in the case of excitation with narrowband pulses and media with low optical depth. In particular, the weak-value formalism suggests that this excitation time could be negative under such conditions. We present experimental progress to investigate this prediction and aim to fully elucidate the history of resonant photons that are ultimately transmitted through a cold cloud of 85Rb atoms.

Presenter name: Daniela Angulo Murcillo

Poster session / Mo-59:   *Quant. optics & hybrid quant. sys.*   ID260

Control and entanglement of Rydberg atoms near a nanophotonic device

Authors: Elmer Guardado-Sanchez[1]; Ivana Dimitrova[1]; Brandon Grinkemeyer[1]; paloma Ocola[1]; Tamara Dordevic[1]; Polnop Samutpraphoot[2]; Vladan Vuletic[3]; Mikhail Lukin.

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[2] *Berkeley*

[3] *MIT*

Rydberg atom arrays are a promising platform for quantum information and quantum computation. However, they lack a photonic link, such as an optical cavity, which could be used for fast nondestructive readout for error correction or for remote entanglement of distant arrays, thus extending the computational capabilities of the platform. The integration between an optical cavity and Rydberg atoms is challenging due to their large polarizability: noise in the electric field generated by surface charges on a cavity can severely limit coherence times. Here we use a nanoscale photonic crystal cavity attached to a fiber. Due to its small size, the nanocavity is a promising candidate for such a photonic interface for Rydberg atom arrays. We characterize the coherence of single- and two-atom Rydberg states near the PCC suggesting a pathway towards their successful integration.

Presenter name: Elmer Guardado-Sanchez

Poster session / Mo-61: *Quant. optics & hybrid quant. sys.* ID316

Towards a continuous wave superradiant calcium laser

Authors: David C. Nak[1]; Andreas Hemmerich[1]

[1] *Institute of Laser Physics, University of Hamburg*

Superradiant lasers are suitable as light sources with an ultranarrow linewidth. Superradiant emission can exhibit a linewidth, which is narrower than the natural decay on the same transition [1]. Like conventional lasers, superradiant lasers usually incorporate a cavity to mitigate the atom-light interaction. In the conventional case the emission frequency is strongly dependent on the cavity and therefore sensitive to mechanical perturbations. However, for superradiant lasers operating in the bad-cavity regime, this dependance is highly suppressed [2]. This makes superradiant Lasers operating on ultranarrow transitions, as the alkaline-earth metal clock transitions, ideal candidates for oscillators of next generation atomic clocks. Currently, our experiment loads cold calcium-40 atoms from a magneto optical trap into a one-dimensional optical lattice prepared inside a cavity. By incoherent population of the metastable triplet state, pulsed superradiant emission on the intercombination line was realized. Due to the incoherent preparation of the atomic sample, it was also possible to show the spontaneous nature of the superradiant pulses and measure a delay distribution [3]. At present, the setup is being extended by an incoherent repumping mechanism, which will allow limited time continuous wave operation.

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Presenter name: David C. Nak

What does entanglement sudden death require?

Authors: Songbo Xie[1]; Daniel Younis[1]; Joseph Eberly[1]

[1] *University of Rochester*

Vacuum is one of the most interesting phenomena of the real world. A two-level atom, frequently treated as a qubit, when unavoidably touched by vacuum, is unstable on its excited level, even if it does not interact with any other system. All states except the ground state suffer from decay due to interaction with vacuum radiation modes. The atom falls to the ground state in asymptotic time and a photon is emitted, a process known as spontaneous decay.

The situation becomes more interesting when multiple atoms are present and placed far apart, such that they can be considered as sitting in distinguishable vacuum states. As in the single-atom case, the excited elements of the multiatom density matrix decay exponentially to zero. However, previous results of Yu and Eberly [Science **323**, 598 (2009)] have shown that two-atom entanglement (also called nonseparability) has a transition to zero in such systems that is temporally abrupt. Such dynamics of entanglement is nonanalytic, and this bizarre behaviour is usually termed entanglement sudden death (ESD).

It is then natural to ask how entanglement among more than two qubits behaves when the qubits decay independently in their respective cavities. Are there also sudden transitions in these more complicated systems? Specifically, what is the requirement for ESD in these systems? These open questions are made difficult by the following two obstacles. First, existing entanglement measures cannot quantify the degree of genuine multipartite entanglement (GME), the measure of the entanglement resource that plays a central role in quantum information and communication tasks such as the three-qubit quantum teleportation. Second, even if a GME measure is used, it is an extremely difficult task to evaluate it for general mixed states, which are ubiquitous for vacuum decay.

In this work, we provide solutions to the above two problems. For the GME measure, we use our recently developed pure-state measure *Concurrence Fill*, which was proven to detect genuine tripartite entanglement [see Xie and Eberly, Phys. Rev. Lett. **127**, 040403 (2021)]. For the mixed-state issue, we avoid deriving an analytic formula, which is currently impossible. Instead, we apply a previous result to convert the evaluation of mixed-state entanglement into a practical numerical task [Eisert, Brandão, and Audenaert, New J. Phys. **9**, 46 (2007)].

With these methods, we study the entanglement dynamics for three-qubit systems, wherein each qubit interacts with its own vacuum environment via the amplitude-damping channel. We numerically examine the dynamics of the Concurrence Fill measure of genuine tripartite entanglement among the three qubits, when different initial three-party states are selected.

Specifically, when the initial state is the generalized GHZ state, $|\text{GHZ}\rangle = \cos\theta|eee\rangle + \sin\theta|ggg\rangle$, where $|e\rangle$ and $|g\rangle$ are the excited and ground states for each atom, ESD occurs when the amplitude of the all-excited state $|eee\rangle$ exceeds a threshold value. Furthermore, we show that ESD does not occur if the initial state is the singly-excited W state, $|W\rangle = (|egg\rangle + |geg\rangle + |gge\rangle)/\sqrt{3}$, or the doubly-excited $\overline{W}$ state, $|\overline{W}\rangle = (|gee\rangle + |ege\rangle + |eeg\rangle)/\sqrt{3}$.

These observations imply that when the three-qubit initial state is pure, the presence of the all-excited $|eee\rangle$ state is a necessary requirement for ESD to occur, despite the fact that $|eee\rangle$ is a product state which cannot exhibit ESD alone. To test this novel conjecture, we consider as the initial state the superposition of $|eee\rangle$ with the no-ESD $|W\rangle$ state, $|S\rangle = \cos\theta|eee\rangle + \sin\theta|W\rangle$. In agreement with our conjecture, ESD occurs when the amplitude of $|eee\rangle$ exceeds a threshold value. Our results bring new insights toward a more complete understanding of entanglement sudden death.

Presenter name: Songbo Xie

Effects of pump pulse length on photon number in quantum dot emission

Authors: Sai Sreesh Venuturumilli[1]; Paul Anderson[1]; Divya Bharadwaj[1]; Rubayet Al Maruf[1]; Yujia Yuan[1]; Behrooz Semnani[1]; Philip Poole[2]; Dan Dalacu[2]; Michael Reimer[1]; Michal Bajcsy[1]

[1] *University of Waterloo*

[2] *National Research Council Canada*

On-demand sources of nonclassical light play an important role in quantum information and metrology [Ref. 1], and semiconductor quantum dot (QD) sources promise high-quality and efficient single and entangled photons [Refs. 1, 2]. At the same time, other states of light have been observed in the QD emission [Refs. 3, 4, 5, 6] as the nature of the emitted light relates with the dynamics of the electronic state of the QD. In particular, when the dot is excited by a pulse of light, charge and/or exciton capture processes within the same pulse cycle can cause multiphoton emission.

Here, we predict and measure – using a photon-number-resolving superconducting-nanowire single photon detector – photon correlations and photon number statistics in light emitted by a QD embedded in a semiconductor nanowire [Ref. 2] excited with nonresonant pulses of different lengths.

We model the excitation and emission process as a Markov chain. This allows one to keep track of the photon number distributions of the involved transitions – such as: exciton (X), bi-exciton (XX) and charged exciton (X-) – along with their coincidences. An illustration of a model and its estimates are presented in Figure 1. We study the role of different parameters in the model, such as pulse lengths and intensities, to explain the observed experimental results.
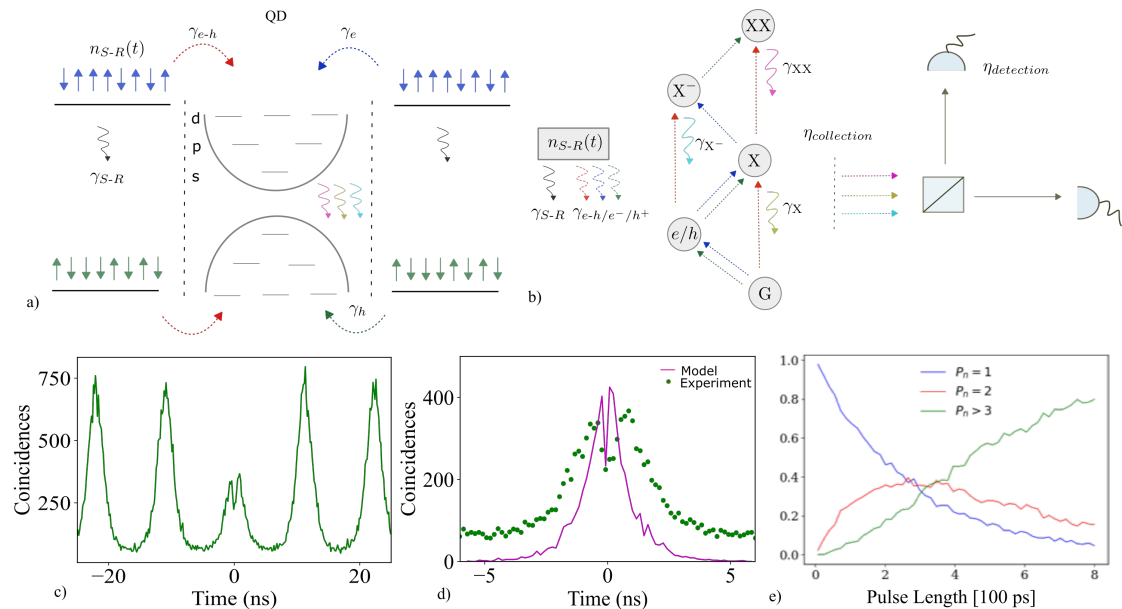
Figure 1: a) Some of the electron-hole pairs created in the bulk semiconductor material ($n_{S-R}(t)$ – linearly following the input pulse) by the non-resonant optical pulse decay (γ_{e-h}) into the electronic states of the dot. Single charges can also decay (γ_e, γ_h) into the dot. b) A Markov chain (following Ref. 6) used to model the experiment. G, e/h are the ground and singly charged states of the dot. c) Raw coincidences (measured using Excellitas SPCM detectors) of the bi-exciton (XX) photons upon $\sim$100 ps pulsed excitation, corresponding to a $g^{(2)}(0)$ value of $\sim$0.3. d) Comparison of the bi-exciton photon coincidence counts with estimates from the Markov model. e) Probability of multi-photon emission versus pulse length for the simplified model where charged excitons and single charges are not considered. For a 100 ps pulse, the additionally emitted photons would result in $g^{(2)}(0)\sim$0.2.

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Presenter name: Sai Sreesh

Nanostructured alkali-metal vapor cells

Authors: Tom Cutler[1]; Charles S. Adams[1]; Ifan G. Hughes[1]; Danielle Pizzey˙; Vahid Sandoghdar[2]; Jan Renger[2]

[1] *Durham University*

[2] *Max Planck Institute for the Science of Light*

We have developed a methodology for manufacturing alkali-metal vapour cells with internal confinement dimensions down to hundreds of nanometers (generally less than the probe laser wavelength). We envisage our nano-cells as a platform for fundamental atom-light interaction experiments, as well as for potential technological applications. Our manufacture process is versatile and our fused-silica cells are robust. The figure below, from our recent paper [Cutler et al, Phys. Rev. Applied 14, 034054 (2020)] shows a schematic and photograph of one of our nano-cells, as well as some example etched nano-structures. Similar cells have already been used to investigate the cooperative Lamb shift in a dense atomic vapour, measure the atom-surface van der Waals interaction, and to study the spectral response and transit time broadening of the vapour under evanescent excitation. This poster will describe recent experiments and developments using our nano-cell platform.
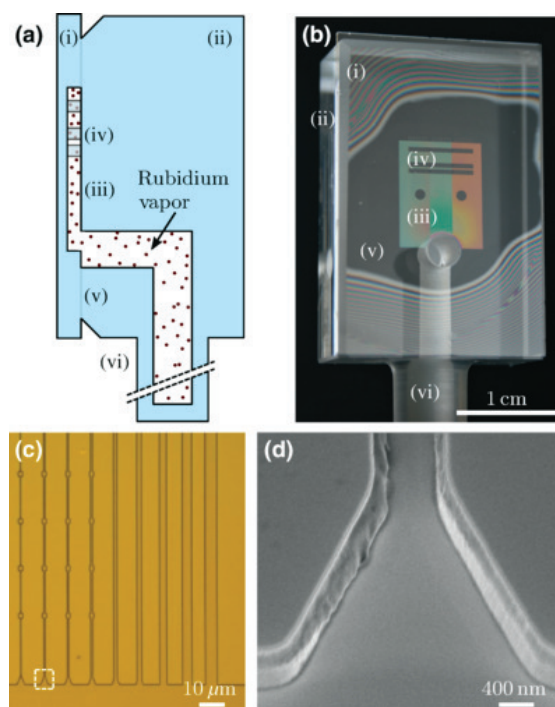
Figure 1: Alkali-metal vapour nano-cell schematic and photograph, with images of nano-scale structures

Presenter name: Tom Cutler

Poster session / Tu-56: *Quant. optics & hybrid quant. sys.* ID37

A single cold atom as a single-photon detector

Authors: Laura Zarraoa[1]; Morgan Mitchell[2]

[1] *ICFO - Institute of Photonic Sciences*
[2] *ICFO*

Single ions and atoms are interesting systems for single-photon detection due to their frequency selectivity and very low dark counts [2,3]. These capabilities are useful for any application in which a very low power signal must be detected against a broadband background. An example of such an application would be free-space quantum communication in daylight. In this work, we present and describe the operation of a quantum jump photodetection (QJPD) technique for measuring single photons using a single neutral 87Rb atom in a strongly-focused optical dipole trap [4,5]. We report results of first-principles calculations for the main dark count contributions: spontaneous Raman transitions driven by readout light (which can be avoided by separating the detection and readout time windows) and spontaneous Raman transitions driven by trap light (which is unavoidable but gives dark count rates two orders of magnitude below that state of the art single-photon detectors). We quantify the frequency selectivity with the equivalent noise bandwidth, which we find is up to two orders of magnitude narrower than the best atomic filters. Preliminary experimental results for these figures of merit in a "Maltese cross" atom trap will be presented.
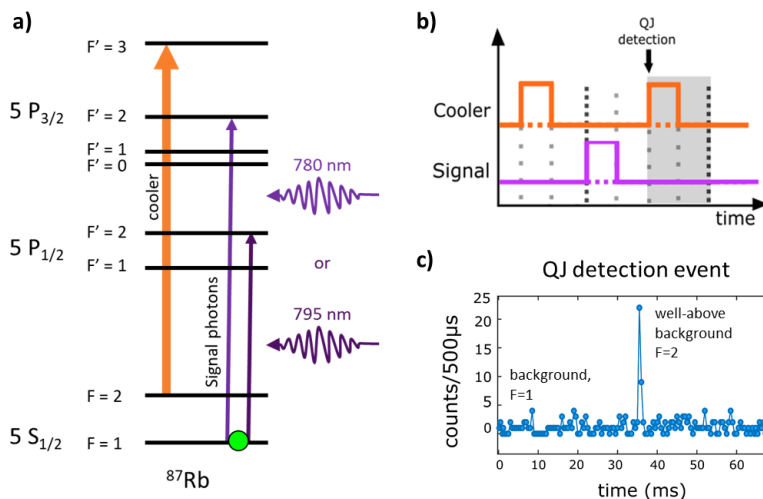
Quantum-Jump Photodetection technique for a single neutral 87Rb atom in a free-space dipole trap. a) Relevant energy levels and lights used in the experiment. Cooler light (orange) for preparation and readout in the closed transition and signal light (purple) that will be measured. b) Measurement sequence. First cooler pulse prepares atom in the dark ground state ($F = 1$), signal pulse causes a quantum jump to the bright state ($F = 2$), readout pulse causes sudden fluorescence if the atom jumped and then reprepares the atom in the dark state. c) Counts as a function of time for a detection event. The sudden increase in fluorescence counts due to the atom cycling in the closed transition after a jump creates a well-above background peak that can be used for counting detections.]

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[5] L. Bianchet, et al., Open Res Europe, 1:102 (2021)

Presenter name: Laura Zarraoa

Poster session / Tu-57:   *Quant. optics & hybrid quant. sys.*   ID66

Atomic spin-controlled nonreciprocal Raman amplification of fibre-guided light

Authors: Sebastian Pucher[1]; Christian Liedl[1]; Jin Shuwei[1]; Arno Rauschenbeutel[1]; Philipp Schneeweiss[1]

[1] *HU Berlin*

In a nonreciprocal optical amplifier, gain depends on whether the light propagates forwards or backwards through the device. Typically, one requires either the magneto-optical effect, a temporal modulation, or an optical nonlinearity to break reciprocity. By contrast, here, we demonstrate nonreciprocal amplification of fibre-guided light using Raman gain provided by spin-polarized atoms that are coupled to the nanofibre waist of a tapered fibre section. The nonreciprocal response originates from the propagation direction-dependent local polarization of the nanofibre-guided mode in conjunction with polarization-dependent atom-light coupling. We show that this novel mechanism can also be implemented without an external magnetic field and that it allows us to fully control the direction of amplification via the atomic spin state. Our results may simplify the construction of complex optical networks. Moreover, using other suitable quantum emitters, our scheme could be implemented in photonic integrated circuits and in circuit quantum electrodynamics.

[1] S. Pucher, C. Liedl, S. Jin, A. Rauschenbeutel, P. Schneeweiss
Atomic spin-controlled nonreciprocal Raman amplification of fibre-guided light
Nature Photonics 16, 380 (2022)

Presenter name: Philipp Schneeweiss

Poster session / Tu-58:   *Quant. optics & hybrid quant. sys.*   ID76

Enhancing fiber atom interferometer by in-fiber laser cooling

Authors: Wui Seng Leong[1]; Yu Wang[1]; Mingjie Xin[1]; Zilong Chen[1]; Shau-Yu Lan[1]

[1] *Nanyang Technological University*

Building cold atomic quantum sensors with photonic structures promise to miniaturize the apparatus that could eventually lead to portable devices. To prepare atoms in photonic platforms to a temperature that can be applied as a sensor requires adopting free-space laser cooling in space-constrained photonic structures. Here, we demonstrate in-fiber Λ-enhanced gray molasses and delta-kick cooling to cool atoms inside a 22-cm-long negative curvature hollow-core photonic crystal fiber from 32 K to sub- K in 4 ms. The in-fiber cooling overcomes the inevitable heating during the atom loading process and allows a shallow guiding optical potential to minimize decoherence. We employ these cold atoms in an inertia sensitive atom interferometer optically guided inside a hollow-core photonic crystal fiber with an interferometer time of 20 ms. The result improves the previous fiber guided atom interferometer sensitivity by three orders of magnitude. Our results permit bringing atoms close to source fields for sensing and could lead to compact inertial quantum sensors with a sub-millimeter resolution.
Reference: arXiv:2112.10088

Presenter name: Leong, Wui Seng

Poster session / Tu-59:   *Quant. optics & hybrid quant. sys.*   ID164

Switching a monolayer atomic mirror using a single Rydberg atom

Authors: Kritsana Srakaew[1]; Pascal Weckesser[1]; Simon Hollerith[1]; David Wei[1]; Daniel Adler[1]; Immanuel Bloch[1]; Johannes Zeiher[1]

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Understanding and tuning light-matter interactions at the level of single quanta is essential for numerous applications in quantum science. Such quantum control seeks to increase the small interaction cross section between single atoms and single photons. Exploiting cooperative response of subwavelength atomic arrays allows for realizing strong light-matter coupling even down to the level of single photons. Here, we control the optical response of an atomically thin mirror using a single ancilla atom excited to a Rydberg state, that is, we use a single atom to control light at the single-photon level. The switching behavior is controlled by admixing a small Rydberg amplitude to the atomic mirror and therefore inducing strong dipolar Rydberg interactions with the ancilla. Driving coherent excitations of the ancilla atom, we demonstrate coherent control over the degree of transmission and reflection. Finally, increasing the mirror size directly reveals a spatial effective "switching" area around the ancilla. Our results pave the way towards novel quantum metasurfaces, the creation of controlled atom-photon entanglement and deterministically engineering quantum states of light.

Presenter name: Kritsana Srakaew

Poster session / Tu-60:   *Quant. optics & hybrid quant. sys.*   ID214

Narrowband biphoton source of maximal spectral brightness at ultralow pump power

Authors: Alexander Bruns[1]; Chia-Yu Hsu[1]; Sergiy Stryzhenko[1]; Leonid P. Yatsenko[2]; Ite A. Yu[3]; Thomas Halfmann[1]; Thorsten Peters[1]

[1] *Institut für Angewandte Physik, Technische Universität Darmstadt*

[2] *Institute of Physics, National Academy of Science of Ukraine*

[3] *Department of Physics, National Tsing Hua University*

Nonclassical photon sources of high brightness are key components of quantum communication technologies. We here demonstrate the generation of narrowband, nonclassical photon pairs up to the ultimate limit of achievable generated spectral brightness at which successive photon pairs start to overlap in time.

Our biphoton source employs spontaneous four-wave mixing in an optically-dense ensemble of cold Rubidium atoms within a hollow-core fiber. To avoid collisions of the cold atoms with the fiber wall, thereby reducing the coherence time, the atoms are guided by an optical dipole trap. By using cold atoms we achieve an orders of magnitude lower biphoton bandwidth as compared to fibers filled with warm gases. As an additional benefit of the hollow-core fiber, all light fields involved in the FWM process are guided in the same optical mode. Thus, we obtain intrinsically optimal mode-matching as well as strong light-atom coupling at orders of magnitude lower pump powers compared to free space experiments. This results in a generated spectral brightness per pump power of up to 2×10^9 pairs/(s $\cdot$ MHz $\cdot$ mW), which is a 10-fold increase over the previous record. Additionally, our results are achieved at a 100-fold reduced pump power and exhibit a 10-fold lower bandwidth of $2\pi \times 6.5$ MHz, which is directly compatible with atomic quantum memories. We verify the nonclassical character of the generated photons with a 97-fold violation of the Cauchy-Schwarz inequality. We further demonstrate that our source can be used as a heralded single-photon source with a heralded auto-correlation as low as 0.08. Moreover, we show that our biphoton source can be tuned to the ultimate achievable limit of generated spectral brightness, at which successive photon pairs start to overlap in time. In this regime, the photon correlations clearly start to deviate from the expected behavior for low brightness sources.

As the photon pairs at wavelengths of 780/795 nm exhibit orthogonal polarizations and are emitted into a single spatial mode, they can be efficiently separated and interfaced to photonic networks as well as atomic quantum memories. Our source combines the advantages of atomic ensembles and waveguide environments, thus representing a step towards interfacing ensemble-based building blocks with photonic quantum networks.

Presenter name: Alexander Bruns

Poster session / Tu-61:   *Quant. optics & hybrid quant. sys.*   ID261

Vector magnetometry with microwave-assisted optical pumping in warm Rb atoms

Authors: Bahar Babaei[1]; Benjamin D. Smith[1]; Lindsay J. LeBlanc[1]

[1] *University of Alberta*

We report a microwave assisted optical vector magnetometer. Our method is based on the frequency difference and relative amplitudes of microwave-optical double resonances for different magnetic dipole transitions. Two hyperfine levels of ^{87}Rb ground state are coupled strongly by a microwave field inside a cylindrical microwave cavity. A strong pump beam connects $F = 2$ (ground state) to $F = 2$ (excited state), while a microwave field of frequency ω_μ pumps atoms between $|1\rangle = |F = 1, m_1\rangle$ and $|2\rangle = |F = 2, m_2\rangle$. The orientation of the microwave field with respect to the static field affects the amplitude of the double resonance peaks due to the polarization of the transitions, which provides us with information about the direction of the static field.

Presenter name: Bahar Babaei

Rotation sensing using point source atom interferometry

Authors: Joel Abraham[1]; Max Carey[1]; Nikolaos Dedes[1]; Tim Freegarde[1]

[1] *University of Southampton*

In Point Source Atom Interferometry (PSI), a sequence of Raman laser pulses interact with an expanding ball of cold atoms, to split, redirect and recombine the matter-wave. It exploits the correlation between the position and velocity of the atoms to produce a spatially imprinted interference pattern across the atomic cloud. Since the phase of atoms contains information about inertial effects on the system, the interferometer can be used to detect angular rates. PSI can therefore be used as a sensor that can take measurements for inertial navigation applications. We plan to develop such a rotation sensor and test out optimal control pulses to improve the performance of the interferometer, tackling issues involving scale factor instability and low contrast. As a preliminary step, we characterised the response of the I&Q modulator needed to control the phase of the optimal pulses, thus reducing the errors caused by potential nonlinearities.

Presenter name: Joel Abraham

Poster session / Tu-63: *Quant. optics & hybrid quant. sys.* ID320

Towards strong photon-photon interactions via cold atoms trapped near a slow-mode photonic crystal waveguide

Authors: Adrien Bouscal[1]; Alban Urvoy[2]; Malik Kemiche[3]; Sukanya Mahapatra[4]; Jérémy Berroir[2]; Tridib Ray[2]; Nikos Fayard[5]; Fabrice Raineri[4]; Kamel Bencheick[4]; Ariel Levenson[4]; Christophe Sauvan[5]; Julien Laurat[2]

[1] *Laboratoire Kastler Brossel, Sorbonne Université*

[2] *Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-PSL, Collège de France, 75005 Paris, France*

[3] *IMEP-LAHC, Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, Grenoble INP, 38000 Grenoble, France*

[4] *Centre de Nanosciences et de Nanotechnologies, CNRS, Université Paris-Saclay, 91120 Palaiseau, France*

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Trapping cold neutral atoms in close proximity to nanostructures has raised a large interest in recent years, pushing the frontiers of cavity-QED and boosting the emergence of the waveguide-QED field of research. Such platforms interfacing trapped cold atoms and guided light in nanoscale waveguides are a promising route to achieve a regime of strong coupling between light and atoms [1].

In this context, we propose to interface ^{87}Rb atoms with a GaInP waveguide based on a 2D photonic crystal waveguide (PCW) [2]. The periodic arangement of holes allows to shape the dispersion relation and engineer slow-modes [3], whose interaction with quantum emitters would be enhanced, allowing for strong coupling even in single pass. At the same time, guided modes are used to form dipole traps for the atoms, a crucial requirement for achieving strong coupling. The coupling of the atoms to the waveguide can be characterized by the Purcell factor, which relates the decay rate of the atoms into the guided mode to the one into free space. At realistic distances 100 nm from the waveguide surface, FDTD calculations reveal that Purcell factors as high as 5 can be expected.

Moreover, dispersion engineering by tuning the geometrical parameters of the PCW can lead to a constant group index ng 30 over a range of 15 nm, centered around $\lambda_{\mathrm{Rb,D_2}} = 780$ nm, making the design more robust to fabrication imperfections. We introduce a stable trapping scheme around our PCW for ^{87}Rb atoms based on an evanescent two-color dipole trap formed by fast guided modes.

This configuration was computed thanks to nanotrappy [4], a Python package developed by our group, to design, calculate and optimize dipole traps around nanoscale waveguides, making the search process faster and more systematic. Experimental realization of the cold atoms system is ongoing and promising first structures are being characterized.

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[2] X. Zang, et al., Phys. Rev. Appl., 5, 024003 (2016)
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Presenter name: Adrien Bouscal

Poster session / Tu-64:   *Quant. optics & hybrid quant. sys.*   ID350

Atomic arrays driven by broadband squeezed light

Authors: Ricardo Gutierrez-Jauregui[1]; Ana Asenjo-Garcia[1]

[1] *Columbia University*

In this theoretical work we describe the evolution of an atomic array driven by broadband squeezed light. Photons in a squeezed field are created as correlated pairs, thus leading to a phase-sensitive amplification and deamplification of fluctuations. These fluctuations depend on the squeezing mechanism and the spatial structure of the modes carrying the correlated pairs [1-3]. By spreading several atoms within this environment, we are able to probe the local structure of the field at different points and study its underlying temporal and spatial correlations. We show that, like the squeezed source illuminating them, atoms correlate in pairs to form a collective state that disentangles from its environment. Being detached from the environment, atoms become trapped in this state, thus increasing the purity of the system as time advances. For this to happen, however, atoms have to be placed at points where the correlations of the field are maximized. We explore these points and discuss the steady states formed outside of them.

This work builds upon a recent trend where the collective radiation of atomic ensembles is used as a tool to extend the standard theory of quantum optics to account for both spatial and temporal correlations of light.

[1] C. W. Gardiner, Phys. Rev. Lett. 56, 1917 (1986).
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[3] K. W. Murch, S. J. Weber, K. M. Beck, E. Ginossar, and I. Siddiqi, Nature 499, 62 (2013).

Presenter name: Gutierrez-Jauregui, Ricardo

Poster session / We-57:   *Quant. optics & hybrid quant. sys.*   ID29

Quasi-BIC mode lasing in a quadrumer plasmonic lattice

Authors: Rebecca Heilmann[1]; Grazia Salerno[1]; Javier Cuerda[1]; Tommi K. Hakala[2]; Päivi Törmä[1]

[1] *Aalto University*

[2] *University of Eastern Finland*

Plasmonic lattices of metal nanoparticles have emerged as an effective platform for strong light-matter coupling, lasing, and Bose-Einstein condensation. However, the full potential of complex unit cell structures has not been exploited. On the other hand, bound states in continuum (BICs) have attracted attention, as they provide topologically protected optical modes with diverging quality factors. Here, we show that quadrumer nanoparticle lattices enable lasing in a quasi-BIC mode with a highly out-of-plane character. By combining theory with polarization-resolved measurements of the emission, we show that the lasing mode has a topological charge. Our analysis reveals that the mode is primarily polarized out-of-plane as a result of the quadrumer structure. The quality factors of the out-of-plane BIC modes of the quadrumer array can be exceedingly high. Our results unveil the power of complex multiparticle unit cells in creating topologically protected high-Q modes in periodic nanostructures.

Presenter name: Salerno Grazia

Poster session / We-58:   *Quant. optics & hybrid quant. sys.*   ID40

Collective excitation and decay of waveguide-coupled atoms: from timed Dicke states to inverted ensembles

Authors: Christian Liedl[1]; Sebastian Pucher[1]; Felix Tebbenjohanns[1]; Philipp Schneeweiss[2]; Arno Rauschenbeutel[2]

[1] *Humboldt University of Berlin*

[2] *Humboldt University Berlin*

The collective absorption and emission of light by an ensemble of atoms is at the heart of many fundamental quantum optical effects and the basis for numerous applications. However, beyond weak excitation, both experiment and theory become increasingly challenging. Here, we explore the regimes from weak excitation to inversion with ensembles of up to one thousand atoms that are trapped and optically interfaced using the evanescent field surrounding an optical nanofiber. We realize strong inversion, with about 80% of the atoms being excited, and study their subsequent radiative decay into the guided modes. The data is very well described by a simple model that assumes a cascaded interaction of the guided light with the atoms. Our results contribute to the fundamental understanding of the collective interaction of light and matter and are relevant for applications ranging from quantum memories to sources of nonclassical light to optical frequency standards.

Presenter name: Christian Liedl

Poster session / We-59:   *Quant. optics & hybrid quant. sys.*   ID70

On-chip trapped cold atom interferometer with spatial splitting

Authors: Benjamin Witschafter[1]; C. I. Westbrook[2]; Matthieu Dupont-Nivet[1]

[1] *Thales*

[2] *LCF*

Since the 90's, many laboratories have developed atom interferometers to sense accelerations and rotations [1]. For many applications, small compact devices are desirable, and the atom chip [2] appears to offer a path towards miniaturization. Moreover, performing the interferometry sequence on-chip with trapped atoms decouples the sensitivity of the sensor from its size, allowing in principle, larger interrogation times while shrinking the device's size. It has been shown that accelerations can be sensed from a Ramsey's interferometer by spatially splitting the two states of the atoms during the interrogation time [3]. This can be done by separating the two states, using state selective, near-field microwave gradients from a coplanar waveguide [4,5].

We have recently demonstrated state-selective displacements of a two component thermal cloud using coplanar waveguides. The separation of the internal states is several microns and we have observed interference fringes upon recombination showing that the separation was coherent. We have also studied the fringe contrast as a function of cloud temperature.

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[3] Dupont-Nivet et al., New J. Phys. 18 113012 (2016)
[4] Ammar et al., Phys. Rev. A, 91:053623 (2015)
[5] Böhi et al., Appl. Phys. Lett. 97, 051101 (2010)

Presenter name: WIRTSCHAFTER Benjamin

Poster session / We-60:   *Quant. optics & hybrid quant. sys.*   ID82

Quantum nonlinear optics in atomic dual arrays

Author: Simon Panyella Pedersen[1]

Co-authors: Lida Zhang [1]; Thomas Pohl [1]

[1] *CCQ, DPA, AU, DK*

Sub-wavelength arrays of atoms have been shown to have remarkable optical properties, like near perfect reflection and low diffraction loss. However, the collective effects resulting in these properties also serve to wash out the otherwise strong underlying nonlinearity of the atoms, rendering the arrays largely linear. We have found that by putting together two arrays we can recover a strong nonlinearity via an emergent cavity-like behaviour with a large delay time that allows photons to interact strongly before being emitted from the system. Such a quantum metasurface opens up new possibilities for manipulating nonclassical light, from implementing quantum information operations to simulating many-body physics with interacting photons.

Presenter name: Simon Panyella Pedersen

Poster session / We-61: *Quant. optics & hybrid quant. sys.* ID181

Tracking the vector acceleration with a hybrid quantum accelerometer triad

Author: Brynle Barrett[1]

Co-authors: Simon Templier [2]; Pierrick Cheiney [2]; Quentin d'Armagnac de Castanet [3]; Baptise Gouraud [2]; Henri Porte [2]; Fabien Napolitano [2]; Baptiste Battelier [3]; Philippe Bouyer [3]

[1] *University of New Brunswick*

[2] *iXblue*

[3] *LP2N*

Robust and accurate tracking of acceleration remains a challenging problem in many fields. For geodesy, geophysics or underground exploration, precise mapping of gravity requires the use of onboard gravimeters or gradiometers as well as inertial navigation systems to compute accurate positioning information from classical accelerometers and gyroscopes. Quantum sensors based on cold-atom interferometry hold enormous potential to provide such high-precision instruments. However, these inherently scalar sensors must be precisely aligned with the acceleration vector of interest. In this work, we present the first three-axis accelerometer exploiting the quantum advantage to measure the full acceleration vector (magnitude and direction). We demonstrate a high data rate (1 kHz) sensor with a magnitude accuracy below 10 μg, and a pointing accuracy of 4 μrad relative to each axis. This is achieved by sequentially applying three atom interferometer sequences along the mutually-orthogonal axes of a triad. By integrating navigation-grade classical accelerometers on each axis, we construct a compact and robust hybrid vector accelerometer. We characterize the ultra-low bias of our triad and track the gravitational acceleration vector over long timescales. We demonstrate a stability of 6×10^{-8} g on the vector norm after 24 h. This corresponds to a 50-fold improvement over that provided by our classical accelerometers. This paves the way toward future strapdown applications with quantum sensors and highlights their potential as future high-grade, inertial navigation units.

Presenter name: Brynle Barrett

Conditions for superluminal light propagation in a three-level medium

Authors: Piotr Gładysz[1]; Szymon Pustelny[2]; Karolina Słowik[1]

[1] *Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Toruń, Grudziadzka 5, 87-100 Torun, Poland*

[2] *Institute of Physics, Jagiellonian University, Łojasiewicza 11, 30-348 Kraków, Poland*

The investigation of propagation of pulses in optically dressed media is one of the most basic problems in optics. I will analyze a new superluminal propagation regime in the ladder-type three-level systems near a two-photon resonance where an anomalous dispersion appears accompanied by a small absorption. These conditions are necessary to achieve group velocities greater than the speed of light in a vacuum ($v_g > c$) or negative ($v_g < 0$). In order to achieve these conditions, previous works exploited population inversion, additional fields, and complicated level configurations. Here, I will demonstrate superluminality can be reached through a relatively simple scenario.
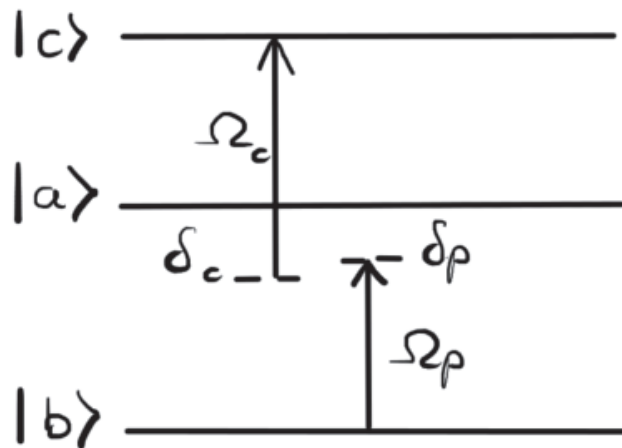
Figure 1: Ladder-type three-level system with marked probe and control fields, and detunings $\delta_p = \omega_{ba} - \omega_p$ and $\delta_c = \omega_{ac} - \omega_c$. The two-photon-resonance condition reads $\delta_p + \delta_c = 0$.

Our model is a one-dimensional medium consisting of three-level systems with the energy levels configuration sketched in Fig. 1. There are electric-dipole-allowed transitions $|b\rangle \to |a\rangle$ with an energy $\hbar\omega_{ba}$, $|a\rangle \to |c\rangle$ with an energy $\hbar\omega_{ac}$ and an electric-dipole-forbidden transition $|b\rangle \not\to |c\rangle$. The lower levels are coupled by the probe field $\Omega_p(z, t)$ (with carrier frequency ω_p), and the upper ones are driven by the control field $\Omega_c(z, t)$ (with carrier frequency ω_c). I will show that to establish the best performance we have to set δ_c to be hundreds of times greater than the width of the energy levels so we are far from the influence of the single-photon resonance.

In the numerical simulations, we chose a real-life example of rubidium vapor in a $L = 5$ cm long cell well approximated by a one-dimensional model. To optimize the conditions for superluminal propagation in terms of the control field properties δ_c, Ω_c, we introduce the parameter

$$\beta(\delta_c, \Omega_c) = \left(1 - \min_{\delta_p}(n_g(\delta_p, \delta_c, \Omega_c))\right)\left(e^{-\frac{\omega_p}{2c}\chi_{ab}(\delta_p^{\min}, \delta_c, \Omega_c)L}\right)^4,$$

where n_g is the group index (related to group velocity by the formula $v_g = c/n_g$) and χ_{ab} is the electric susceptibility of the medium. The left bracket simply maximizes group velocity

in the given conditions while the right one describes absorption. The forth power forces absorption to be no more than 20% to prevent pulse distortions.

As a result, we come up with Fig. 2a where the greater the value of the parameter β, the better the superluminal conditions. The point for which we analyze the propagation in Fig 2b and 2c is marked with the white plus sign. We consider an input Gaussian pulse with the carrier frequency near two-photon resonance. Fig. 2b shows pulse shapes at the end of the sample for several detunings δ_p selected to be near two-photon resonance, and indeed, the absorption is limited as expected. Finally, in Fig. 2c, we have group index as a function of detuning δ_p, hence, we have evidence that near the two-photon resonance superluminal propagation occurs as n_g values are well below one (grey region).

In my contribution, I will present a more comprehensive discussion of superluminal propagation regimes.
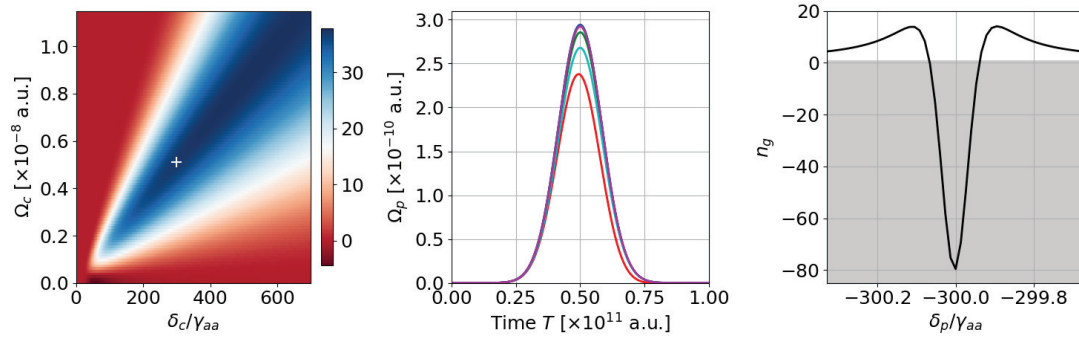
Figure 2: a. Auxiliary parameter $\beta(\delta_c, \Omega_c)$ with a point chosen for further investigation marked by a plus sign. Control field detuning is presented in units of the middle-level width γ_{aa}. b. Shapes of the probe pulses at the end of the sample for several detuning values (different colors) near two-photon resonance. c. Group index as a function of detuning of the probe field. The gray area indicates the superluminal regime.

Presenter name: Piotr Gładysz

Poster session / We-63: *Quant. optics & hybrid quant. sys.* ID264

How much time do resonant photons spend as atomic excitations before being transmitted?

Authors: Kyle Thompson[1]; Kehui Li[1]; Daniela Angulo Murcillo[1]; Vida-Michelle Nixon[1]; Josiah Sinclair[2]; Howard Wiseman[3]; Aephraim Steinberg[1]

[1] *University of Toronto*

[2] *MIT*

[3] *Griffith University*

When a single photon traverses a cloud of 2-level atoms on resonance, how much time does it spend as an atomic excitation, as measured by weakly probing the atoms? It turns out that the answer, on average, is simply the spontaneous lifetime, multiplied by the probability of the photon being scattered into a side mode. It is tempting to infer from this that photons that are scattered spend, on average, one spontaneous lifetime as an atomic excitation, and photons that are transmitted through the cloud spend no time at all as an atomic excitation. Our recent experimental work [PRX Quantum 3, 010314] shows that this inference is incorrect, and that transmitted photons do spend time as atomic excitations. However, a complete theoretical treatment of the open-system dynamics for such a system has never, to our knowledge, been carried out. We examine this problem using the weak-value formalism, and find that the time that a transmitted photon spends as an atomic excitation is equal to the group delay experienced by the photon. Surprisingly, this equivalence remains true even for resonant, narrowband photons, for which the group delay is negative. We also determine the corresponding time for scattered photons, which turns out to be related to the "Wigner time" associated with elastic scattering. This work provides insight into the complex histories of photons travelling through absorptive media.

Presenter name: Kyle Thompson

Poster session / We-64:   *Quant. optics & hybrid quant. sys.*   ID303

Error budget in cold atom-based inertial sensors

Authors: Nikolaos Dedes[1]; Joel Abraham [1]; Max Carey[1]; Jack Saywell[1]; Ilya Kuprov[1]; Tim Freegarde[1]

[1] *University of Southampton*

Cold Atom-based technology promises a new generation of navigation systems potentially suitable for Global Navigation Satellite System-denied environments. However, despite the promise of superior inertial navigation capabilities, a correct identification and quantification of the errors must be carried out to assess what and how system parameters affect the sensor performance. In this context, sensitivity function represents a theoretical tool that allows to quantify the output of a Cold Atom-based Inertial Sensor in terms of scale factor, bias, and noise. As a result of time-dependent perturbation theory, the sensitivity function can be used to link quantum optimal control and Bloch sphere picture, thus enabling the design of tailored Raman beam-splitter pulses resilient to phase dispersion errors.

Presenter name: Nikolaos Dedes

Poster session / We-66:   *Quant. optics & hybrid quant. sys.*   ID379

Dicke superradiance and photon statistics in waveguide QED

Authors: Silvia Cardenas-Lopez[1]; Stuart Masson[1]; Zoe Zager[1]; Ana Asenjo-Garcia[1]

[1] *Columbia University*

Dicke superradiance is a phenomenon where atoms at an identical location synchronize and collectively emit photons in a short, bright burst. We investigate the many-body decay of an extended array of atoms coupled to a one-dimensional optical channel. We show that Dicke superradiance in waveguides is intrinsically different from superradiance in cavities and free space, as there are two distinct decay channels competing with each other. We derive the minimal condition for the burst to happen as a function of the number of atoms, the interatomic distance, and decay rates into the waveguide and nonguided modes. The existence of two decay channels gives rise to the creation of dark states in the few-excitation subspace. Exotic probability distributions for the emitted photons emerge: while the first photon is emitted randomly to the left or to the right, correlations imprinted on the array enhance the possibility of a subsequent photon to be emitted in the same direction, yielding an avalanche process. These results are relevant to current experiments in waveguide QED with cold atoms coupled to nanofibers and superconducting qubits coupled to transmission lines.

Presenter name: Silvia Cardenas-Lopez

Poster session / Th-57:   *Quant. optics & hybrid quant. sys.*   ID6

Thermodynamics in nonequilibrium atom-field interactions

Author: Daniel Reiche[1]

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Modern quantum sensors on the basis of ultra-cold atoms allow for an unprecedented experimental accuracy and have shown to be useful in fundamental science and real-world applications alike. With the advent of integration and miniaturization of such systems, the shrinking dimension of the setup leads to an increasing impact of the environment on the atoms' dynamics.

To name only a few examples, thermal and quantum fluctuations, fluctuating-near-fields in the vicinity of a surface, or decoherence due to system+bath coupling will fundamentally limit the uncertainty of the experiment.

We explore the use of stochastic methods, i.e. the quantum Langevin equation, to describe the fundamental uncertainties in nonequilibrium atom-field interactions. To this end, we determine thermodynamic quantities such as dissipated power or the density matrix of the evolving system which can ultimately lead to a concise quantification of fundamental uncertainties. Our approach can be of use in the design and interpretation of future generations of quantum sensors.

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Presenter name: Daniel Reiche

Poster session / Th-58: *Quant. optics & hybrid quant. sys.* ID34

Observation of a continuous time crystal

Authors: Hans Keßler[1]; Phatthamon Kongkhambut[1]; Jim Skulte[1]; Ludwig Mathey[1]; Jayson G. Cosme[2]; Andreas Hemmerich[1]

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[2] *National Institute of Physics, University of the Philippines*

Time crystals are classified as discrete or continuous depending on whether they spontaneously break discrete or continuous time translation symmetry. While discrete time crystals have been extensively studied in periodically driven systems since their recent discovery, the experimental realisation of a continuous time crystal [1,2] is still pending. We report the observation of a limit cycle phase in a continuously pumped dissipative atom-cavity system [3], which is characterized by emergent oscillations in the intracavity photon number. We observe that the phase of this oscillation is random for different realisations, and hence this dynamical many-body state breaks continuous time translation symmetry spontaneously. The observed robustness of the limit cycles against temporal perturbations confirms the realisation of a continuous time crystal.

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Presenter name: Hans Keßler

Poster session / Th-59:   *Quant. optics & hybrid quant. sys.*   ID51

Manipulating and measuring states of an optomechanical resonator in the quantum regime

Authors: Yiqi Wang[1]; Yogesh Patil[2]; Jiaxin Yu[1]; Jakob Reichel[3]; Jack Harris[2]

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[2] *Department of Physics, Yale University*

[3] *Laboratoire Kastler Brossel, ENS-Université PSL*

Macroscopic mechanical devices in the quantum regime can play a key role in quantum communication, quantum sensing and fundamental tests of quantum mechanics. We use a fiber cavity filled with superfluid ^{4}He of mass ~ 1 ng as our mechanical resonator. Leveraging single photon counting techniques, we manipulate and probe the motional state of a superfluid ^{4}He resonator. The arrival times of Stokes and anti-Stokes photons are used to measure the resonator's phonon coherences. We demonstrate the coherences of a thermal state near the motional ground state, a nonclassical photon-phonon squeezed state, and a high amplitude coherent state in this superfluid ^{4}He resonator. These measurements pave the avenue of realizing a nonclassical state in a milligram resonator in future experiments.

Presenter name: Wang, Yiqi

Dynamical phases of matter in a periodic driven atom-cavity system

Authors: phatthamon kongkhambut[1]; Jim Skulte[2]; Ludwig Mathey[2]; Jayson G. Cosme[3]; Hans Keßler[4]; Andreas Hemmerich[2]

[1] *Institut für Laser-Physik, Universität Hamburg, Germany*

[2] *Institut für Laser-Physik, Universität Hamburg*

[3] *National Institute of Physics, University of the Philippines*

[4] *Universität Hamburg*

We report realizations of various dynamical hybrid light-matter phases, as a discrete dissipative time crystal [1], dynamical bond density wave phase [2-4], and limit cycle phase [5], by strongly coupling an atomic quantum gas to the light field of an optical cavity. The key feature of the cavity is a very small field decay rate ($\kappa/2\pi = 3.6$kHz), which is in an order of the recoil frequency ($\omega_{rec}/2\pi = 3.6$kHz). This leads to a unique situation where cavity field evolves with the same timescale as the atomic density distribution, which is called a recoil resolved regime. For standing wave pumping, transversely with respect to the cavity axis, the system undergoes a phase transition from a normal homogeneous phase to a superradiant self-organization phase, accompanied by spontaneously breaking of Z2 symmetry. Modulating the amplitude of the pump field leads to the realization of a dissipative discrete time crystalline phase, whose signature is a rigid sub-harmonic oscillation between the two symmetry broken states [1]. On the other hand, shaking the pump potential by modulating the phase of the pump field give rise to an incommensurate time crystalline phase [3], whose dynamics can be captured by a nonstandard three-level Dicke model [2, 4]. The phase modulation can also be used to create a dark state by transferring the atoms to the $p-$band of the system, which has an anti-symmetric parity of the condensate wave function, and hence, the atoms decouple from the cavity field.

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Presenter name: Phatthamon Kongkhambut

Poster session / Th-61:   *Quant. optics & hybrid quant. sys.*   ID104

Dicke superradiance in arrays of multilevel atoms

Authors: Stuart Masson[1]; Ana Asenjo-Garcia[1]

[1] *Columbia University*

We investigate the physics of Dicke superradiance with multilevel atoms. Dicke superradiance is a dissipative many-body phenomenon where excited atoms collectively emit a short and intense burst of light. While this physics is well understood for two-level systems in a cavity, our work involves extended arrays of multilevel atoms in free space. In previous work, we showed that Dicke superradiance generically occurs for two-level systems in arrays, provided that the distance between them is sufficiently small. Here, we consider atoms that can decay into multiple states and show that a superradiant burst can be emitted on all transitions. We develop constraints on the relative rates of each transition, and on the geometry of the atomic ensemble, and show that the intensity emitted in particular directions features a superradiant burst in arrays of large interatomic spacing. Our results provide a guide to explore this many-body phenomenon in state-of-the-art experimental setups.

Presenter name: Stuart Masson

Poster session / Th-62: *Quant. optics & hybrid quant. sys.* ID187

Time-delayed optical feedback to a cold atom ensemble

Authors: Maarten Hoogerland[1]; Mohammad Sadeghi[1]

[1] *The University of Auckland*

The interaction of quantum systems with themselves has been the subject of extensive theoretical[1] and experimental investigations [2,3]. Here, we present new results on the interaction of an ensemble of cold atoms with a time-delayed version of its own spontaneous emission light.

Experimentally, we form a magneto-optical trap (MOT) of caesium atoms around the waist of an optical nanofibre (diameter ~400 nm). One end of the nanofibre terminates in a single-photon detector module (SPCM) and the other end is connected to a 250 m length of normal optical fibre and terminated with a Fibre Bragg Grating (FBG). After accumulating the desired number of atoms, the MOT trapping beams are turned off, and the ensemble is illuminated with a train of short pulses (pulse duration ~200 ns) of an external pump beam, close to resonance with the D_2 transition in caesium and intersecting the optical nanofibre at right angles. We detect the arrival times of the spontaneous emission photons into the optical nanofibre.

We observe photons emitted directly towards the SPCM, but also photons that have been emitted towards the FBG, are reflected back, interact with the atoms again and arrive at the detector after a time delay. The delayed photons are partially absorbed by the MOT atoms, thereby creating a system of atoms interacting with a distant mirror image [3].

We present an investigation into this interaction, changing the pump laser power, polarisation and detuning, as well as the atom number in the MOT. We also investigate the interaction of the spontaneous emission photons with excited atoms by matching the repetition time of the short pulses to the flight time of the photons going to the FBG and back.

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Presenter name: Maarten Hoogerland

Poster session / Th-63:   *Quant. optics & hybrid quant. sys.*   ID251

Sagnac atom interferometer gyroscope with large enclosed area and multiple orbits

Authors: Cass Sackett[1]; Edward Moan[1]; Marybeth Beydler[1]

[1] *University of Virginia*

Sagnac atom interferometers are a promising technique for high-performance rotation sensing, with potential applications for inertial navigation. The use of trapped atoms for the interferometer avoids the need for long free-fall distances that would be incompatible with a navigation apparatus. We have previously demonstrated a dual Sagnac interferometer using Bose-condensed atoms in a time-orbiting potential trap. We report here on improvements to this approach, including a 3-fold increase in the orbit radius and the use of multiple orbits. These improvements lead to an enclosed area of 8.2 mm^2, which corresponds to a rotation sensitivity of 6×10^{-7} rad/s at shot-noise-limited detection. While shot-noise-limited performance has not yet be achieved, the interferometer operation is sufficiently stable to permit useful averaging times longer than 10^4 s. We also discuss a new, more compact, version of the apparatus that is based on an atom chip and which will be suitable for environmental testing.

Presenter name: Marybeth Beydler

Poster session / Th-64: *Quant. optics & hybrid quant. sys.* ID288

Creating and measuring sub-wavelength volumes using quantitative absorption imaging of optically dense ensembles

Authors: Romain Veyron[1]; Jean-baptiste Gerent[2]; Guillaume Baclet[1]; Vincent Mancois[1]; Philippe Bouyer[1]; Simon Bernon[3]

[1] *Laboratoire de photonique numérique et nansciences*

[2] *LP2N - Université de Bordeaux - CNRS*

[3] *University Bordeaux*

Quantum gas microscopes have become a major element for quantum simulations using ultra-cold atoms in optical lattices. They are for example used to observe long-range order such as anti-ferromagnetic correlations in far field optical lattices using density and spin resolved microscopy. Decreasing the period of such lattice offer interesting perspective to increase atom-atom interaction energies and engineer atom-light coupling that our group tackles via the hybridization of cold atoms and nano-structured surfaces.

In this poster, we will present how such type of sub-wavelength lattice potentials can be generated by trapping atoms in proximity (tens to hundreds of nanometers) of a nano-structured surface. At such atom to surface distance, the attractive Casimir-Polder force can be compensated by a doubly dressed state trapping method that I will discuss. Such method additionally offers solutions to overcome the diffraction limit of conventional imaging that become critical for sub-wavelength lattices. In this work, I will present the experimental characterization of a sub-wavelength resolution absorption imaging applicable to quantum gas detection. This method requires a quantitative determination of the atom number of dense clouds which has been characterized in this work and demonstrate that the scattering cross section reduces linearly with the optical density. Modelling the propagation of light in dense cloud we show that this reduction can be attributed to re-scattering of the incoherent part of the resonant fluorescence spectrum.

The poster will additionally present an update on our recent work on the spectroscopy of Acetylene in sealed hollow core fibers.

Presenter name: Simon Bernon

Poster session / Th-65: *Quant. optics & hybrid quant. sys.* ID310

An atomic Fabry-Perot for the generation and measurement of ultracold wavepackets

Authors: Nick Mantella[.]; Joseph McGowan[1]; Harshil Neeraj[1]; David Spierings[1]; Aephraim Steinberg[1]

[1] *University of Toronto*

A matter-wave Fabry-Perot (FP) for the generation of ultracold wavepackets could be implemented using an optical double barrier. Observation of the transmission spectrum of a single such FP becomes impractical for wavepacket temperatures above about 100pK. The resonances are washed out due to the velocity width of the incident wavepacket being larger than the width of the resonances. We propose a scheme for using a second atomic FP with a tunable cavity length to characterize the filtering properties of the first. Gross-Pitaevskii (GP) simulations of a 87Rb BEC interacting with double-Gaussian potentials show that evidence of resonant transmission can be observed using this scheme. The GP simulations use experimentally achievable parameters of a 1nK 87Rb BEC of a few thousand atoms, incident on barriers with a $1/e^2$ radius of 1.3 μm. With these parameters, BECs containing a few hundred atoms could be generated at a temperature less than 50pK. We plan to realize this scheme experimentally using a spatial light modulator to manipulate the optical potential for the tunable cavity length matter-wave FP.

Presenter name: Nick Mantella

Poster session / Th-66: *Quant. optics & hybrid quant. sys.* ID336

Optical switching of an atomic Bragg mirror around a nanofiber

Authors: Jérémy Berroir[1]; Tridib Ray[2]; Alban Urvoy[2]; Julien Laurat[2]

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[2] *Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-PSL, Collège de France, 75005 Paris, France*

In the recent years, the use of nanoscale waveguides providing tight transverse confinement of light has been pushed forward in the waveguide-QED field as a mean to enhance atom-photon interactions for large number of atoms. On our experiment, we use a two-color dipole trap scheme to interface cold Cesium atoms with the evanescent field of a tapered optical nanofiber. By tuning the properties of the dipole trap, we arrange the atoms in a 1D lattice geometry with controllable distance between them.

In the past, we used this platform to demonstrate an all-fibered optical memory at the single-photon level using dynamical electromagnetically-induced transparency (EIT) [1]. We also investigated collective behaviors in such 1D chains of trapped atoms. We demonstrated up to 80% Bragg reflection with as low as 2000 atoms when carefully tuning the interatomic distance [2]. More recently, we heralded the creation of a single collective excitation in the atomic chain, which was subsequently stored and retrieved as a single photon in the guided mode of the nanofiber [3]. We also theoretically studied the collective dynamics of cavity-QED-like atomic arrangements in both markovian and nonmarkovian regimes [4].

A strong motivation is also to reach quantum nonlinearity at few-photon levels. In this context, controlling the propagation of a single photon with powers at the single-photon levels in cavity-free platforms has been studied in few systems [5], and still remains an important milestone for the community. Here, we report on guided optical switching and routing of single-photon level coherent fields using an atomic Bragg mirror controlled by very low energy fields. Focusing first on the regular three-level setup, we switch the reflection and the transmission paths of a Bragg mirror using EIT. The control beam is guided and contains around few thousand photons. In order to push this number even lower, we employ a four-level scheme consisting of the previous scheme to which we add an additional level coupled with the metastable state by a switch field. We demonstrate optical switching with a switch field at the few-tens of photons level, thus reducing by one to two order of magnitude the number of photons needed. Routing, or controlled directionnality of the probe photon, is also achieved using the same four-level scheme with a switch field at at the few hundred photons level.

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Presenter name: Jérémy Berroir

Poster session / Th-67:   *Quant. optics & hybrid quant. sys.*   ID384

Quantum correlated light beams from cascade four-wave mixing in cold atoms

Authors: Gabriel C. Borba[1]; Raoni S. N. Moreira[2]; Marcelo Martinelli[1]; Daniel Felinto[2]; José W. R. Tabosa[2]

[1] *Universidade de São Paulo*

[2] *Universidade Federal de Pernambuco*

Optical parametric amplifiers are known in the literature as a tool for the generation of quantum correlated beams. Forward four-wave mixing (FWM) with gain factors on the order of 10 associated with strong intensity squeezing [1] is behind, for example, the generation of entangled fields [2].

In this work, we explore both the internal and external atomic degrees of freedom to demonstrate the observation of giant gain and parametric oscillation in multiple FWM processes in a sample of cold cesium atoms. The parametric probe-beam amplification exceeds 2000 and is accompanied by the generation of three other beams of equivalent power emitted along the directions satisfying the phase-matching conditions for multiple cascade forward and backward FWM [3, 4].

The quantum correlations among these fields are investigated by combining in-quadrature electronic local oscillators and heterodyne detection, allowing the measurement of the fields' quadratures and the reconstruction of the covariance matrix.

Also, a full Liouville–Maxwell equations calculation in the extended Hilbert space of the internal and external atomic degrees of freedom allows us to obtain, from first principles, the four-wave propagation equations.

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Presenter name: Gabriel C. Borba

Virtual poster / Vir33:   *Quant. optics & hybrid quant. sys.*   ID93

Strong chiral coupling of an atomic array in nanophotonic cavity

Authors: Wei Seng Hiew[1]; Hsiang-Hua Jen[2]

[1] *National Taiwan University*

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A nanophotonic cavity system strongly coupled to one or multiple neutral atoms is a very useful platform for the quantum information processing. Single qubit control and entanglement between two qubits on this system has been experimentally realized recently based on the fact that the number of atoms coupled to this system has distinct reflectivity spectrum. Here we theoretically studied the effect of spin exchange interaction along chiral waveguide in this system to understand the collective effect of neutral atoms on the reflectivity spectrum. Furthermore, we discovered that in some nonreciprocal chiral cases the coupling between the atoms and cavity has no effect on the reflectivity spectrum due to cancelling caused by the space-dependent spin exchange interaction. We also studied the properties of the reflectivity spectrum as the number of atoms coupled to this system is increased.

Presenter name: Hiew Wei Seng

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Slow atoms traverse an optical cavity field: diffusive atomic motion

Authors: Taegyu Ha[1]; Dowon Lee[1]; Donggeon Kim[1]; Jinuk Kim[1]; Changsuk Noh[2]; Kyungwon An[3]; Moonjoo Lee[1]

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[2] *Department of Physics, Kyungpook National University, 41566 Daegu, Korea*

[3] *Department of Physics and Astronomy & Institute of Applied Physics, Seoul National University, 08826 Seoul, Korea*

We investigate the atomic motion while single, laser-cooled ^{87}Rb atoms propagate through a high-finesse cavity. Generating a cold trapped atomic ensemble 4-mm above the cavity [J. Kim, K. Kim *et al.*, Sensors 21, 6255 (2021)], the trap is released, and single atoms fall through the resonator mode by gravity. Strong atom-cavity interaction causes large decreases in the transmission of a weak resonant probe field. In order to understand the various magnitudes of the transmission reduction, we perform numerical calculation of the Itô stochastic differential equations for atomic motion [A. Doherty *et al.*, Phys. Rev. A 63, 013401 (2000)]. The calculation shows that the atomic trajectory is strongly diffusive along the cavity axis, which averages the spatially modulated atom-cavity coupling constant in this direction. Therefore, we would attribute the atom-by-atom difference of the transmission change to the different atomic arrival position along the transverse mode direction.

In addition, we demonstrate a dipole trap of single atoms with an intracavity field. We also present a precise characterization of our optical resonator, resulting in the estimation of the atom-cavity coupling constant up to four significant figures [D. Lee *et al.*, Opt. Continuum 1, 603 (2022)].
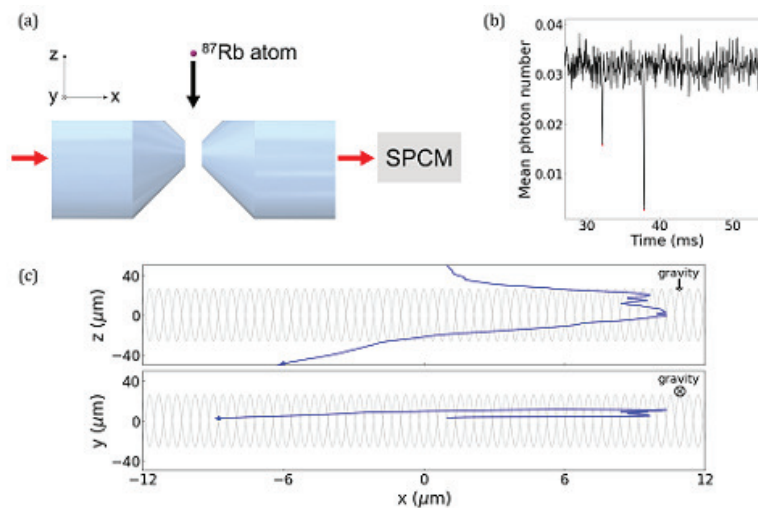
Figure 1:

Figure 1 (a) Experimental setup. Single Photon Counting Module (SPCM). (b) Probe transmission drops when single atoms traverse the resonant cavity mode. (c) Simulation result of atomic trajectory.

Presenter name: Taegyu Ha

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Virtual poster / Vir35:   *Quant. optics & hybrid quant. sys.*   **ID186**

Fano-Lorentz shape controlled by the collective effect of the nuclear ensemble

Authors: Tian-Jun Li[.]; Lin-Fan Zhu[1]

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Synopsis The asymmetric profiles of Fano interference in the thin-film planar cavity have been studied by changing the nuclear abundance. It is found that the resonant nuclear resonance seems to be unexcited superficially at a critical nuclear abundance in the overcritical regime and the reflectivity shows a flat line. The mechanism behind the flat line is the controllable relative amplitude of the discrete state in the framework of destructive interference.

An ensemble of N static atoms can be excited into an entangled state by the photon field, resulting in some novel intriguing effects caused by the resonant dipole-dipole interaction, such as the directed spontaneous emission, subradiance as well as the collective Lamb Shift (CLS) that arise form the surreal virtual process within the atomic ensemble. Except for the unique phenomena, the collective effect of the atomic ensemble is also excepted, because the enhancement factor $\sqrt{N}$ is important in various systems.

Over the past decade, x-ray quantum optics thrives with the development of the high-brilliance synchrotron radiation and x-ray free electron laser (XFEL) [1-3]. Designed several nm-scale thickness layers and probed in the mrad grazing incidence, the thin-film planar cavity becomes one promising platform to study the x-ray photons-matter interaction and opens new avenue for the x-ray quantum optics [4,5].

In the present work, Fano interference influenced by the collective effect is investigated by intercalating the resonant Mössbauer nuclei (^{57}Fe) with various nuclear abundance in the thin-film planar cavity. By introducing the complex q, the asymmetric profiles in the overcritical and undercritical regimes are considered as the Fano-Lorentz type viz. the incoherent superposition between the normal Fano resonance and a Lorentz peak. In the framework of the Fano-Lorentz profile, the weight and its range of the normal Fano resonance are related to the collective effect of the nuclear ensemble and cavity regime, respectively. By adjusting the nuclear abundance, the undercritical cavity always has the symmetric peak at the cavity mode angle, while the transformation among the symmetric peak, flat line, and valley is observed in the overcritical cavity. As for the flat line, it corresponds to a critical nuclear abundance where the resonant nuclear ensemble seems to be unexcited superficially. From the viewpoint of destructive interference, this interesting phenomenon is explained self-consistently by the controllable relative amplitude of the two pathways.

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Presenter name: Tian-Jun Li

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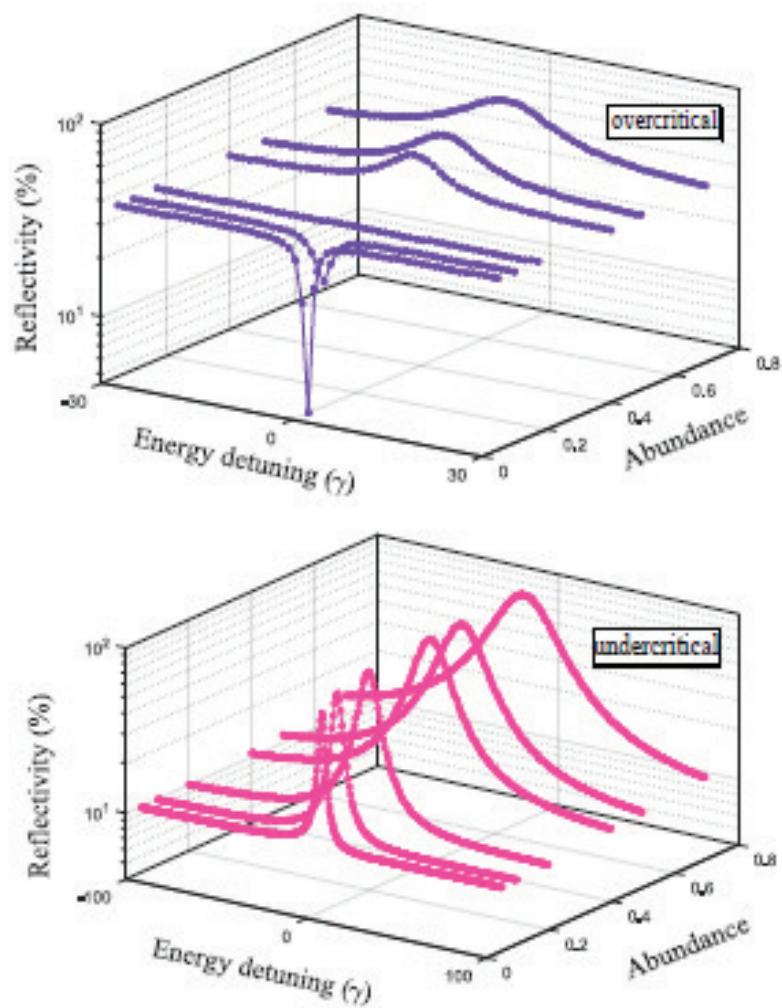
Figure 1: The Fano-Lorentz shapes adjusted by the nuclear abundance in the overcritical and undercritical regimes.

Virtual poster / Vir36:   *Quant. optics & hybrid quant. sys.*   ID211

The first observation of new flat line Fano profile via an x-ray planar cavity

Authors: Ziru Ma[1]; Xinchao Huang[1]; Tianjun Li[1]; Hongchang Wang[2]; Genchang Liu[3]; Zhanshan Wang[4]; Bo Li[1]; Wenbin Li[3]; Linfan Zhu[5]

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Fano formula, describing the ubiquitous interference between nonresonance continuum and resonant discrete state, is one of the most important formulas in modern physics [1,2]. As we all known, according to the real number of the line profile index q, the Fano profile can be divided into the symmetric and asymmetric line shape. In this work, we propose a new perspective on the regulation of Fano's line shape by modulating the Imaginary part of complex q-factor. We demonstrate that Fano interference not only has asymmetric and symmetric line, but also has flat-line cases that can be used to hide atomic resonance information when q taking the pure imaginary number of -1 in x-ray regime.

In the experiment, the dual-channel interferometer is constructed by embedding an X-ray planar cavity into an ultrathin atomic layer, in which the cavity and atoms reflect grazing-incidence X-rays to form tunable continuum and resonant discrete state channels, respectively [3,4]. By changing the thickness of Pt on the top layer of the planar cavity, the amplitude of the continuum channel can be controlled. The underlying mechanism is that the interference term in the scattering will cancel the discrete one exactly. This new Fano profile renders an only observable continuum along with an invisible response to the discrete state of atomic resonance.
Key words: Fano interferes, flat line, complex q, x-ray cavity

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Presenter name: Ziru Ma

Figure 1: The 2D maps of the reflectivity spectra vs. the energy and angle offset. (a-c) Reflectivity spectra of the samples with t_{top} as 0.0 nm, 1.0 nm, 2.2 nm, respectively. Panels (d-f) show the experimental results of (a-c), with the absorption edge being subtracted. Panels (g-i) show the calculations by quantum optics model. From the left to the right panels, the conversion from peaks to valleys is clearly observed at the corresponding mode angles (dashed lines).

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中国科学技术大学
University of Science and Technology of China

The first observation of new flat line Fano profile via an x-ray planar cavity

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INTRODUCTION

- Fano formula is universally used to depict the complex physical phenomena in many physical systems such as nuclear physics, atomic, molecular and optical physics. In Fano's original treatment, according to the value of real number q, the Fano profile can be divided into two types, i.e., the symmetric and asymmetric line shapes [1,2].
- Further researches revealed that q can take a complex number in quantum systems with decoherence [3]. Subsequent theoretical studies on the complex q demonstrate that a new type of Fano line shape of a flat line induced by the effect of the Im(q), which has never been verified experimentally due to the difficulties to manipulate Im(q) in a wide range [4].
- Here, the Im(q) was strong regulated using the thin film cavity, which is an outstanding system for manipulating the light-matter interaction in the x-ray regime, casts alternative light into the manipulatable two-path interference in both phase and the relative amplitude [5, 6].
- In this work, a new Fano profile of flat line is achieved experimentally by manipulating the relative amplitude of the continuum path with q taking the pure imaginary number of -1 in x-ray regime. The relative amplitude is controlled by changing the thickness of the top layer of the thin film cavity. The underlying mechanism is that the interference term in the scattering will cancel the discrete one exactly. This new Fano profile renders an only observable continuum along with an invisible response to the discrete state of atomic resonance.

THEORETICAL MODEL

- Schematic design of the thin-film planar cavity
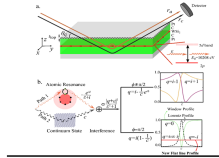
Fig. 1. (a) The two-path interferometer is built by an x-ray planar cavity with embedding ultrathin atomic layer. In the present work three cavity samples with different t_{top} as 0.0 nm, 1.0 nm and 2.2 nm are prepared. The reflectivity of the bare cavity (r_c) can be regarded as the continuum, while the reflectivity of the nuclear ensemble (r_a) is the discrete state. (b) Conception of the two-path interference mechanism. ϕ is the relative phase of the two paths. If $\phi = \pi/2$, q is a complex number. Fano interference spectrum is the asymmetric lines as shown in the top. If $\phi = \pi/2$, the parameter q is a pure imaginary number, and generally symmetric Lorentz line or window resonance is observed. when Im(q)$^2 = -1$, the spectrum becomes a flat line which is equal to the intensity of the continuum path.

After fixing the phase at the mode angle, the two-path interference is given as [6,7]

$$r_a = -c' \frac{\gamma_c}{\Gamma} \frac{i\Gamma}{\Delta + i\Gamma}$$
$$r_c = -1 + c'$$
$$r = r_a + r_c$$

Where γ_c is the enhanced emission rate arising from the cavity effect and superradiance. c' is the key factor in the present study whose value can be experimentally adjusted by changing the thickness of the top layer. Evidently, we can write $|r|^2$ as a Fano profile,

$$|r|^2 = \sigma \frac{|q + \varepsilon|^2}{\varepsilon^2 + 1} = \sigma \left(\frac{\varepsilon^2}{\varepsilon^2 + 1} + \frac{\text{Im}(q)^2}{\varepsilon^2 + 1} \right)$$

$$q = i\left(1 - \frac{1}{c}\right), \sigma = \left|c' \frac{\gamma_c}{\Gamma}\right|^2 c^2, c = \frac{c' - 1}{c'} \frac{\Gamma}{\gamma_c}$$

It can be seen clearly that the asymmetry parameter q is a pure imaginary and is determined by the relative amplitude c directly. Im(q) can be controlled by the manipulatable experimental factor c' directly because Γ/γ_c varies slowly. The three representative situations can be concluded as:

$$|r|^2 / \sigma = \begin{cases} \dfrac{\varepsilon^2}{1 + \varepsilon^2}, & \text{Im}(q) = 0, \text{ Window profile} \\ c^2, & \text{Im}(q) = -1, \text{ Constant} \\ \dfrac{1}{1 + \varepsilon^2}, & \text{Im}(q) = \pm\infty, \text{ Lorentz profile} \end{cases}$$
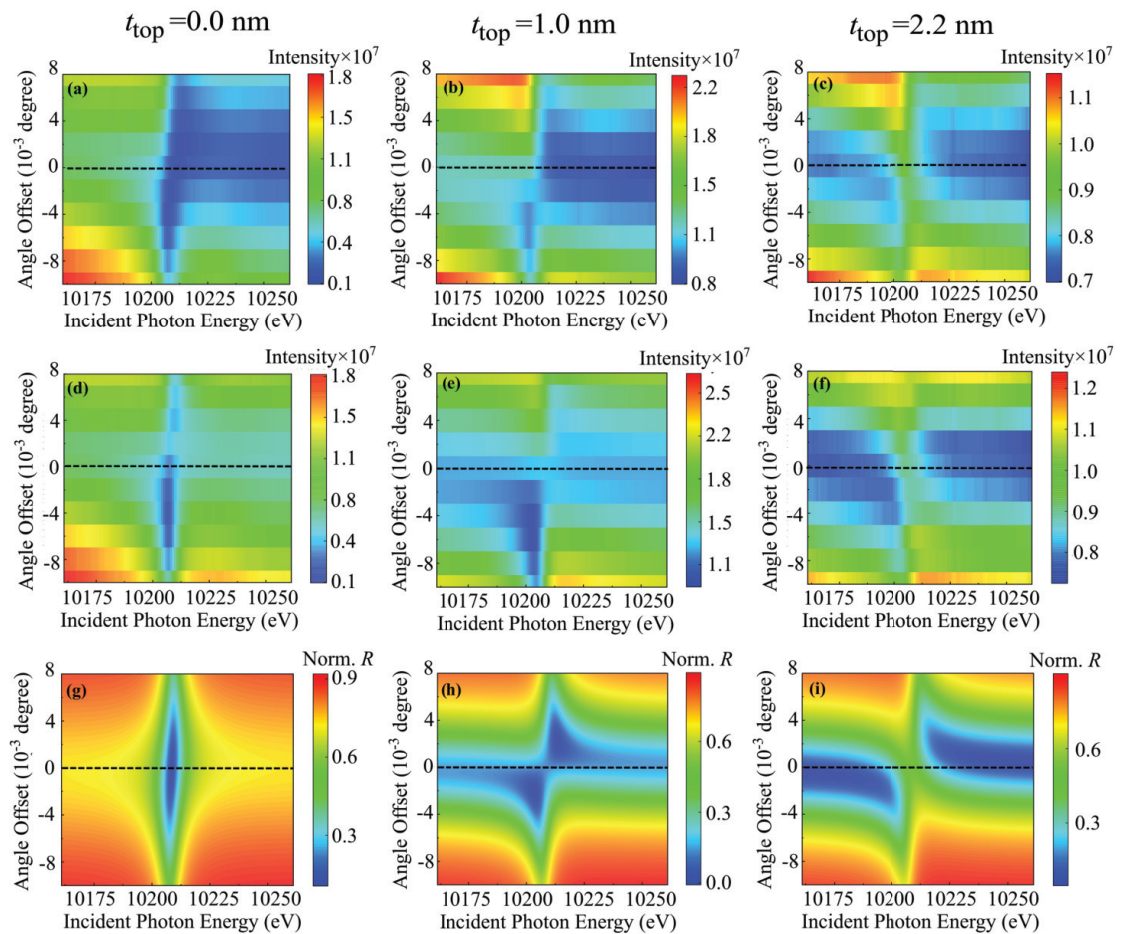
RESULTS AND DISCUSSION
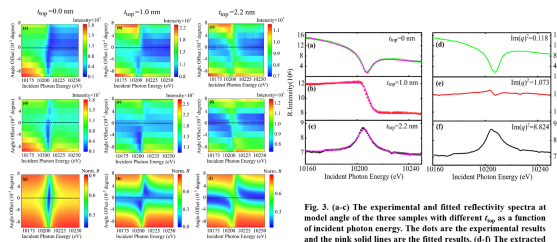
Fig. 2. The 2D maps of the reflectivity spectra vs. the energy and angle offset. (a-c) Reflectivity spectra of the samples with t_{top} as 0.0 nm, 1.0 nm, 2.2 nm, respectively. Panels (d-f) show the experimental results of (a-c), with the absorption edge being subtracted. Panels (g-i) show the calculations by quantum optics model. From the left to the right panels, the conversion from peaks to valleys is clearly observed at the corresponding mode angles (dashed lines).

Fig. 3. (a-c) The experimental and fitted reflectivity spectra at model angle of the three samples with different t_{top} as a function of incident photon energy. The dots are the experimental results and the pink solid lines are the fitted results. (d-f) The extracted results after discarding the contribution of the absorption edge.

The measurement was performed at the B16 Test beamline of the Diamond Light Source. The new type Fano profile of the flat line is realized experimentally for the first time based on the pure imaginary q modulation. The Fano interferometer used here is built by an x-ray planar cavity, in which the amplitude regulation of continuum path enlarges the Im(q) space. With the large range of Im(q), the window-Lorentz profiles conversion is observed experimentally and the new Fano profile of flat line emerges when the value of Im(q) is approaching to -1.

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Virtual poster / Vir37:   *Quant. optics & hybrid quant. sys.*   ID234

Composite picosecond control of atomic state through a nanofiber interface

Authors: Yudi Ma[1]; Ruijuan Liu[1]; Liyang Qiu[1]; Lingjing Ji[1]; Yimin Li[1]; Yanting Zhao[2]; Wei Fang[3]; saijun Wu[1]

[1] *Fudan University*

[2] *Shanxi University*

[3] *Zhejiang University*

Accurate control of single emitters at nanophotonic interfaces may greatly expand the accessible quantum states of coupled optical spins in the confined geometry and to unveil exotic nonlinear quantum optical effects. However, the optical control is challenged by spatially varying light-atom coupling strength generic to nanophotonics. We demonstrate numerically that despite the near-field inhomogenuity, nearly perfect atomic state control can be achieved by exploiting geometric robustness of optical transitions with composite picosecond excitations. Our proposal is followed by a proof-of-principle demonstration where an $N = 3$ composite sequence is applied to robustly invert the D1 population of free-flying ^{85}Rb atoms trespassing a nanofiber interface. The precise control is confirmed by comparing the D2 fiber transmission with full-level simulation of the mesoscopic light-atom interaction across the composite parameter space.

We project the scheme to large N for precise phase patterning and arbitrary optical dipole control at the nanophotonic interface.

Presenter name: Yudi Ma

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https://ultracontrol.fudan.edu.cn/_upload/article/files/f5/92/ad97144949b8a1d360a5c0d35f79/7203e3c7-78d9-4119-aa00-2f76d7dd593f.pdf

Virtual poster / Vir38: *Quant. optics & hybrid quant. sys.* ID236

Composite acousto-optical modulation

Authors: Liu Ruijuan[1]; Ma Yudi[1]; Ji Lingjing[1]; Qiu LiYang[1]; Ji Minbiao[1]; Tao Zhensheng[1]; Wu Saijun[1]

[1] *Fudan University*

Acousto-optical modulators are ubiquitously equipped in modern research labs across fields for modulation of amplitude, phase, frequency and propagation direction of light. Efficient AOM diffraction relies on phase-matching the light beams with the sound wave. Deviation of operation parameters from the pre-aligned Bragg condition leads to reduced diffraction efficiency and distorted diffraction phase, severely limiting the tuning range and control bandwidth in traditional AOM applications. Inspired by coherent control techniques for atom interferometry, we propose a new class of AOM techniques, by splitting a single Bragg-diffraction into an N-AOM process, for efficient diffraction beyond the Bragg condition and rapid modulation with close-to-unity efficiency. In a simplest 2-AOM example, we demonstrate rapid routing of a mode-locked laser output into two paths with >90% efficiency and 15 20 dB side pulse suppression. We further demonstrate coherent stacking of successive pulses for 1/4 repetition rate prescaling with nearly two-fold enhancement of peak power. With the unprecedented acoustic optical modulation efficiency and bandwidth combination, we expect the composite AOM technique to help paving a practical pathway toward arbitrary modulation of mode-locked lasers with up to GHz repetition rate.

Presenter name: Ruijuan Liu

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Virtual poster / Vir39:   *Quant. optics & hybrid quant. sys.*   ID243

High efficiency, coherent control of light with multipass acousto-optical modulation

Authors: Yuxiang Zhao[1]; Yudi Ma[1]; Saujun Wu[1]

[1] *Fudan University*

From laser cooling to light-pulse atom interferometry, precise control of light-atom interaction requires precise modulation of optical waveforms in the time-domain. To this end, Acousto-Optical Modulation (AOM) is uniquely powerful for achieving high speed, high contrast optical control. However, based on two-mode resonant Bragg diffraction, the AOM efficiency and bandwidth are prone to high-order and off-resonant perturbations. Here, following a recent work (arXiv:2110.15537), we propose and demonstrate a few new tricks to go beyond the traditional limits by modulating light with double-passing single AOMs. In the first setup, the AOM sound wave with frequency $f_S^{(0)}$ is re-imaged to itself after an optical delay of $L_d = c/f_S^{(0)}$. The setup coherently splits the Bragg-diffraction process into two. In this simple setup, we demonstrate diffraction efficiency as high as $\eta = 98\%$ for both $\pm 1^{st}$-orders, when the AOM is driven at merely a fourth of the regularly required rf power. Furthermore, we find the highly efficient diffraction is accompanied by extinction of the 0th order by 18 dB, thereby enabling efficient optical routing on demand. Finally, for the +1-order, we find the ω_S can be be deviate from $\omega^{(0)}$ substantially while maintaining $\eta > 80\%$. In the 2nd setup, we still re-image the AOM sound-wave to itself, but with the propagation direction of sound field reversed. In this case, we demonstrate high-contrast modulation of AOM output to support efficient routing of a synchronized mode-locked laser. In particular, the double-pass AOM pre-scales the repetition rate of the pulsed laser from $f_{\rm rep} = 4f_S^0/(2N+1)$ to $f_{\rm rep} = 2f_S^0/(2N+1)$, with close to unity efficiency and ~ 18dB side-pulse suppression efficiency. We discuss extension of the new method for synthesizing multifrequency optical waveforms by cascading arrays of multipass AOMs.

Presenter name: YuxiangZhao

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Virtual poster / Vir40:   *Quant. optics & hybrid quant. sys.*   ID252

Photon storage in an interrupted waveguide

Authors: David Johnson[1]; Lucia Hackermuller[1]; Nathan Cooper[1]; Daniele Baldolini[1]; Matt Overton[1]

[1] *University of Nottingham*

Cold atoms are useful for many quantum information applications. Their strong interactions with light give them many uses in atom-photon junctions. However, one difficulty with cold atoms is integrating them with waveguides and other photonic devices. Here we demonstrate a method that involves trapping the atoms inside a laser drilled hole through an optical fibre. By carefully selecting the geometry of the cavity, one can tune the transmission of light through it, with parabolic convex surfaces having the greatest transmission.

Once the atoms are trapped in the fibre, they can be used to demonstrate many interesting and useful phenomena. Our goal is to demonstrate electromagnetically induced transparency (EIT); which allows not just for control over the transparency of the atoms, but also leads to slow light effects and even photon storage.

Presenter name: David Johnson

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Virtual poster / Vir41: *Quant. optics & hybrid quant. sys.* ID273

A biased-rotation approach to efficient precise spinor matterwave Raman control

Authors: Liyang Qiu[1]; Saijun Wu[1]

[1] *Fudan University*

Fast and accurate Raman spinor matterwave control is key to implementing advanced quantum technology for quantum sensing, simulation, and computation. Typical Raman controls are achieved at large single-photon detunings, not only to avoid spontaneous emissions but also for reducing the differential Stark shifts. Our work focuses on moderate single-photon detuning where the universal rotations of atomic spinors by the Raman coupling are biased by a significant Stark shift at a fixed "biased angle". We demonstrate that within this "biased rotation" regime, composite pulses can be efficiently derived with simple SU(2) dynamics for their precise implementation to alkaline atoms on a hyperfine manifold. Our scheme fills the gap between related techniques in atom interferometry and trapped-ions for stark-shift compensation, enabling ultra-precise universal Raman spin-wave control within nanoseconds with moderate laser power.

Presenter name: Liyang Qiu

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Towards feedback cooling of a single trapped ion in a deep parabolic mirror

Authors: Atish Roy[1]; Martin Fischer[1]; Hans Dang[2]; Lakhi Sharma[1]; Markus Sondermann[3]; Gerd Leuchs[4]

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In applications in quantum technologies as well as in many experimental scenarios, the residual thermal motion of a trapped and laser cooled ion has detrimental effects, e.g. a reduction of the coupling to tightly focused light fields [1]. One possible method to cool the ion beyond the Doppler limit is feedback cooling [2]. Here, we apply feedback cooling in a set-up based on a deep parabolic mirror, exploiting the mirror's large collection efficiency [3]. The fluorescence signal collected by the parabolic mirror
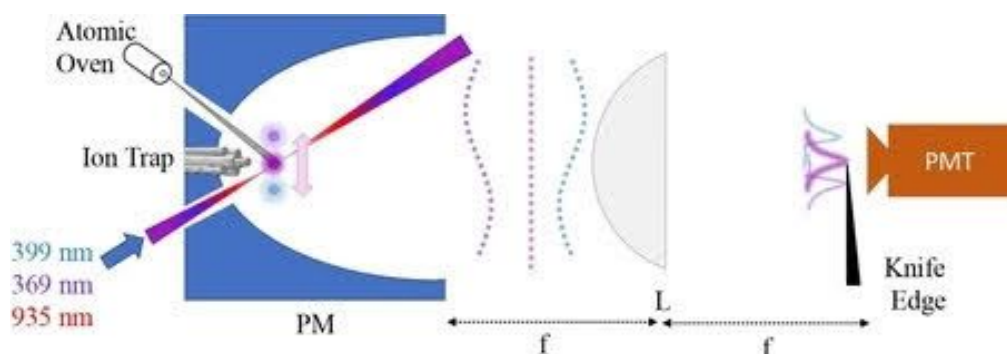
contains information of the position of the ion in its phase front. Upon Fourier transformation by a lens, this information is transformed to an intensity distribution with a shape and position governed by the shift of the ion off the focus of the parabolic mirror. Changes to this intensity distribution are measured using a knife edge and a photo multiplier tube, enabling direct detection of the secular motion of the ion. The detected signal is used to produce a feedback signal that is applied to one of the electrodes of the trap assembly. The phase and gain of this signal determines the amplitude of the feedback cooled ion's secular motion. We report on our progress towards lowering the ion's temperature below the limit set by Doppler cooling [4].

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Presenter name: Atish Roy

Poster session / Mo-64:   *Structure, properties of atoms, ions & mol.*   ID80

On the prospects of optical cycling in diatomic cations: Effects of transition metals, spin-orbit couplings, and multiple bonds

Authors: Pawel Wojcik[1]; Eric Hudson[2]; Anna Krylov[3]

[1] *USC*

[2] *Department of Physics and Astronomy, University of California Los Angeles*

[3] *Department of Chemistry, University of Southern California*

Molecules with optical cycling centers (OCCs) are highly desirable in the context of fundamental studies as well as applications (e.g., quantum computing) because they can be effectively cooled to very low temperatures by repeated absorption and emission (hence, cycling). Charged species offer additional advantages for experimental control and manipulation. We present a systematic computational study of a series of diatomic radical-cations made of a d-block metal and a p-block ligand, that are isoelectronic (in their valence shell) to the successfully laser-cooled neutral molecules. Using high-level electronic structure methods, we characterize state and transition properties of low-lying electronic states and compute Franck-Condon factors. The computed branching ratios and radiative lifetimes reveal that the electronic transitions analogous to those successfully used in the laser cooling of neutral molecules are less than optimal in the cations. We propose alternative transitions suitable for optical cycling and highlight trends that could assist future designs of OCCs in charged or neutral molecules.

Presenter name: Pawel Wojcik

Poster session / Mo-65: *Structure, properties of atoms, ions & mol.* ID165

Size-energy universality in van der Waals self-bound systems

Authors: Petar Stipanović[1]; Leandra Vranješ Markić[1]; Jordi Boronat[2]

[1] *University of Split, Faculty of Science, Split, Croatia*

[2] *Department of Physics, Universitat Politècnica de Catalunya, Barcelona, Spain*

A universal relationship between scaled size and scaled energy was explored in few-body systems[1,2,3]. Ground-state self-binding energies were obtained by the diffusion Monte Carlo method. Obtained energies support generalized Tjon lines. Structural properties were extracted by pure estimators[4], which proved successful in evaluating theoretical predictions of distribution functions[5] in comparison with the experimental Coulomb explosion imaging results[6,7].

Strengthening the inter-particle interaction, the exploration was extended from halo systems, which are extremely weakly bound and prefer to be in classically forbidden regions, to classical systems.

Universal size-energy law has been found for a homogeneous system of particles when pair-potentials decay predominantly with r^{-6}. The law is also valid for mixed systems with homogeneous-like structure.

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Presenter name: Stipanović, Petar

Poster session / Mo-66: *Structure, properties of atoms, ions & mol.* ID176

Mollow triplet in optically trapped single atom

Authors: Boon Long Ng[1]; Chang Hoong Chow[1]; Christian Kurtsiefer[1]

[1] *Centre for Quantum Technologies*

Resonance fluorescence spectrum of a two-level system consists of a single peak that evolves into a triplet structure, known as Mollow triplet , when it is driven by a radiation field above its saturation intensity. Particularly, photons originated from different peaks of the triplet show distinct photon correlations, which allows the fluorescence to be engineered as a useful light source for quantum information processing purposes. Surprisingly, the Mollow triplet was never studied for an optically trapped single atom given the advantages it has. We study experimentally the fluorescence spectrum of an optically trapped single ^{87}Rb atom by exciting a closed two-level transition with an on-resonant laser at different powers. The second-order intensity correlation measurement demonstrates the photon anti-bunching characteristic from a single atom emission as well as the Rabi oscillation undergone by the atom. Next, we measure the cross correlation between photons coming from the two sidebands of the fluorescence spectrum when an off-resonant field is applied on the atom. The asymmetry in the timing correlation clearly indicates that there is a preferred time-ordering for the photon emission process in the two sidebands. The cascaded generation of time-correlated fluorescence photons with a tunable frequency difference will be useful for quantum optics experiments and quantum communication protocols.

Presenter name: Boon Long Ng

Poster session / Mo-67: *Structure, properties of atoms, ions & mol.* ID304

Enhancing production of slow beams of laser-coolable molecules

Authors: Derick Gonzalez-Acevedo[1]; Zack Lasner[1]; Annika Lunstad[1]; Benjamin Augenbraun[1]; John Doyle[1]

[1] *Harvard University*

Radical polyatomic molecules can be produced from gas-phase atomic metal precursors in the presence of a reagent gas. Previous work with YbOH [1] and CaOH [2] has shown that molecular production in a cryogenic buffer-gas cell can be enhanced more than ten-fold by populating metastable triplet electronic states of metal atom precursors. These demonstrations, while highly effective, required excitation of weak intercombination (i.e., spin-flip) transitions. Here we report work exploring alternative pathways to populate these metastable states via two-step excitation on strong transitions followed by spontaneous decay to the target states. Candidate pathways have been identified for calcium- and strontium-containing molecules. We present our results measuring enhancement factors for production of several molecules used in ongoing molecular physics experiments.

[1] Jadbabaie et al., New J. Phys. 22, 022002 (2020); [2] Zhang et al., J. Chem. Phys. 155, 091101 (2021)

Presenter name: Derick E Gonzalez-Acevedo

Poster session / Mo-68:   *Structure, properties of atoms, ions & mol.*   ID356

Laser cooling AlCl molecules in the deep-ultraviolet

Authors: Jamie Shaw[1]; Mark Semco[1]; William Wortley[1]; Daniel McCarron[1]

[1] *University of Connecticut*

Laser-cooled molecules promise access to a diverse range of research directions from quantum simulation to controlled ultracold chemistry. Today, inefficient slowing of cold molecular beams remains a key barrier preventing molecular magneto-optical traps (MOTs) from trapping large, dense samples of ultracold molecules with properties similar to their atomic counterparts. Our experiment aims to remove this barrier by using bright continuous beams of cold molecules [1] and a molecular species susceptible to large optical forces by photon scattering. Our molecule of choice, aluminum monochloride (AlCl) has favorable properties for laser cooling and efficient trap loading, including a lack of spin-rotation structure and strong optical transitions in the deep-ultraviolet. Here we will present our latest work spectroscopically characterizing and manipulating a beam of AlCl with multiple high-power ultraviolet lasers [2].

[1] J. C. Shaw and D. J. McCarron Phys. Rev. A 102, 041302(R) (2020).
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Presenter name: Jamie Shaw

Poster session / Mo-69: *Structure, properties of atoms, ions & mol.* ID390

Low-phase-noise diode laser systems for the STIRAP transfer of ultracold ^{6}Li^{40}K molecules

Authors: Victor Avalos Pinillos[1]; Xiaoyu Nie[1]; Anbang Yang[1]; Canming He[1]; Kai Dieckmann[1]

[1] *Centre for Quantum Technologies*

In our group, we are interested in ^{6}Li^{40}K molecules at their rovibrational ground-state, which posses a large 3.6 Debye absolute dipole moment. This makes them suitable for the quantum many-body simulation of anisotropic and long range interactions. In order to transfer the molecules from a weakly bounded Feshbach-state to their ground-state, the method to be used is stimulated raman adiabatic passage (STIRAP). Excessive residual laser phase noise will drive unwanted transitions and therefore decrease the STIRAP efficiency. To deal with this issue, we extended the length (from 2 cm to 20 cm) of our external cavity diode lasers to narrow the free-running linewidth. The phase noise measurement method consisted in recording the spectral noise density of the beat note produced between the laser and a high-finesse cavity filtered version of itself. The integrated phase noise was reduced from 200 mrad to 40 mrad.

Theoretical calculations of the STIRAP efficiency also show the critical dependence on the pulse duration. The stochastic nature of the phase noise means that to reduce its effect, the pulse duration should be reduced. But on the other hand one should consider that the pulse should not be too short such that the adiabaticity criterion is violated. Additionally, we included tapered amplifiers to increase the Rabi frequency while preserving the low phase noise of the long external cavity diode lasers.

Presenter name: Victor Avalos Pinillos

Poster session / Tu-65:   *Structure, properties of atoms, ions & mol.*   ID15

Precision calculation of polarizability of heavy ions and atoms for physisorption with 2D materials

Authors: Harpreet Kaur[1]; Bindiya Arora[1]

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The calculations of different properties of the atoms and ions play a crucial role in many applications of various fields for instance, atomic physics, material science, astronomy, plasma, nanotechnology etc. An accurate description of different atomic properties is highly challenging with the standard approximations resulting in failure in providing the good data. Therefore, the surge for accurate calculation of atomic properties has emerged from last decade using promising theoretical methods. Here, in this paper, we have evaluated one of the most important atomic property, i.e., dipole polarizability of heavy ions - Zn^+, Cd^+, Hg^+, Pb^+ and atoms - Zn, Cd, Hg and Pb using two different relativistic many body methods. The known dynamic dipole polarizability values at imaginary frequencies are then used to derive characteristic van der Waal (vdW) dispersion coefficients with two dimensional (2D) materials - graphene and carbon nanotube walls, essential for physisorption applications. The agreement of the calculated dispersion coefficients is satisfactory with the recent study conducted using density functional theory (DFT) for the case of graphene. The present work is useful in sensing and storage applications of heavy elements with the considered 2D material walls. The future aspect of this work includes the accurate modelling of vdW correction based on inclusion of the higher-order coefficients which can be used to procure a higher accuracy towards total vdW potential between element and material wall.

Presenter name: Harpreet Kaur

Observation of two-photon induced fluorescence of neutral carbon atom gases

Authors: Takashi Sakamoto[1]; Kosuke Yoshioka[2]

[1] *Department of Applied Physics, School of Engineering, the University of Tokyo*

[2] *Department of Applied Physics, School of Engineering, the University of Tokyo, Photon Science Center, the University of Tokyo*

Ultracold atoms, made possible by laser cooling and trapping, are used as platforms for a wide range of applications such as observation of quantum degeneracy [1], quantum simulation [2], frequency standards [3] and ultracold collision studies [4]. While experiments using ultracold atoms of alkali metals and alkaline earth metals have made great progress, laser cooling has not been realized for atomic species of chemical and biological interest including carbon and hydrogen. The reason is that the optically allowed electronic transitions from the ground state of these atoms lie in the vacuum ultraviolet (VUV) region, making it difficult to construct light sources to drive effective cooling. In the case of carbon, laser cooling on two-photon transitions with a mode-locked laser has been discussed [5]. However, a gas production method in vacuum for neutral carbon with low vapor pressure has not been established. Furthermore, to the best of our knowledge, two-photon excitation of carbon atoms in vacuum has not also been demonstrated.

Here we demonstrate gas production of carbon atoms in the ground state using laser ablation of a graphite in vacuum and observation of produced atoms through two-photon induced fluorescence. This method is expected to be a fundamental technique applicable to laser cooling of carbon.

Figure 1 shows the experimental setup and the schematic energy level diagram of carbon showing the involved levels and transitions. Carbon atoms were produced by focusing the 266 nm radiation from the fourth harmonic of a Q-switched Nd:YAG laser on a rotating highly oriented pyrolytic graphite (HOPG) target. Produced particles including ions and molecules as well as atoms were expanded in a vacuum chamber.
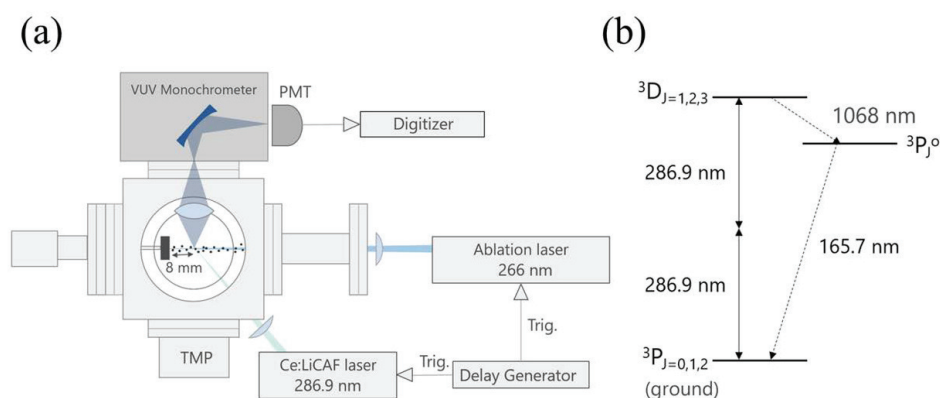
Figure 1: (a) Experimental setup (TMP: turbo molecular pump, PMT: photomultiplier tube). (b) Schematic energy level diagram of carbon related to this study.

Nanosecond pulses from a homebuilt, tunable Ce:LiCAF laser pumped by the fourth harmonic of another Q-switched Nd:YAG laser were used for the two-photon excitation. The laser wavelength was tuned to the two-photon resonances of the ^3P-^3D transition at 286.9 nm. The laser beam was focused into a spatial region at a distance of 8 mm from the target. The delay time between atomic gas production and two-photon excitation was adjusted with

a digital delay generator. The two-photon induced fluorescence at 165.7 nm was detected perpendicular to both the excitation laser beam and the atomic beam. A 0.2 m monochromator equipped with a solar-blind photomultiplier tube (PMT) was used for the detection. We will introduce the density and the temperature of produced atoms evaluated through the observation of the two-photon induced fluorescence. It was confirmed that when the laser fluence was excessively high, carbon atoms were produced in the high-energy excited states with long lifetimes unsuitable for laser cooling. The dependence of the behavior of the produced particles on the laser fluence will be discussed in conjunction with the results of plume emission spectra and time-resolved emission measurements. In addition, the precooling method for actual laser cooling of the atoms produced by our method and the design of our cooling laser at a wavelength of 286.9 nm will also be presented.

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Presenter name: Takashi Sakamoto

Poster session / Tu-67:   *Structure, properties of atoms, ions & mol.*   ID170

Accurate and complete atomic data set for Cd XLVII

Authors: Dhia Elhak Salhi[1]; Soumaya Manai[2]; Sirine Ben Nasr[1]; Haikel Jelassi[2]

[1] *National Center for Nuclear Sciences and Technologies, Tunisia*

[2] *National Center for Nuclear Sciences and Technologies*

Atomic data have received a great deal of attention, due to their need for the upcoming ITER project (International Thermonuclear Experimental Reactor). So, extensive spectroscopic studies both experimental and theoretical have been performed in the last years in order to estimate the power loss from the impurities in the forthcoming fusion reactors. Accurate values of wavelengths and their errors are required for interpretation of a wealth of high-resolution data obtained in the last two decades by the Chandra X-ray Observatory and the European Space Agency's X-ray multiMirror Mission [1].

As previously published [2, 3, 4, 5, 6, 7], we continue to focus on He-like ions. Energy levels, wavelengths, weighted oscillator strengths, transition probabilities and lifetimes are calculated for all levels of 1s2 and 1snl (n = 2−6) configurations of He-like cadmium ion.

The calculations were carried out using the GRASP2018 code based on the multiconfiguration Dirac-Hartree-Fock (MCDHF) [8]. Transition probabilities are reported for all types of transitions (E1, E2, M1 and M2 transitions). Breit interactions and quantum electrodynamics effects are included in the RCI calculations. Comparisons were made with other data found in the literature and a good agreement was found which confirms the reliability of our results. We identified some new data that are calculated for the first time. This computational approach enables us to present a consistent and improved data set of all important transitions of the Cd XLVII spectrum, which are useful for identifying transition lines in further investigations.

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Presenter name: Dhia Elhak Salhi

Functionalized aromatic molecules for laser cooling and trapping

Author: Debayan Mitra[1]

Co-authors: Guozhu Zhu [2]; Zack Lasner [3]; Benjamin Augenbraun [3]; Claire Dickerson [2]; Guanming Lao [2]; Michael Frim [3]; Austin Bailey [2]; Justin Caram [2]; Anastassia Alexandrova [2]; Wes Campbell [2]; Eric Hudson [2]; John Doyle [3]

[1] *Columbia University*

[2] *UCLA*

[3] *Harvard University*

Laser cooling relies on photon cycling, which can be enabled in polyatomic molecules when an "optical cycling center" (OCC) is attached to an electronegative ligand. It was proposed that molecules with a (metal) alkaline-earth(I)-oxide-radical structure, would have good OCC properties and, thus, would be amenable to laser cooling [1]. More recent theoretical work has indicated that the alkaline-earth(I)-oxide unit attached to a benzene ring would offer a good OCC that would be tunable by substituting the ring hydrogen atoms with more electronegative species [2]. Theory has also indicated that larger rings (such as naphthalene, pyrene, and coronene) can also provide good optical cycling properties [3]. We report the results of dispersed fluorescence measurements on CaO-Ph-X (Ph : phenyl, X = F, CH3, CF3) in a cryogenic buffer gas at 9 K. We find that the vibrational branching ratio (VBR) to the ground vibrational state is ~95% for all species and 99% for CaO-Ph-3,4,5F [4]. We also study the napthol-based molecules CaO-Nap and SrO-Nap, and find that the 2-naphthyl positional variant of CaO-Nap also has a highly diagonal VBR, 96% [5]. These results demonstrate that the same principles that have led to laser cooling of di-, tri- and poly-atomic molecules (e.g. SrF, CaOH and CaOCH3) can likely be extended to phenolic and aromatic molecules.

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Presenter name: Debayan Mitra

Relativistic corrections to two-photon decay rates in heliumlike ions

Authors: Aaron Bondy[1]; Gordon Drake[1]; Donald C. Morton[2]

[1] *University of Windsor*

[2] *NRC Herzberg Astronomy and Astrophysics Research Centre*

Two-photon transition rates are important in determining astrophysical quantities such as population balance in planetary nebulae. Our group recently calculated two-photon decay rates in heliumlike ions including the finite nuclear mass effects [1]. We have now perturbatively added relativistic corrections to these results, giving the most precise and accurate calculations to date for these transitions. In the process of calculating the two-electron Breit matrix elements, we first tested the derived two-photon, two-electron decay (2nd order field +1st order relativistic) perturbation equation on the equivalent one-electron process which obeys the same formula. In this process, we derived (and will report on) one-electron Breit-Pauli operators that were shown to be equivalent to the corresponding Dirac operators. A continuous gauge parameter is considered, and the operators are compared to the long-wavelength QED operators derived for few-electron atoms by Pachucki [2].

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Presenter name: Aaron T. Bondy

A cold and slow beam of CH radicals for laser cooling and trapping experiments

Authors: Jamie Shaw[1]; Joseph Schnaubelt[1]; John Montgomery[1]; Daniel McCarron[1]

[1] *University of Connecticut*

Techniques to directly laser cool and trap molecules at ultracold temperatures have revealed a new path towards the full quantum control of a diverse range of species with a variety of internal structures. Our experiment will capitalize on this generality by directly laser cooling and trapping CH radicals for tests of ultracold organic chemistry. The low mass and blue optical transitions in this species lead to high recoil velocities which can significantly reduce the photon budget and rovibrational closure needed to slow, cool and trap a molecular beam from our cryogenic source. Here we will present the latest results characterizing our slow molecular beam and probing the chemistry of CH radicals at ~1 K.

Presenter name: Daniel McCarron

Ultracold mixtures of Cr and Li atoms: theoretical prospects for controlled atomic collisions, LiCr molecule formation, and molecular precision measurements

Authors: Klaudia Zaremba-Kopczyk[1]; Marcin Gronowski[2]; Michal Tomza[1]

[1] *Faculty of Physics, University of Warsaw*

[2] *Institute of Physical Chemistry, Polish Academy of Sciences*

We theoretically investigate interatomic interactions and ultracold collisions between chromium and lithium atoms. We use the coupled cluster and multireference configuration interaction methods to calculate the potential energy curves and the permanent and transition electric dipole moments for the quartet, sextet, and octet electronic states of the LiCr molecule correlated to the four lowest atomic dissociation limits. We find that the LiCr molecule in the $X\,^6\Sigma^+$ ground electronic state is strongly bound with the well depth of $8406(100)\,\mathrm{cm}^{-1}$ and has a large permanent electric dipole moment of $3.3\,\mathrm{D}$ at an equilibrium distance of $4.87\,\mathrm{bohr}$, while the $a\,^8\Sigma^+$ first excited electronic states is weakly bound with the well depth of $565(18)\,\mathrm{cm}^{-1}$ and has a noticeable permanent electric dipole moment of $0.7\,\mathrm{D}$ at the equilibrium distance of $6.48\,\mathrm{bohr}$. We investigate the optical paths of forming deeply-bound LiCr molecules via photoassociation and stimulated Raman adiabatic passage. We propose precision measurements of the variation of electron-to-proton mass ratio using ultracold LiCr molecules. We predict the scattering lengths for the ultracold spin-polarized Cr+Li collisions ($37^{+29}_{-22}\,\mathrm{bohr}$ for $^{53}\mathrm{Cr}+^6\mathrm{Li}$) governed by the $a\,^8\Sigma^+$ electronic state without any adjustment to experimental data and in good agreement with recent experimental measurements. Finally, we calculate magnetically tunable Feshbach resonances for ultracold $^{52}\mathrm{Cr}+^6\mathrm{Li}$ and $^{53}\mathrm{Cr}+^6\mathrm{Li}$ collisions and assess prospects for magnetoassociation into polar and highly magnetic LiCr molecules. Present theoretical results may guide ongoing experimental studies on ultracold strongly-interacting mass-imbalanced Fermi-Fermi Li+Cr mixtures and LiCr molecules.

Presenter name: Klaudia Zaremba-Kopczyk

Poster session / **We-68:** *Structure, properties of atoms, ions & mol.* ID119

Progress towards a magneto-optical trap for MgF molecules

Authors: Kikyeong Kwon[1]; Seunghwan Roh[1]; Youngju Cho[1]; Changhyuk Yoo[1]; Dongkyu Lim[1]; Giseok Lee[1]; Eunmi Chae[1]

[1] *Department of physics, Korea University*

Achieving ultracold temperature of neutral diatomic molecules is one of the pre-requested key steps for using them as a quantum platform. Owing to molecules' abundant internal structures and large electric dipole moments, a long coherence time and a long-range interaction could be achieved when we make an array of diatomic molecules trapped in optical tweezers.

To make an ultracold molecular array, several steps are planned in this research. First, a cold buffer-gas beam of molecules is generated by elastic collisions with He buffer gas after the ablation of a molecule target. Second, the molecular beam is captured in a magneto-optical trap, cooling the molecules down to the Doppler-limit regime. The last step is sub-Doppler cooling and transferring the molecules into optical dipole traps to construct an ultracold molecular array.

MgF molecules are chosen here because of their favorable energy structure for laser cooling and abundant bosonic and fermionic isotopes. We constructed a buffer-gas beam source that can generate MgF molecules and cool them down below 4 K. At this temperature, 30 % of the molecules are in the $v = 0, N = 1$ state, which is the electronic ground state of the quasi-cycling transition for the magneto-optical trap. The poster will provide detailed information about the overall experiment and the performance of the buffer-gas beam source.

Presenter name: Kikyeong Kwon

Poster session / **We-69:** *Structure, properties of atoms, ions & mol.* ID171

Accurate and complete atomic data set for helium-like ions using Relativistic Configuration Interaction approach for singly and doubly excited states with Z = 5 - 9

Authors: Soumaya Manai[1]; Dhia Elhak Salhi[2]; Haikel Jelassi[2]

[1] *National Centre for Nuclear Sciences and Technologies, Tunisia*

[2] *National Centre for Nuclear Sciences and Technologies, Tunisia*

Accurate atomic data is considered to be the principal way to effectively solve the future energy problem as a clean and infinite energy resource and it is being developed internationally via the International Thermonuclear Experimental Reactor ($ITER$) Project [1]. Then, extensive spectroscopic studies both experimental and theoretical have been performed in the last few years in order to estimate the power loss from the impurities in the forthcoming fusion reactors. Furthermore, accurate values of wavelengths and their errors are required for the interpretation of a wealth of high-resolution data obtained in the last two decades by the Chandra X-ray Observatory and the European Space Agency's X-ray multiMirror Mission.

As previously published [2, 3], we continue to focus on helium-like ions. In this work, energy levels, wavelengths and transitions rates have been calculated for the lowest singly excited 70 levels among $1snl(n \leq 6, l \leq (n-1))$ configurations and the lowest doubly excited 250 levels arising from the K-vacancy $2ln'l'(n' \leq 6, l' \leq (n'-1))$ configurations of helium-like ions with $Z = 5 - 9$ namely $B\,IV$, $C\,V$, $N\,VI$, $O\,VII$ and $F\,VIII$ [4]. The calculations were performed using the Relativistic Configuration Interaction (RCI) method implemented in the Flexible Atomic Code (FAC) [5]. Comparisons were made with other available theories reported in the literature [6, 7, 8, 9]. Finally, the accuracy of the present calculations is enough to facilitate the identification of many observed spectral lines, plasma modelling as well as diagnostics of astrophysical plasma and controlled thermonuclear fusion.

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Presenter name: Manai, Soumaya

Poster session / We-70:   *Structure, properties of atoms, ions & mol.*   ID190

Study of radiative properties of helium isoelectronic sequence

Authors: Haikel Jelassi[1]; Dhia Elhak Salhi[.]; Soumaya Manai[1]; Sirine Ben Nasr[1]

[1] *National Centre for Nuclear Sciences and Technologies*

The radiative properties of ions (Z= 2-53) belonging to the helium isoelectronic sequence are reported. Energy levels for the ground state and the lowest 1s2l singly excited states are considered. The effects of correlation effects are studied for the selected ions by increasing the active set (AS). Relativistic effects such as the Breit interaction and the QED corrections are also computed. The heavy elements with high Z are of potential interest in controlled thermonuclear fusion and astrophysics. Indeed, they could be used in plasma-facing materials such as the divertors in tokamaks or/and could be generated by neutron-induced transmutations of divertor's materials. So, extensive spectroscopic studies both experimental and theoretical have been performed in the last years in order to estimate the power loss from the impurities in the forthcoming fusion reactors [1].

In this work, two independent theoretical atomic structure computational approaches have been considered, i.e. the ab initio multiconfiguration Dirac-Hartree-Fock with subsequent relativistic configuration interaction method (MCDHF-RCI) implemented in the code GRASP2018 [2] and the Dirac-Fock-Slater (DFS) implemented in the code FAC (Flexible Atomic Code) [3]. The relativistic configuration interaction method was applied to estimate the electron correlation effects. The transition probabilities and the oscillator strengths w calculated for E1, E2, M1 and M2 transitions spanning the spectral range from UV to IR. Our results are compared with available experimental and other theoretical values. Good agreement is found for the majority of cases. Lifetimes are also considered in this work, first to check the accuracy of calculated results of transitions rates and second, to complete the databases by a complete and accurate values of lifetimes. This can help future works by experimentalists to compare their results with those results calculated theoretically. Finally, this study underlines the importance of relativistic corrections especially for the heavy atomic ions. This computational approach enables us to present a consistent and improved data set of all important atomic data of the helium isoelectronic sequence, which are useful for identifying transition lines in further investigations.

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Presenter name: Haikel Jelassi

Poster session / We-71:   *Structure, properties of atoms, ions & mol.*   ID344

Photoassociation specroscopy of RbYb near the Yb inter-combination line

Authors: Axel Goerlitz[1]; Bastian Pollklesener[1]; Christian Sillus[1]; Tobias Franzen[1]

[1] *University Duesseldorf*

Ultracold dipolar molecules are a promising system for interesting research in ultracold chemistry, novel interactions in quantum gases, precision measurements or quantum information.

Here we report on photoassociation spectroscpoy in an ultracold mixture of Yb and Rb near the $^1S_0 \to {}^3P_1$ intercombination line of Yb at 556 nm. While in previous work we have identified several one- and two-photon photoassociation transitions near the D1-line of Rb at 795 nm [1,2], photoassociation near the narrow intercombination line promises to open up new pathways for the production of YbRb-molecules in the absolute molecular ground state.

The experiments presented here, have been carried out in a completely new setup which is designed to spatially separate the production of ultracold atomic samples from the actual experimental studies [3]. In this setup we employ optical tweezers to transport individually cooled samples of ultracold Rb and Yb atoms from their separate production chambers to a dedicated common science chamber. In the science chamber the atoms can be further manipulated and trapped using various optical dipole trap geometries.

So far, we have experimentally observed one unbound-bound transition in a mixture of ^{170}Yb and ^{87}Rb near the intercombination line. We attribute the fact that no more transitions could be detected to the fact that the unbound-bound transition matrix elements are significantly smaller than expected. Using the observed excited RbYb* molecular level as an intermediate state we could also identify two two-photon transitions to vibrationally excited levels in the electronic ground state of the molecule using a dark-resonance technique. We plan to use the dark-resonances to identify deeply bound rovibrational levels in the electonically excited $1^2\Pi_{1/2}$ molecular state, which are suitable for an efficient transfer of the RbYb molecules into the absolute ground state.

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Presenter name: Goerlitz, Axel

Poster session / We-72:   *Structure, properties of atoms, ions & mol.*   ID378

Suppression of Raman interaction due to destructive interference in alkali atoms

Authors: Nicholas Milson[1]; Arina Tashchilina[1]; Joseph Lindon[1]; Logan W. Cooke[1]; Evgeny Moiseev[2]; Lindsay J. LeBlanc[1]

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Raman interactions are a powerful tool for performing arbitrary rotations between two Zeeman levels of an individual ion or a neutral atom. Universality of the technique places it in a central role in many quantum technologies: single qubit gates in atomic quantum processors, mediating interactions in quantum simulators, and mapping quantum information into long-lived states in optical quantum memories, to name a few.

The conventional three-level effective theory manifests that the fidelity of the Raman operation grows inversely proportional to the single photon detuning. In our work we show that this approximation does not always hold for all alkali atoms due to their multilevel structure. The destructive interference of the hyperfine sub-levels could fully suppress the Raman interaction at large detunings leaving us with some finite optimal fidelity in comparison to asymptotically ideal theoretical case. We use a formalism based on Clebsch-Gordan coefficients and rotational symmetries of atoms, which allows us to generalize our results to all alkali atoms. We experimentally show the effect on Rb-87 and discuss how to circumvent the problem.

Presenter name: Nicholas Milson

Poster session / Th-68:   *Structure, properties of atoms, ions & mol.*   ID147

Controlled interactions between ultracold KRb molecules in two dimensions

Authors: Calder Miller[1]; Annette Carroll[1]; Jun-Ru Li[1]; Kyle Matsuda[1]; William Tobias[1]; Jun Ye[1]

[1] *JILA, National Institute of Standards and Technology, and Department of Physics, University of Colorado Boulder*

Dipolar molecules in two dimensions are a powerful platform for the study of quantum many-body physics, thanks to their long-range, anisotropic dipolar interactions. We have developed key experimental capabilities required for the study of such systems, including layer-resolved state control and detection, field-tunable dipole orientation and strength, and control of both intralayer and interlayer interactions. The interactions between layers are probed through chemical reactions mediated by exchange of rotational excitations. The reaction rate is controlled through application of an electric field gradient, revealing an interplay between the thermal energy and spin exchange. Within a layer the interactions realize a spin Hamiltonian, where the Ising and exchange interactions are controlled through electric field strength and orientation, and molecular rotational state. The interactions manifest through shifts in the rotational transition frequency and decays in the Ramsey contrast. We discuss the outlook for the platform, including a path towards creation of a spin squeezed state.

Presenter name: Calder Miller

Poster session / Th-69:   *Structure, properties of atoms, ions & mol.*   ID175

Analyzing the hyperfine structure using the quantum orbit eccentricity

Authors: Alejandra del Rio Lima[1]; Ana Karen Cuervo Montiel[2]; Francisco Javier Cárcamo Verde[2]; Freddy Jackson Poveda Cuevas[3]

[1] *IF-UNAM*

[2] *Instituto de Física, Universidad Nacional Autónoma de México*

[3] *Cátedras Conacyt - Instituto de Física - Universidad Nacional Autónoma de México*

The old problem of the discrete spectrum of the hydrogen atom obeys a SO(4) symmetry, which is isomorphous to two subgroups that obey the algebra of angular momentum. The algebraic structure allows us to formulate a basis closely related to the properties of the wave function in parabolic coordinates. On the other hand, the properties of other angular momenta, such as electron spin and nucleus spin, are introduced by adding angular momentum. All these contributions are known as the hyperfine structure. In this work, we explore the symmetries of the problem to analyze the atomic hyperfine structure strictly using the properties of the SO(4) group of the Laplace-Runge-Lenz vector. Additionally, we have done a brief analysis of the symmetry breaking in the presence of electric and magnetic fields.

Presenter name: Freddy Jackson Poveda Cuevas

0_g^- potential in Cs2, revisited: observation of missing levels

Authors: Koray Dincer[1]; Mariusz Semczuk[1]

[1] *University of Warsaw*

We use photoassociation of spin polarized ($F = 3$, $m_f = 3$), ultracold cesium atoms confined in a 1D optical lattice to confirm the existence of the two lowest lying vibrational levels in the 0_g^- pure long-range molecular potential of Cs_2. The observation of these two levels confirms the theoretical predictions of Bouloufa et al. [1] postulating that the numbering of vibrational levels of this potential needs to be shifted by two in order to agree theory with experimental data. We also provide unambiguous evidence that the work of Zhang et al. [2] which claimed priority of observing these new levels, in fact observed levels belonging to the 0_u^+ molecular potential.

Due to the expected low molecular formation rate we have implemented Feshbach resonance-enhanced association of molecules in $v = 0$ and $v = 1$. Several of such resonances are present at fields below 70 G but the newly discovered vibrational levels could be detected only in the vicinity of the Feshbach resonance at 19.9 G [3].

We have determined the binding energies of the $(v,J) = (0, 2)$, $(1, 0)$, $(1, 2)$ and $(1, 4)$ with absolute accuracy better than 1 MHz by referencing the photoassociation laser to a frequency comb. For the $v = 1$ level we have extracted the rotational constant of ~56 MHz.

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Presenter name: Mariusz Semczuk

Poster session / Th-71:   *Structure, properties of atoms, ions & mol.*   ID353

Quantum state control of optically trapped polyatomic molecules

Authors: Nathaniel Vilas[1]; Christian Hallas[1]; Loic Anderegg[1]; Paige Robichaud[1]; Andrew Winnicki[1]; John M Doyle[1]

[1] *Harvard University*

The degrees of freedom inherent in the structure of polyatomic molecules allow for new applications spanning the fields of quantum simulation and computation, ultracold chemistry, and precision measurements of fundamental physics. For example, the complex rovibrational structure of polyatomic molecules generically gives rise to closely-spaced levels of opposite parity that result in linear Stark shifts at modest electric fields, along with states that have zero first-order electric field sensitivity. Here we present our results on laser cooling of CaOH and optical trapping of CaOH in the vibrational bending mode, which possesses such a parity doublet structure. We present microwave spectroscopy of this state for its potential use in quantum science applications. In addition, we discuss the creation of an optical tweezer array of CaOH molecules. The single particle control lent by this platform will open the door to future efforts studying interactions between molecules in optical traps.

Presenter name: Nathaniel Vilas

Poster session / Th-72: *Structure, properties of atoms, ions & mol.* ID386

Progress towards direct laser cooling and trapping of CaH molecules

Authors: Qi Sun[1]; Jinyu Dai[1]; Sebastian Vazquez-Carson[1]; Debayan Mitra[1]; Tanya Zelevinsky[1]

[1] *Columbia University*

The past decade has seen tremendous progress in the field of direct laser cooling and trapping of molecules, extending to new candidate platforms for quantum computing, quantum simulation, precision measurement and metrology. Here we present our progress towards laser cooling and trapping of CaH molecules. We demonstrate experimental results on transverse Sisyphus cooling of a cold beam of CaH molecules. We obtain good agreement with the optical Bloch equations and Monte Carlo simulations, and establish that a high scattering rate (10^6 photons/s) is achievable for this molecule. Next, we present our characterization of molecular predissociation and discuss potential dissociation pathways for the creation of atomic hydrogen from CaH. Looking toward the future, we describe our plans to perform longitudinal white-light slowing and 3D magneto-optical trapping with the application of the first two vibrational repumps. This work sets the stage for a trapped, dilute cloud of ultracold hydrogen, which could further improve on the current limits in hydrogen spectroscopy.

Presenter name: Qi Sun

Virtual poster / Vir43: *Structure, properties of atoms, ions & mol.* ID265

Electrostatic interactions involving exotic long-range Rydberg molecules

Authors: Homar Rivera Rodríguez[1]; Rocío Jáuregui[1]

[1] *Instituto de Física, Universidad Nacional Autónoma de México*

A ground state atom immersed in the wave function of the valence electron of a Rydberg atom can generate a long-range Rydberg molecule (LRRM). In this work, using the multipole expansion of the electrostatic interaction in prolate spheroidal coordinates, approximate and compact expressions of the electrostatic potential that determine the chemistry of trilobite and butterfly LRRM are explored. It is shown that even the prolate spheroidal monopole term can be used to describe general features of the potential generated by an LRRM at short distances. It is also shown that even at long separations that allow a perturbative description of the intermolecular interaction between two LRRM, the convergence of the spheroidal multipole expansion is faster than that of its spherical analogue.

Presenter name: Rivera Rodríguez, Homar

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Virtual poster / Vir44:   *Structure, properties of atoms, ions & mol.*   ID278

Valence-shell electronic excitations of CH$_3$I studied by fast electron scattering

Authors: Qiang Sun[1]; Shu-Xing Wang[1]; Tian-Jun Li[1]; Lin-Fan Zhu[1]

[1] *University of Science and Technology of China*

CH$_3$I is an important trace species in the Earth's atmosphere, which is mainly produced by biogenic processes. Meanwhile, CH$_3$I can release iodine atom, whose ozone depleting efficiency is about two to three orders of magnitude larger than that of chlorine. However, CH$_3$I is considered to be relatively environmentally friendly because of its short lifetime in the troposphere due to solar photolysis. Therefore, benchmark physical quantities including the oscillator strengths and cross sections of the valence-shell excitations of CH$_3$I are vital for monitoring the concentrations of CH$_3$I as well as for understanding its photophysics.

Since Price observed the first VUV photoabsorption spectrum of CH$_3$I, extensive experimental and theoretical researches on the electronic structure of CH$_3$I were reported and well summarized by Locht et al. recently[1]. However, there are few reports on the optical oscillator strengths (OOSs) of the valence-shell excitations of CH$_3$I, which have been summarized by Olney et al. [2]. Unfortunately, the generalized oscillator strengths (GOSs) and integral cross sections (ICSs) of the valence-shell excitations of CH$_3$I have not been reported until now, to the best of our knowledge.

In this context, the GOSs of the valence-shell excitations of CH$_3$I have been determined by an angle-resolved electron energy loss spectrometer at an incident electron energy of 1.5 keV and an energy resolution of 80 meV. The corresponding OOSs have been obtained by extrapolating the GOSs to the zero limit of squared momentum transfer K^2→0, which are in good agreement with the previous data. Moreover, the ICSs of the valence-shell excitations of CH$_3$I from the threshold to 5000 eV have also been obtained by means of the BE-scaling method[3,4]. The GOSs of the first two Rydberg states and some of their vibrational states are shown in Fig. 1 and Fig. 2. It is obvious that all GOSs show a similar trend, i.e., decreasing with the K^2 in the small K^2 region, which is the typical behavior of the dipole allowed transitions.

In general, we measure the GOSs of the valence-shell excitations of CH$_3$I and obtain the corresponding extrapolated OOSs by a completely different experimental method, thus providing an independent cross-check for previous results. Furthermore, the ICSs of the valence-shell excitations of CH$_3$I were systematically obtained, which enrich the fundamental spectroscopic data of CH$_3$I and have important application value in photochemical models of atmospheric physics.

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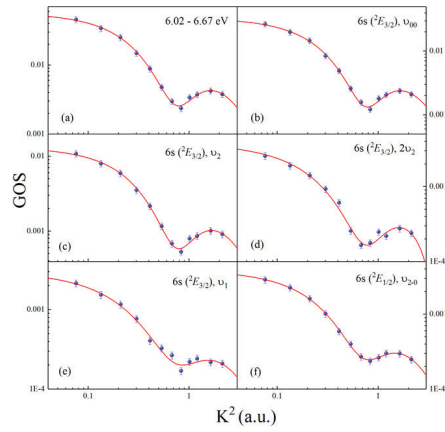
Fig. 1. Present GOSs of the (a) 6.02 - 6.67 eV, (b) 6s $(^2E_{3/2})$, υ_{00}, (c) 6s $(^2E_{3/2})$, υ_2, (d) 6s $(^2E_{3/2})$, $2\upsilon_2$, (e) 6s $(^2E_{3/2})$, υ_1, (f) 6s $(^2E_{1/2})$, υ_{2-0}. The solid blue dots are the experimental results and the solid red lines are the fitted curves.

Figure 1:

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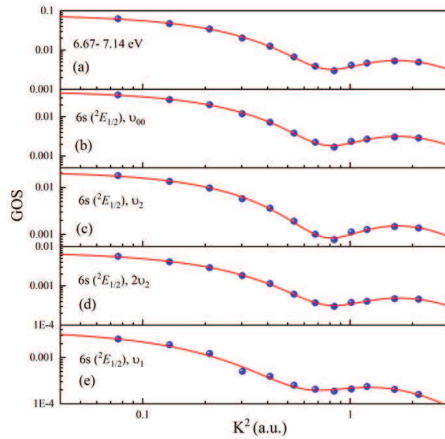
Fig. 2. Present GOSs of the (a) 6.67 - 7.14 eV, (b) 6s $(^2E_{1/2})$, υ_{00}, (c) 6s $(^2E_{1/2})$, υ_2, (d) 6s $(^2E_{1/2})$, $2\upsilon_2$, (e) 6s $(^2E_{1/2})$, υ_1. The solid blue dots are the experimental results and the solid red lines are the fitted curves.

Figure 2:

Presenter name: Qiang Sun

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Virtual poster / Vir45:   *Structure, properties of atoms, ions & mol.*   ID348

Theoretical study of properties of radioactive molecules

Authors: Aleksandra Kiuberis[1]; Anastasia Borschevsky[1]; Lukáš Félix Pašteka[2]

[1] *University of Groningen*

[2] *Comenius University*

Heavy diatomic molecules are currently considered to be among the most sensitive systems used in the search for the P,T-violating effects and in probing of the Standard Model of particle physics. In certain molecules effects resulting from both parity violation and time-reversal violation (P,T - odd effects) are considerably enhanced with respect to atomic systems. The strength of these interactions grows with atomic number, nuclear spin and nuclear deformation. Molecules with atomic nuclear octupole deformation are sensitive for investigating of parity and time-reversal violating effects, in particular nuclear EDM or electric EDM. Diatomic molecules, like AcF and RaF, has been proposed to be sensitive to the various effects, for example, Schiff moment of the nucleus. Nowadays different laboratories plan to perform experimental study of radioactive molecules in aim to measure isotopologue shifts, hyperfine structures and so on.

Pursuing studies on AcF can also provide insight into dynamics of molecular extraction of Ac, as a pathway to delivering a wider range of actinium isotopes for experiments.

This work aims to determine molecular properties of the RaF and AcF at the highest possible level of computational accuracy using the couple cluster in relativistic framework.

The ionization potential, excitation energies, and spectroscopic constants of AcF, RaF will be presented and the uncertainty of the predicted values will be discussed.

Presenter name: Kiuberis Aleksandra

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Poster session / Mo-70: *Trapped ions, Rydberg atoms, cold plasmas* ID100

Scalable arrays of micro-fabricated Penning traps for quantum computation and simulation

Authors: Tobias Sägesser[1]; Shreyans Jain[1]; Pavel Hrmo[1]; Daniel Kienzler[1]; Jonathan Home[1]

[1] *Trapped Ion Quantum Information Group, ETH Zürich*

Although radio-frequency (r.f.) traps have been widely used in trapped-ion quantum information and simulation, they face some inherent challenges in scaling up the number of qubits. Precise alignment of static and r.f. field nulls is necessary to achieve confinement of the ions without r.f. driven motion. As the r.f. null is inherently 1-dimensional, attempts at scaling into 2-d are beset by micromotion.

Instead we propose to use a two-dimensional array of Penning traps, implemented by micro-fabricated electrodes. Applying suitable electrical potentials to the surface electrodes generates an array of quadrupole fields above the chip, with a single ion trapped at each. This allows for individual control of secular frequencies and trapping heights with coupling provided by the Coulomb interaction. Micromotion and bulk crystal rotation are absent in this approach.

We have constructed an experimental apparatus containing the first micro-fabricated planar Penning trap in a 3 T field. The trap can produce a potential with two trap sites separated radially. To achieve ultra-high vacuum and low ion heating rates, the trap is held at cryogenic temperatures of around 6 K, with optics to allow for imaging and laser manipulation of ions as part of the cryogenic structure as well.

We report on our current efforts to initially trap $^9\text{Be}^+$ ions in this setup. Potential challenges that may prevent successful trapping are identified. We attempt cooling of the radial motion by the axialisation technique, coupling the cyclotron and magnetron motions. The required strength of the weak coupling r.f. field is predicted as well as the precision of positioning of the r.f. null. Stray electric potentials may lead to unstable trapping conditions as well as perturb the axialisation frequency, requiring appropriate compensation. Neutral Be atoms are produced by pulsed-laser ablation, a process we have studied in depth.

Presenter name: Tobias Sägesser

Poster session / Mo-71:   *Trapped ions, Rydberg atoms, cold plasmas*   ID126

Ultrafast Rydberg experiments with ultracold atoms in optical tweezers

Author: Sylvain DE LESELEUC[1]

Co-authors: Yeelai Chew [2]; Takafumi Tomita [2]; Tirumalasetty Panduranga Mahesh [2]; Seiji Sugawa [2]; Kenji Ohmori [2]

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[2] *IMS*

Rydberg atoms, with their giant electronic orbitals, exhibit dipole-dipole interaction reaching the GHz range at a distance of a micron, making them a prominent contender for realizing ultrafast quantum operations. However, such strong interactions between single atoms have never been harnessed so far because of the stringent requirements on the fluctuation of the atom positions and the necessary excitation strength. Here, we introduce novel techniques to explore this regime [1]. First, we trap and cool atoms to the motional quantum ground-state of holographic optical tweezers allowing to control the inter-atomic distance down to 1.5 µm with a quantum-limited precision of 30 nm. Then, we use ultrashort laser pulses to excite a pair of these close-by atoms to a Rydberg state simultaneously, far beyond the Rydberg blockade regime [2], and perform Ramsey interferometry with attosecond precision. This allows us to induce and track an ultrafast interaction-driven energy exchange completed on a timescale of nanoseconds, two orders of magnitude faster than in any other Rydberg experiments with individual atoms. This ultrafast coherent dynamic gives rise to a conditional phase which is the key resource for a quantum gate, opening the path for quantum simulation [2] and computation operating at the speed-limit set by dipole-dipole interactions with this ultrafast Rydberg platform.

[1] Y. Chew et al., arXiv: 2111.12314
[2] V. Bharti et al., arXiv : 2201.09590

Presenter name: Sylvain DE LESELEUC

Poster session / Mo-72:   *Trapped ions, Rydberg atoms, cold plasmas*   ID151

Progress in experimental control of trapped ion motional states with applications for CVQC and quantum sensing*

Authors: Jeremy Metzner[1]; Isamm Daniel Moore[1]; Alex Quinn[1]; Sean Brudney[1]; Colin Bruzewicz[2]; John Chiaverini[3]; David Wineland[1]; David Allcock[1]

[1] *University of Oregon*

[2] *Lincoln Lab*

[3] *MIT, Lincoln Lab*

Motional modes of trapped ions have been shown to be a useful tool for quantum sensing as well as a potential platform for performing continuous variable quantum computing (CVQC) [1,2]. Both applications require the ability to prepare well-defined motional states with high fidelity. These states can be generated without the use of laser fields which could reduce the experimental overhead in future systems. We report our progress towards generation of single and two-mode squeezed states as well as beam splitters [3] by means of parametric excitation. Additionally, we can apply displacements and phase shift operations. These operations comprise part of the tool box to create motional state interferometers such as the Mach-Zender or SU(1,1) interferometers and can be used to achieve Heisenberg limited phase sensitivities. In order to characterize these motional states, measurements require coupling the motion to the ions' internal "spin" states followed by detection of spin-dependent fluorescence. Photon scattering, giving rise to fluorescence, causes the ion to recoil, which generally decoheres the ions' motional modes. This decoherence prevents mid-algorithm measurements, which are necessary for processes that require classical feedback. To address this issue, we also describe progress towards the use of 'protected' [3] modes within chains consisting of an odd number of ions, where the center ion has zero displacement (3(N-1)/2 protected modes with N ions). The protection offered by these ions can be measured by analysis of the heating rates and coherence time of the protected mode during scattering events. *This research was supported by the U.S. Army Research Office through grant W911NF-19-1-0481 as well as support from NSF through the Q-SEnSE Quantum Leap Challenge Institute, Award # 2016244.

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Presenter name: Jeremy Metzner

Poster session / Mo-73:   *Trapped ions, Rydberg atoms, cold plasmas*   ID200

Fast preparation and detection of a Rydberg qubit using atomic ensembles

Authors: Wenchao Xu˙; Emily Qiu˙; Aditya Venkatramani˙; Sergio Cantu˙; Tamara Sumarac˙; Valentin Klusener˙; Matthew Peters˙; Mikhail Lukin˙; Vladan Vuletic˙

Arrays of neutral atoms have recently emerged as a competitive platform for quantum simulation and computation with many properties favorable for scaling. Rydberg states of atoms are often used because the strong Rydberg-Rydberg interactions can facilitate two-qubit gate operations and simulate many-body systems. However, for most schemes, readout of a Rydberg qubit is a destructive process that precludes its reuse and the application of many error-correcting codes. To address this challenge, we demonstrate a nondestructive implementation of preparation, manipulation, and readout of a single Rydberg qubit embedded in an atomic ensemble with high fidelity. By harnessing the collective optical response of the atomic ensemble, we detect the state of a qubit ~1000x faster than single-atom fluorescence imaging. This method determines the state of the Rydberg qubit without affecting the other atoms in the ensemble to first order, which can then be reused for further operations. With this developed technique, we are making progress towards realizing a quantum computer based on arrays of atomic ensembles, which can significantly improve the computation speed.

Presenter name: Emily Qiu, Wenchao Xu

Poster session / Mo-74:   *Trapped ions, Rydberg atoms, cold plasmas*   ID218

Aquila: a field-programmable atom array on the cloud

Authors: Alexei Bylinskii[1]; Alexander Keesling[1]; Nathan Gemelke[1]; Florian Huber[1]; Alexander Lukin[1]; Jesse Amato-Grill[1]; Sergio Cantu[1]; Boris Braverman[1]

[1] *QuEra Computing Inc.*

Neutral atom arrays, trapped and arranged using optical tweezers and interacting with each other when excited to Rydberg states, constitute a rapidly evolving platform for quantum simulation and quantum computation. QuEra Inc. presents Aquila: a 256-qubit cloud-accessible machine, with a connectivity that is programmable by the user via their arrangement in 2D, enabling the encoding of problems ranging from quantum simulation to combinatorial optimization. A global drive to the Rydberg state is also programmable, lending itself to a variety of protocols ranging from collective gate pulses to adiabatic state preparation. Finally, a programmable pattern of local detunings of the Rydberg drive offers a degree of individual addressability for state preparation and optimization over weighted graphs. The field-programmable nature of the Aquila platform makes it a very versatile platform for NISQ-era applications, as well as a versatile testbed for developments towards a fully-controllable neutral atom quantum computer.

Presenter name: Alexei Bylinskii

Poster session / Mo-75: *Trapped ions, Rydberg atoms, cold plasmas* ID237

Quantum computing with metastable states in trapped Barium ions

Authors: Jamie Leppard[1]; Ana Sotirova[1]; Andres Vazquez-Brennan[1]; Fabian Pokorny[1]; Chris Ballance[1]

[1] *University of Oxford*

Trapped ion devices make some of the best candidates for quantum information processors as they provide naturally identical qubits with long coherence times. One approach to scaling these systems is using large registers of ions. This can be achieved through implementing qubits in multiple atomic species, where each qubit type is insensitive to the others' light fields, eliminating scattering errors. This allows for advanced qubit control and manipulation schemes. However, using multiple species adds significant experimental overhead [1].

An alternative to using multiple species is using long lived metastable states to encode, store, and manipulate quantum information. In our experiment, we use Barium ions, which have a metastable $5D_{5/2}$ manifold with a lifetime of $\sim 30\,$s, long enough for quantum information processing. When combined with the stable $6S_{1/2}$ ground state manifold, we can gain all of the benefits of having two atomic species, while maintaining the technical simplicity of having just one [1,2]. Additionally, the Barium isotope we use, $^{137}Ba^+$, has nuclear spin $3/2$, giving magnetically insensitive 'clock' qubits in both the $6S_{1/2}$ and $5D_{5/2}$ manifolds as well as 'clock' transitions between the manifolds. Both the ground state qubits and metastable state qubits can be driven using a 2-photon Raman process with 532nm light and very low scattering error.

We demonstrate individual manipulation of 'clock' qubits in these separate manifolds, a prerequisite for partial projective measurements and mid-circuit measurements. Such techniques can be used for error correction schemes using ancilla qubits. Additionally, we can perform in-sequence cooling of the ions to keep error rates low and constant.

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Presenter name: Jamie Leppard

Poster session / Mo-76:   *Trapped ions, Rydberg atoms, cold plasmas*   ID328

Towards the creation of ultracold, neutral plasmas with oppositely charged particles of equal mass via long-range Rydberg molecules

Authors: Johannes Deiglmayr[1]; Michael Peper[1]; Martin Trautmann[1]

[1] *University of Leipzig, Department of Physics and Geosciences*

Long-range Rydberg molecules are molecules in highly-excited electronic states where the binding results from the scattering of an almost free electron of a neutral atom within its orbit. In our lab, we have in recent years developed a detailed experimental and theoretical understanding of the binding in homo- and heteronuclear long-range Rydberg molecules [1]. Our experimental techniques include high-resolution photoassociation and millimeter-wave spectroscopy in ultracold atomic mixture spectroscopy. A novel, especially insightful tool is photodissociation spectroscopy of long-range Rydberg molecules, which allows for a tomographic characterization of the molecular electronic and vibrational state [2].

In this presentation I will focus on our recent progress towards the creation of an ultracold plasma consisting of Cs^+ ions and Cs^- ions [3]. Our experimental route starts with the photoassociation of long-range Rydberg molecules from an ultracold gas of ground-state atoms using a single-photon UV excitation. These molecules are then deexcited to ion-pair states, also called heavy Rydberg molecules, by nanosecond-long pulses from a mir-IR laser. Products are characterized by time-of-flight mass spectrometry. The dense gas of ultracold molecules in ion-pair states forms an ideal starting point to form an ultracold neutral plasma, e.g. by RF dissociation.

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Presenter name: Johannes Deiglmayr

Poster session / Tu-71:   *Trapped ions, Rydberg atoms, cold plasmas*   ID20

Electric-field measurement in cold ion clouds

Authors: Alisher Duspayev[1]; Georg Raithel[1]

[1] *University of Michigan, Ann Arbor*

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The influence of inhomogeneous electric fields in ion clouds on high-angular-momentum Rydberg states is investigated. The fields follow from a superposition of macroscopic and random microscopic (Holtsmark) fields. The ion clouds are induced experimentally by photo-ionizing cold rubidium atoms in the $5D_{3/2}$ state near the focal spot of a near-concentric 1064 nm intracavity optical lattice. We observe how the $n = 57$ F-state mixes with the neighboring hydrogenic manifold and study evolution of spectroscopic features, such as line broadening and excitation-strength distribution for different numbers of created ions. Pump-probe experiments are performed to study the dynamics of the ion-Rydberg-atom system. Our data is utilized to evaluate the experimental feasibility of inhomogeneous-electric-field sensing with subsequent determination of the ion density. Additional experiments with Rydberg P-states are reported as well. Our results might be of interest for future studies of electric fields in nonneutral plasmas and in hybrid cold-atom-ion systems.

Presenter name: Alisher Duspayev

Poster session / Tu-72:   *Trapped ions, Rydberg atoms, cold plasmas*   ID102

Rydberg engineering: recent techniques for sensitive field measurements

Authors: Andrew Rotunno[1]; Nikunjkumar Prajapati[1]; Amy Robinson[2]; Samuel Berweger[1]; Alexandra Artusio-Glimpse[1]; Matthew Simons[1]; Christopher Holloway[1]

[1] *National Institute of Standards and Technology*

[2] *CU Boulder*

Highly-excited Rydberg atoms have been used for International System of Unit (SI)-traceable radio-frequency (RF) electric field and power measurements, but are limited in sensitivity to order 100 μV/m/$\sqrt{Hz}$ by noise and linewidth issues. These Rydberg atom-based sensors have far-reaching capabilities, ranging from SI-traceable measurements to receiving communication signals, even streaming video. We survey several recent experimental schemes and analysis techniques which help increase sensitivity in Rydberg spectroscopy measurements. Two methods to amplify signals without introducing electronic noise are the optical homodyne detection scheme to reduce laser power noise fluctuations, and using a metamaterial split-ring resonator to enhance the field at the location of the atoms. Linewidths can be narrowed via significant experimental adjustments, such as cooling atoms or using Doppler-narrowed three-photon schemes, which are efficiently simulated via a new calculation method. We also examine methods to lower the noise floor of the 'super-heterodyne' scheme, which enables detection of phase and amplitude for very weak RF signals using an RF local oscillator, as well as a separate 'all-optical' phase detection method in Rubidium. We also develop theoretical methods for fitting experimental spectra which are broadened by spatially inhomogeneous fields, as are present in vapor cells and unmatched waveguides. Each of these methods helps increase sensitivity of atomic electric field measurements, to the point where they have enabled wireless live video reception. Taken together, they demonstrate the many opportunities in Rydberg engineering for refining measurements.

Presenter name: Andrew Rotunno

Higher-order effects of electric quadrupole fields on a single Rydberg ion

Authors: Shalina Salim[1]; Gerard Higgins[1]; Chi Zhang[1]; Fabian Pokorny[1]; Harry Parke [1]; Erik Jansson[1]; Markus Hennrich[1]

[1] *Stockholm University*

Rydberg ions have large dipole and quadrupole polarizabilities which makes them extremely sensitive to external electric fields [1],[2]. As a result, an ion in the Rydberg state experiences altered trapping potential which leads to motion-dependent Rydberg excitation energies [3]. Higher the Rydberg state more is the sensitivity to the electric quadrupole trapping fields. The oscillating trapping field induces an energy shift in these states which oscillates at the trap drive frequency and generates sidebands in the spectrum. Unwanted couplings to these field-induced sidebands reduces the fidelity of Rydberg ion quantum gate operations. To mitigate this MW field are used which induces dressed states with opposite polarizabilities to create Rydberg state with vanishing polarizability which are insensitive to electric fields [4].

Here we study the higher order effects of the quadrupole electric filed on a single trapped Sr^+ Rydberg ion confined in a Paul trap, which arises due to the quadrupole polarizability of the Rydberg states. The effects were investigated on $nS_{\frac{1}{2}}$ and $nP_{\frac{1}{2}}$ states and resonance shifts and spectral sidebands were observed experimentally. The Rydberg excitation energies depend quadratically on the trapping RF field amplitude. For the $nS_{\frac{1}{2}}$ state the first order spectral sidebands were much weaker whereas in the $nP_{\frac{1}{2}}$ state the spectrum showed a forest of sidebands. All results are in good agreement with theory [5].

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Presenter name: Shalina Salim

Poster session / Tu-74: *Trapped ions, Rydberg atoms, cold plasmas* ID159

A novel trapped-ion quantum computer using optical tweezers and electric fields

Authors: Arghavan Safavi-Naini[1]; Liam Bond[2]; Matteo Mazzanti[2]; Rene Gerritsma[2]; Rima Schussler[2]; Robert Spreeuw[2]

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[2] *Universiteit van Amsterdam*

Trapped-ions are one of the most mature platforms for quantum computation and quantum simulation. In trapped-ion quantum simulators the spin-spin interactions are mediated by the collective motion of the ions in the crystal (phonons). We show that additional optical tweezer potentials can be used to engineer the phonon spectrum, and thus tune the interactions and connectivity of the ion qubits beyond the power-law interactions accessible in current setups [1].

Moreover, we use optical tweezers to create two new scalable architectures for trapped-ion quantum computing. Neither scheme relies on ground state cooling or the Lamb-Dicke approximation. In the first we use a combination of optical tweezers delivering qubit state-dependent local potentials with an oscillating electric field [2]. Since the electric field allows for long-range qubit-qubit interactions mediated by the center-of-mass motion of the ion crystal alone, it is inherently scalable to large ion crystals. In the second scheme, the strong curvature of the light field of the tightly focused tweezer creates strong polarization gradients that lead to qubit-state dependent forces on the ion (optical Magnus effect [3]). We show that these may be used to implement quantum logic gates on pairs of ion qubits in a crystal [4].

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Presenter name: Arghavan Safavi-Naini

Poster session / Tu-75:   *Trapped ions, Rydberg atoms, cold plasmas*   ID207

Correlation spectroscopy of a planar 91-ion crystal in a novel monolithic Paul trap

Authors: Helene Hainzer[1]; Dominik Kiesenhofer[1]; Tuomas Ollikainen[1]; Matthias Bock[2]; Artem Zhdanov[1]; Tuvia Gefen[3]; Christian Roos[1]

[1] *University of Innsbruck*

[2] *Austrian Academy of Sciences*

[3] *Caltech*

The development of fully controlled quantum systems in the laboratory has seen tremendous progress in recent years. One experimental platform which has shown to allow for an excellent level of control are trapped atomic ions, stored in linear radio-frequency traps. Here, one-dimensional chains of up to several tens of ions have already been employed successfully to carry out quantum simulation tasks [1,2]. In our work we aim to scale up the number of individually controllable trapped ions for quantum simulations beyond the state of the art of ~50 particles, by using the platform of planar ion crystals stored in a linear Paul trap. In this way some scalability-related problems of long ion chains, such as high heating rates of the axial motional modes and difficulties in laser-addressing outer ions, can be circumvented. On this poster we present our new apparatus, the centerpiece of which is a novel monolithic linear Paul trap, enabling us to trap stable 2-dimensional crystals of up to 100 40Ca+ ions. Moreover, we demonstrate our recent results on correlation spectroscopy, implemented in a planar crystal consisting of 91 ions [3]. Correlation spectroscopy is a powerful tool, initially developed in the context of precision metrology, and allows phase differences between qubits to be measured precisely even in the presence of strong correlated phase noise [4,5]. The key idea here is that due to their spatial proximity to each other in the trap the qubits, encoded in each of the 91 ions, will be affected in a collective way by noise processes such as ambient magnetic field fluctuations. Correlations in the outcomes of collective Ramsey measurements provide information about the phase differences between the qubits, even for probe times significantly longer than the coherence time of the individual particles. We apply correlation spectroscopy to characterize a magnetic field gradient, which gives rise to transition frequency differences across the planar ion crystal. In the context of measurement uncertainties, we are able to show that considering N-qubit correlations reduces the phase uncertainty with respect to 2-qubit correlations, and the advantage of using entangled states becomes negligible for N→∞.

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Presenter name: Helene Hainzer

Poster session / Tu-76: *Trapped ions, Rydberg atoms, cold plasmas* ID223

A programmable quantum simulator with two-electron Rydberg atoms in optical tweezer arrays

Authors: Luca Guariento[1]; Vladislav Gavryusev[2]; Jacopo Catani[3]; Leonardo Fallani[2]; Giacomo Cappellini[3]

[1] *Dipartimento di Fisica 'Ettore Pancini', Università degli Studi di Napoli Federico II*

[2] *Dipartimento di Fisica e Astronomia, Università degli Studi di Firenze*

[3] *Istituto Nazionale di Ottica del Consiglio Nazionale delle Ricerche (CNR-INO)*

I will present a new programmable quantum simulator based on Rydberg strontium atoms trapped in optical tweezers arrays at CNR-INO and LENS in Florence. This new experimental setup, supported by an infrastructural program of CNR, is now under construction in our laboratories as a joint effort of CNR and the University of Florence.

I will present the main features of the apparatus, including the techniques that will be employed for the generation of programmable arrays of optical tweezers and for the control of the different sources of decoherence. I will also discuss the advantages offered by two-electron atoms, including narrow optical transitions that can be exploited for effective atomic cooling schemes, and the existence of a metastable state that provides an additional degree of freedom for the manipulation of individual atoms, as well as a direct connection to frequency metrology. I will finally discuss the applications that we envision for this new setup, in particular the simulation of quantum spin models with different types of interactions and topologies, and the realization of multiparticle entangled states.

Presenter name: Giacomo Cappellini

Poster session / Tu-77: *Trapped ions, Rydberg atoms, cold plasmas* ID238

High speed THz imaging with Rydberg atoms

Authors: Matt Jamieson[1]; Lucy Downes[1]; Shuying Chen[1]; Nourah Almuharish[1]; Andrew Mackellar[1]; Gianluca Allinson[1]; Kevin Weatherill[1]; Charles Adams[1]

[1] *University of Durham*

THz imaging and THz technologies are of great interest for a variety of applications, including nondestructive testing and medical diagnosis. Here, we demonstrate a THz imaging setup that employs Cs Rydberg atoms as THz-to-optical photon converters to provide full field images at many thousands of frames per second, that can be captured with conventional optical cameras [1]. The primary mechanism that enables this is the introduction of a strong visible decay pathway when the atoms are coupled with a terahertz field. Due to the density of Rydberg energy states, a relatively continuous spectrum of THz frequencies can imaged by careful choice of these states; we show imaging capabilities at 0.55THz and 1.05THz, for example. Full characterization of the system and progress towards a Rb imager will extend its versatility, and open up the potential for two-colour imaging.
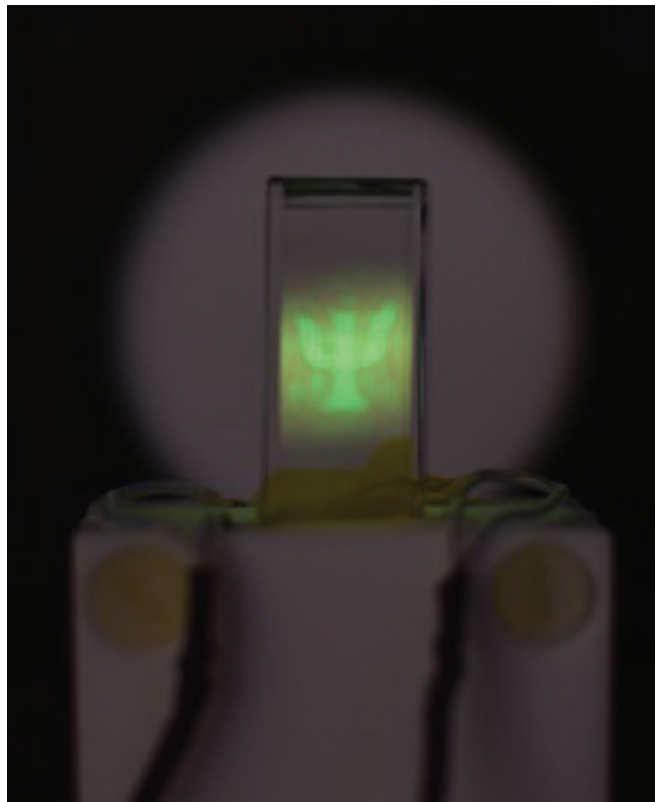
Figure 1: Image

[1] L. A. Downes, A. R. MacKellar, D. J. Whiting, C. Bourgenot, C. S. Adams, and K. J. Weatherill, "Full-field terahertz imaging at kilohertz frame rates using atomic vapor," Phys. Rev. X 10, 011027 (2020).

Presenter name: Matt Jamieson

Benchmarking a large-scale quantum simulator with useful applications

Authors: Adam Shaw[1]; Joonhee Choi[1]; Ran Finklestein[1]; Pascal Scholl[1]; Daniel Mark[2]; Manuel Endres[1]; Soonwon Choi[2]

[1] *Caltech*

[2] *MIT*

Using a Rydberg atom-array quantum simulator, we experimentally demonstrate new applications which become possible through verifiable quantum evolution. At the outset, we show experimental benchmarking of system sizes with up to 60 atoms, and demonstrate new techniques in approximate verification beyond the classical simulation threshold. Further, we show how such benchmarking allows us to perform *in situ* local Hamiltonian learning, to optimize Hamiltonian engineering for preparing interesting quantum states, and to make quantitative comparisons between analog and digital quantum devices aiming to create maximum entanglement entropy states. These developments showcase practically useful applications for device benchmarking protocols in quantum devices, and further demonstrate concrete steps towards quantum advantage with a near term quantum simulator.

Presenter name: Adam Shaw

Poster session / We-74: *Trapped ions, Rydberg atoms, cold plasmas* ID38

A cryogenic neutral atom optical tweezer array

Authors: Ting You Tan[1]; Ting-wei Hsu[2]; Zhenpu Zhang [2]; Matteo Marinelli[1]; Daniel Slichter[3]; Adam Kaufman[4]; Cindy Regal[1]

[1] *University of Colorado, Boulder*

[2] *University of Colorado, Boulder and JILA*

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[4] *JILA*

Scalable ultracold Rydberg atom arrays provide an intriguing platform for programmable quantum computation. We present a new system for a 2D Rydberg qubit array of 87Rb atoms embedded in a low-vibration cryostat. Cryopumping will improve the atom vacuum lifetime to fully leverage the scalability of Rydberg platforms, and a 30 K environment will extend the Rydberg lifetime to several times its value at room temperature. To create a large and controlled array, we will utilize a 2D optical lattice with the site-resolved addressability and interaction control aided by optical tweezers. We will harness a bi-chromatic magic lattice to provide identical confinement for both ground and Rydberg states. We will report our results on cryocooling and vibration isolation performance, as well as our progress towards atom trapping within the cryogenic environment.

Presenter name: Ting You Tan

Poster session / We-75:   *Trapped ions, Rydberg atoms, cold plasmas*   ID111

Rydberg atom interactions with an optical nanofiber

Authors: Alexey Vylegzhanin[1]; Aswathy Raj[1]; Dylan Brown[1]; Sile Nic Chormaic[1]

[1] *Light-Matter Interactions for Quantum Technologies Unit, Okinawa Institute of Science and Technology Graduate University, Japan*

Cold Rydberg atoms have recently become a promising platform for quantum information processing and quantum simulations due to their specific properties. The Rydberg blockade regime allows us to entangle qubits and to make CNOT and CPhase gates. Optical nanofibers (ONFs) are an excellent tool to interact with such atoms. They are relatively easy to install into experimental setups because of the simplicity of coupling light into and out of them. The evanescent field decaying from the nanofiber can excite the atoms from the ground state or produce a dipole trap to localize them around the nanofiber. A probe light sent through the fiber is sensitive to the presence of the atoms in the vicinity of the nanofiber and can be used to collect information from neutral atom qubits. To have a precise control over such a system one needs to know all the interactions happening between the atoms and the nanofiber material. We exploit a two-photon ladder-type excitation in ^{87}Rb by using 780 nm magneto-optical trap (MOT) cooling lasers and 480 nm light coming from the evanescent field of an ONF. The 480 nm light is locked by an external vapor cell EIT to a particular Rydberg transition. During the experiment, the MOT is overlapped with the ONF region and, firstly, reaches an equilibrium atom population. Then, the 480 nm laser is turned on, and the atoms in the vicinity of the ONF undergo Rydberg excitation and get lost from the MOT. This process introduces an additional loss rate to the MOT population, which we measure by collecting the fluorescence signal. By scanning the 480 nm light across the transition we observe coherent and incoherent Rydberg excitation processes. The experiment was reproduced for excitation to $nS_{1/2}$, $nD_{3/2}$ and $nD_{5/2}$ Rydberg states for a wide range of principal quantum number, n, values.

Presenter name: Alexey Vylegzhanin

Polyatomic ultralong range Rydberg molecules

Authors: David Mellado-Alcedo[1]; Janine Shertzer[2]; H. R. Sadeghpour[3]; Rosario González-Férez[1]

[1] *Universidad de Granada*

[2] *Department of Physics, College of the Holy Cross*

[3] *ITAMP, Center for Astrophysics, Harvard & Smithsonian*

In cold and ultracold mixtures of atoms and molecules, Rydberg interactions with surrounding atoms or molecules may, under certain conditions, lead to the formation of special long-range Rydberg molecules [1, 2, 3]. These exotic molecules provide an excellent toolkit for manipulation and control of interatomic and atom-molecule interactions, with applications in ultracold chemistry, quantum information processing and many-body quantum physics. In this poster, we discuss ultralong-range polyatomic Rydberg molecules formed when a heteronuclear diatomic molecule is bound to a Rydberg atom [3, 4]. The binding mechanism appears due to anisotropic scattering of the Rydberg electron from the permanent electric dipole moment of the polar molecule. We propose an experimentally realizable scheme to produce these triatomic ultralong-range Rydberg molecules in ultracold RbCs traps, which might use the excitation of cesium or rubidium [5]. By exploiting the Rydberg electron-molecule anisotropic dipole interaction, we induce a near resonant coupling of the nonzero quantum defect Rydberg levels with the RbCs molecule in an excited rotational level. This coupling enhances the binding of the triatomic ultralong-range Rydberg molecule and produces favorable Franck-Condon factors.

Another type of ultralong-range Rydberg molecule is formed in collisions between polar molecules in cold and ultracold settings [6]. The interaction of -doublet nitric oxide (NO) with long-lived Rydberg NO molecules forms ultralong-range Rydberg bimolecules with GHz energies and kilo-Debye permanent electric dipole moments. The description includes both the anisotropic charge-molecular dipole interaction and the electron-NO scattering. The rotational constant for the Rydberg bimolecules is in the MHz range, allowing for microwave spectroscopy of rotational transitions in Rydberg bimolecules. The Rydberg molecules described here hold promise for studies of a special class of long-range bimolecular interactions.

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[5] R. Gonzalez-Ferez, et al, J. Phys. B 53, 074002 (2020).
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Presenter name: Rosario González-Férez

Superradiance decoherence caused by long-range Rydberg-atom pair interactions

Authors: Elmer Suarez[1]; Philip Wolf[1]; Patrizia Weiss[1]; Sebastian Slama[1]

[1] *Center for Quantum Science and Physikalisches Institut, Eberhard-Karls Universität Tübingen*

This work reports on the observation of superradiance decoherence caused by long-range dipole-dipole interactions between Rydberg atoms. A cold atom cloud is prepared in the mode volume of a weakly driven optical cavity, and excited to a Rydberg state. The cavity transmission monitors the Rydberg dynamics in real-time and detects superradiant enhancement of the transition rates between neighboring Rydberg states. The observed enhancement is reduced for increasing Rydberg atom density: a signature of atom pair-interactions. The observations are explained within a model based on the idea of Rydberg blockade reducing the atom number participating in the Dicke state, responsible for superradiance.

Presenter name: Elmer Suarez

Poster session / We-78: *Trapped ions, Rydberg atoms, cold plasmas* ID209

Waveguide QED with Rydberg superatoms

Authors: Hannes Busche[1]; Nina Stiesdal[1]; Jan Kumlin[2]; Kevin Kleinbeck[2]; Lukas Ahlheit[1]; Cedric Wind[1]; Julia Gamper[1]; Hans Peter Büchler[2]; Sebastian Hofferberth[1]

[1] *University of Bonn*

[2] *University of Stuttgart*

Rydberg quantum optics allows to create strong optical nonlinearities at the level of individual photons by mapping the strong dipolar interactions between collective Rydberg excitations onto optical photons. The interactions lead to a blockade effect such that an optical medium smaller than the blockaded volume only supports a single excitation which is collectively shared amongst all blockaded atoms forming a 'Rydberg superatom'. Thanks to the collective nature of the excitation, the superatom effectively represents a single emitter with a strongly enhanced coupling to few-photon probe fields with directional emission into the initial probe mode [1].

This makes Rydberg superatoms an ideal platform to study the interaction of individual two-level emitters with quantised light fields. The interaction leads for example to the emergence of two- and three-photon correlations in the transmitted light, while exchange interactions between the constituent atoms within a superatom lead to nontrivial decay dynamics of the collective state [2].

When combined with controlled dephasing into dark, collectively excited states, we exploit the strong photon-emitter coupling to subtract exact photon numbers from incoming light fields providing a means to precisely manipulate their quantum state [3]. To this end, we cascade multiple superatoms in 1D chain along mode of the probe field. In the regime of low dephasing, such a cascaded quantum system of multiple superatoms also offers the prospect to observe photon-mediated interactions and entanglement along the probe mode which effectively forms a freespace 'waveguide'.

We also provide a brief outlook on a new cryogenic experimental platform in which we plan to study hybrid quantum systems of Rydberg atoms combined with e.g. electromechanical oscillators or integrated photonic and microwave circuits.

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[3] N. Stiesdal, H. Busche, K. Kleinbeck, J. Kumlin, M. G. Hansen, H. P. Büchler and S. Hofferberth, Nat. Commun. 12, 4328 (2021).

Presenter name: Hannes Busche

Poster session / We-79:   *Trapped ions, Rydberg atoms, cold plasmas*   ID369

Towards a dual-species tweezer array of Na and Cs atoms

Authors: Kenneth Wang[1]; Ryan Cimmino[1]; Fang Fang[1]; Yu Wang[1]; Kang-Kuen Ni[1]

[1] *Harvard University*

Optical tweezer arrays of neutral atoms provide a controllable and scalable platform for quantum computing and quantum simulation. Neutral atoms in these arrays interact via long-range van der Waals interactions, when excited into Rydberg states. A dual species array adds to the toolbox of atom arrays and allow for schemes involving multiple species. For example, nondestructive measurement, a key ingredient in quantum error correction, can be achieved by entangling "ancillary" qubits with "data" qubits and performing readout on the ancillary qubits. Having two distinct species to play the role of "data" and "ancilla" minimizes crosstalk when performing measurements on "ancilla" qubits or realizing gates between "data" qubits. We present our progress towards a dual species tweezer array platform using Na and Cs atoms. We stochastically load Cs atoms into static traps created by a spatial light modulator and can rearrange them into a desired defect-free pattern with high fidelity using traps formed by acousto-optic deflectors. We can perform Raman sideband cooling on the entire array. We also coherently excite atoms to the Rydberg state and see signatures of the interactions between the atoms.

Presenter name: Kenneth Wang

Evaluating states in trapped ions with local correlation between internal and motional degrees of freedom

Author: Silpa Muralidharan[1]

[1] *Osaka University*

We propose and demonstrate a scalable scheme for the simultaneous determination of internal and motional states in trapped ions with single-site resolution. The scheme is applied to the study of polaritonic excitations in the Jaynes-Cummings-Hubbard model with trapped ions, in which the internal and motional states of the ions are strongly correlated. We observe quantum phase crossovers of polaritonic excitations in two ions by directly evaluating their variances per ion site. Our work establishes an essential technological method for large-scale quantum simulations of polaritonic systems. Quantum simulations allow us to study the properties of many-body quantum systems that are hard to investigate with classical computers. A promising platform for realizing quantum simulations is a system of trapped ions. Trapped ions have advantages over other systems from such perspectives as ease of preparation and control, and we can address individual particles with little perturbation to neighboring particles. The Jaynes-Cummings (JC) model describes the atom-field interaction in a combined system of a two-level atom and a quantized electric-field mode. An interconnected array of two-level atoms interacting with quantized wave modes is known as the Jaynes-Cummings-Hubbard (JCH) model, and related systems of coupled cavity arrays have been extensively investigated. The JCH model can be realized with arrays of cavity QED systems [12,13] and of circuit QED systems, as well as systems of trapped ions. These systems can be flexibly controlled with sets of system parameters. Therefore, they can be considered to be attractive systems for studying quantum many-body phenomena. In the JCH model, quasiparticles called polaritons play an essential role. Each polariton is represented as the superposition of an internal excitation and a photon or a motional excitation (phonon). Polaritons are well-defined particles in the JCH model and their total number is conserved. The implications for understanding the JCH model are apparent in the quantum phase transition of a JCH system between the Mott-insulator (MI) 1 and superfluid (SF) phases, which are characterized by a drastic change in the polariton-number variance per site. In conclusion, we proposed a scalable scheme for the simultaneous determination of internal and motional states in trapped ions based on conditional measurements. The scheme was applied to a system of polaritons in the JCH model, and a phase crossover was studied by evaluating the quantities such as the variance for the total excitation number (polariton number) per site. The scheme proposed here can be applied to larger JCH systems where steeper phase crossovers and transitions as well as nonequilibrium behaviors reflecting interactions are expected. In addition, the scheme can also be applied to other subjects in quantum simulations with trapped ions where both the internal and motional degrees of freedom are fully exploited as the simulation resources.

Presenter name: Silpa Muralidharan

Poster session / Th-73:   *Trapped ions, Rydberg atoms, cold plasmas*   ID92

Towards quantum control and spectroscopy of a single hydrogen molecular ion

Authors: David Holzapfel[1]; Nick Schwegler[1]; Jonathan Home[1]; Daniel Kienzler[1]

[1] *ETH Zürich*

The complexity and variety of molecules offer opportunities for metrology and quantum information that go beyond what is possible with atomic systems. The hydrogen molecular ion is the simplest of all molecules and can thus be calculated ab initio to very high precision [1]. In combination with spectroscopy this allows to determine fundamental constants and test fundamental theory at record precision [2–4]. Spectroscopy of the hydrogen molecular ion should improve substantially by performing experiments with single hydrogen molecular ions, reducing systematic uncertainties and improving signal strength. This necessitates quantum control.

I will present our progress towards full quantum control of a single hydrogen molecular ion. Our most recent results demonstrate the co-trapping of single H_2^+ and $^9Be^+$ ions. We observe H_2^+ trapping lifetimes of $\approx 10h$. We perform ground-state cooling of the ion pair's axial in-phase mode of motion, resulting in an average phonon number of 0.088(4), which corresponds to a temperature of 24.8(4) K.

The experimental apparatus features a cryogenic ultra-high vacuum chamber, housing a microfabricated monolithic linear Paul trap. H_2^+ is loaded into the trap by electron bombardment of H_2. We aim to use He buffer gas cooling in combination with quantum logic spectroscopy to initialize the internal state of H_2^+ in a pure quantum state and implement nondestructive readout [5, 6].

[1] V. I. Korobov, J.-P. Karr, M. Haidar, and Z.-X. Zhong, "Hyperfine structure in the H_2^+ and HD^+ molecular ions at order m ^{6}," Phys. Rev. A **102**, 022804, (2020).

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[3] S. Patra, M. Germann, J.-P. Karr, M. Haidar, L. Hilico, V. I. Korobov, F. M. J. Cozijn, K. S. E. Eikema, W. Ubachs, and J. C. J. Koelemeij, "Proton-electron mass ratio from laser spectroscopy of HD^+ at the part-per-trillion level," Science **369** 1238–1241 (2020).

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[6] P. O. Schmidt, T. Rosenband, C. Langer, W. M. Itano, J. C. Bergquist, and D. J. Wineland, "Spectroscopy using quantum logic," Science **309**, 749–752 (2005).

Presenter name: David Holzapfel

Poster session / Th-74: *Trapped ions, Rydberg atoms, cold plasmas* ID116

Quantum control of motional states in mixed-species trapped-ion crystals

Authors: Jenny Wu[1]; Pan-Yu Hou[1]; Stephen Erickson[1]; Yong Wan[1]; Giorgio Zarantonello[1]; Adam Brandt[1]; Daniel Cole[2]; Andrew Wilson[2]; Daniel Slichter[2]; Dietrich Leibfried[2]

[1] *NIST/University of Colorado Boulder*

[2] *National Institute of Standards and Technology*

The spectral separation between resonant transitions of different ion species offers mutual isolation that can be advantageous for scaling trapped ion quantum computing systems, and numerous groups are now performing experiments with mixed-species crystals of trapped ions. In our group at NIST, trapped ^{9}Be$^+$ and $^{24/25}$Mg$^+$ ions in a linear RF trap have been utilized to demonstrate sympathetic cooling, logic gates, gate teleportation, quantum-logic spectroscopy, and high-fidelity indirect readout. Here we discuss two further experiments on quantum control of mixed-species trapped-ion chains.

We modify electromagnetically-induced-transparency (EIT) cooling techniques to accommodate the hyperfine structure of ^{25}Mg$^+$. EIT cooling, as originally conceived, is a broad-bandwidth, rapid, sub-Doppler cooling method suitable for three-level Λ systems. EIT cooling also requires less laser power than far-detuned Raman sideband cooling. While the hyperfine levels of ^{25}Mg$^+$ are suitable for the implementation of qubits, the presence of more than two ground levels (in contrast to ^{24}Mg$^+$) requires modification of the original EIT cooling approach. We present experimental progress in applying EIT cooling to a single ^{25}Mg$^+$ ion, theoretical understanding of limitations of the technique, and extensions to sympathetic cooling of mixed-species crystals. In particular, we show EIT cooling of a 1.2 MHz axial mode of a single ^{25}Mg$^+$ ion to an average motional occupation number $\bar{n} < 0.4$ in under 1 ms.

We have also coupled pairs of motional modes of various mixed- and same-species ion crystals using an electric potential that oscillates at the difference of two motional frequencies and has suitable spatial dependence. Mode coupling can be used for increased motional control and can aid in sympathetic cooling and quantum-logic spectroscopy. This coupling can enable certain ions within a mixed-species chain to cool and read out states of motional modes in which the addressed ions' participation is small or zero. We demonstrate this by using ^{25}Mg$^+$ in a ^{9}Be$^+$-^{25}Mg$^+$-^{9}Be$^+$ crystal to perform sympathetic cooling and repeated readout of the axial "Stretch" mode in which the center ^{25}Mg$^+$ ion does not participate.

Presenter name: Jenny Wu

Poster session / Th-75:   *Trapped ions, Rydberg atoms, cold plasmas*   ID146

Chasing the last bit of STIRAP efficiency between metastable helium and Rydberg state

Authors: Xiaoyang Liu[1]; Eli Rafkin[1]; Christian Zaprianov[1]; Harold Metcalf[1]

[1] *Stony Brook University*

Using laser pulses to manipulate the internal quantum states of atoms and molecules provides new opportunities to create novel quantum devices. Coherent population transfer is the fundamental tool for many potential quantum applications such as atomic lithography, Rydberg arrays, and quantum information processing. We describe the Rydberg state excitation in a three-level system through Stimulated Raman Adiabatic Passage (STIRAP) and an excitation efficiency measurement method with bichromatic force. Theoretically, STIRAP can produce 100% population transfer, but it is typically far less efficient in practice. We will discuss the potential reasons for efficiency loss in three-level population transfer, especially the effect of velocity spread in atomic beam, and the solutions to overcome the efficiency loss.

Presenter name: Harold Metcalf

Intra-cavity frequency-doubled VECSEL system for narrow linewidth Rydberg EIT spectroscopy

Authors: Joshua Hill[.]; William Holland[1]; Paul Kunz[1]; Kevin Cox[1]; David Meyer[1]

[1] *US Army Research Laboratory*

Vertical external-cavity surface-emitting lasers (VECSELs) augmented by intracavity nonlinear optical frequency conversion have emerged as an attractive light source of ultraviolet to visible light for demanding scientific applications, relative to other laser technologies. They offer high power, low phase noise, wide frequency tunability, and excellent beam quality in a simple and inexpensive system architecture. Here, we characterize the frequency stability of an intra-cavity frequency-doubled VECSEL with 690 mW of output power at 475 nm using the delayed self-heterodyne technique and direct comparison with a commercial external-cavity diode laser (ECDL). We measure the fundamental's Lorentzian linewidth to be $2\pi \times 5.3(2)$ kHz, and the total linewidth to be $2\pi \times 23(2)$ kHz. In addition, we perform Rydberg-state spectroscopy via electromagnetically induced transparency (EIT), observing narrow 3.5 MHz full-width half maximum EIT. By doing so, we demonstrate that intra-cavity frequency-doubled VECSELs can perform precision spectroscopy at the MHz level, and are a promising tool for contemporary, and future, quantum technologies

Presenter name: Joshua Hill

Poster session / Th-77:   *Trapped ions, Rydberg atoms, cold plasmas*   ID217

Effect of an optical dipole trap on resonant atom-light interactions

Authors: Teresa Karanikolaou[1]; Darrick Chang[1]

[1] *ICFO*

The optical properties of a fixed atom are exquisitely well-known and investigated. For example, one important phenomenon is that the atom can have an extraordinarily strong response to a resonant photon, as characterized by a resonant elastic scattering cross section given by the wavelength of the transition itself, $\sigma_{sc} \propto \lambda^2$. The case of a tightly trapped ion, where the ground and excited states are equally trapped, is also well-known. Then, the elastic cross section is reduced by a fraction corresponding to the square of the "Lamb-Dicke parameter", while this same parameter also dictates the probability of inelastic scattering that gives rise to motional heating.

In contrast, there are many emerging quantum optics setups involving neutral atoms in tight optical dipole traps, such as coupled to nanophotonic waveguides and cavities or in atomic arrays, where the goal is to utilize efficient atom-light interactions on resonance. Often, while the ground state is trapped, the excited state may in fact be untrapped or even anti-trapped. Here, we systematically analyze the consequences that this unequal trapping has on reducing the elastic scattering cross section, and increasing the motional heating rate. This analysis may be useful to optimize the performance of quantum optics platforms where equal trapping cannot be readily realized.

Presenter name: Teresa Karanikolaou

Poster session / Th-78:   *Trapped ions, Rydberg atoms, cold plasmas*   ID229

Experimental setup for trapping and controlling large registers of barium-ion qubits

Authors: Fabian Pokorny[1]; Andres Vazquez-Brennan[1]; Jamie Leppard[1]; Ana Sotirova[1]; Chris Ballance[1]

[1] *University of Oxford*

Trapped-ion systems are amongst the most promising approaches for realizing useful quantum computers and simulators. However, scaling up the qubit register size without compromising performance remains challenging. In the experimental setup presented here we work on realizing large registers of trapped barium-ion qubits.

Barium-ion qubits offer several features favourable for quantum computation experiments. Among these features are optical transitions in the visible range as well as long-lived metastable states which allow for mixed qubit registers that enable novel qubit control schemes like mid-circuit or partial projective measurements and in-sequence cooling. We show an all-fiber Raman system consisting of low-noise 532 nm lasers, standard fiber modulators, and a custom laser-written waveguide beam delivery system capable of single-ion addressing. We confine the ions in a segmented monolithic 3D microfabricated trap [1] that allows for advanced trapping potential control while simultaneously providing a low heating rate.

Odd barium isotopes additionally offer a range of magnetically insensitive "clock"-states in the ground and metastable states. Amongst them, the radioactive isotope $^{133}Ba^+$, with a nuclear spin of $I = 1/2$, has the simplest level structure [2]. While its lifetime of 10.51 years is not problematic for its use as qubit, radiation safety considerations require sample sizes of only a few micrograms, too little for conventional oven loading schemes. Here we present our work towards fabricating $BaCl_2$ targets that are suitable for ablation loading.

[1] P. See, et al., Journal of Microelectromechanical Systems 22, (2013)
[2] J. E. Christensen, et al., npj Quantum Information 6, (2020)

Presenter name: Fabian Pokorny

Poster session / Th-79: *Precision measurement and tests of fundamental physics* ID407

Rydberg-dressed Ising interactions for spin squeezing

Authors: Jacob A. Hines; Shankari V. Rajagopal; Gabriel L. Moreau; Nazli U. Koyluoglu; Michael D. Wahrman; Neomi A. Lewis; Monika H. Schleier-Smith

Stanford University

Rydberg dressing provides a versatile way to create strong coherent interactions between ground-state neutral atoms. These local, optically controlled interactions can theoretically be used to create metrologically useful entanglement, such as spin squeezing in an atomic ensemble. We present progress on spin squeezing in a cesium atomic clock with Ising interactions produced by single-photon coupling to nP states. The resulting finite-range interactions generate an analog of one-axis twisting, which is well-established for squeezing in all-to-all-coupled systems. We implement optimized pulse sequences incorporating Rydberg dressing and an effective transverse field to generate strong twisting dynamics with limited decoherence. The inclusion of the transverse field additionally opens prospects for Floquet engineering to realize a modified two-axis countertwisting Hamiltonian for optimized squeezing.

Presenter name:

Jacob Hines

Poster session / Th-80:   *Quant. optics & hybrid quant. sys.*   ID291

Towards nanostructured potentials: coupling of an ultracold atomic gas with a surface and subwavelength imaging

Authors: Jean-baptiste Gerent[1]; Romain Veyron [1]; Guillaume Baclet[2]; Philippe Bouyer[1]; Simon Bernon[1]

[1] *LP2N - Université de Bordeaux - CNRS*

[2] *LP2N - Université de Bordeaux - CNRS*

Cold atoms in lattices have appeared as good candidates to mimic the properties of electrons in solid-state systems and to simulate quantum materials. However, experimental techniques currently use optical lattices in the far-field. This limits the lattice spacing to /2 and gives an upper bound to the relevant energy scale (tunneling and interaction), making it difficult to enter deeply into the proper quantum regimes to observe magnetic quantum correlations or strongly correlated phases. Our project aims at reducing the lattice period to bridge the gap between solid-state (Å) and far-field lattice (500nm) by developing a hybrid quantum system of Bose and Fermi quantum gas in close proximity of a nanostructured surface generating subwavelength lattice potentials. To push toward this goal, we have developed a novel method to transport and trap an ultracold atomic cloud in the vicinity of a surface. In this poster, we will discuss the design of the first atom-chip that will implement this method, and report on tests about the transport sequence. In particular, by measuring the power spectral density of the trap parameters, we predict the noise-induced heating of the trapped cloud. Subwavelength lattice analysis requires addressing each site individually with a resolution better than the diffraction limit. For that purpose, we implemented a tunable subwavelength imaging system with a theoretical resolution of 30nm and we demonstrated its performance by resolving the wave-packet of a cloud in a single lattice site. This scheme involves two superimposed optical lattices at 1064 nm and 1529 nm, whose interfringe can be tuned. In the poster, the experimental setup will be presented, and the data will be compared to the theoretical expectation.

Presenter name: Gerent Jean-Baptiste

Virtual poster / Vir46:   *Trapped ions, Rydberg atoms, cold plasmas*   ID120

Enhanced sideband cooling of trapped ions via resonant dipole-dipole interaction

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Resolved sideband cooling provides an important technique in preparing the trapped ions to their motional ground state, which is essential in ion-based quantum computation. Here we present a surpassing sideband cooling performance in trapped ions utilizing light-mediated dipole-dipole interactions among them. By placing the ions at magic interparticle distances, we find that the target ion can be cooled closer to the zero-phonon state, outperforming the single-ion limit. We further investigate the effect of different ionic configurations, number of ions, and laser detuning, where we identify various optimal parameter regimes in superior cooling performance. Our results provide insights to cooling ions with collective dipole-dipole interactions and pave the way toward implementing genuine quantum operations in multiple quantum registers.

Presenter name: Wang, Chung-Hsien

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Virtual poster / Vir47:   *Trapped ions, Rydberg atoms, cold plasmas*   ID138

A segmented-blade ion trap with biasing rods

Authors: Jungsoo Hong[1]; Myunghun Kim[1]; Keumhyun Kim[1]; Wonchan Lee[2]; Hyegoo Lee[1]; Youngil Moon[1]; Moonjoo Lee[1]

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We report the construction of a segmented-blade linear trap [Hong et al., arXiv:2202.07465 (2022)]. Our trap has auxiliary biasing rods that would be used for compensating the micromotion. Complete development process is discussed, including the laser machining of an alumina and electroplating with gold. The surface roughness of the blade is examined via both electron and optical microscopy. Trapping laser-cooled $^{174}Yb^+$ ions in our device, the ion's nonlinear mechanical oscillation is investigated.
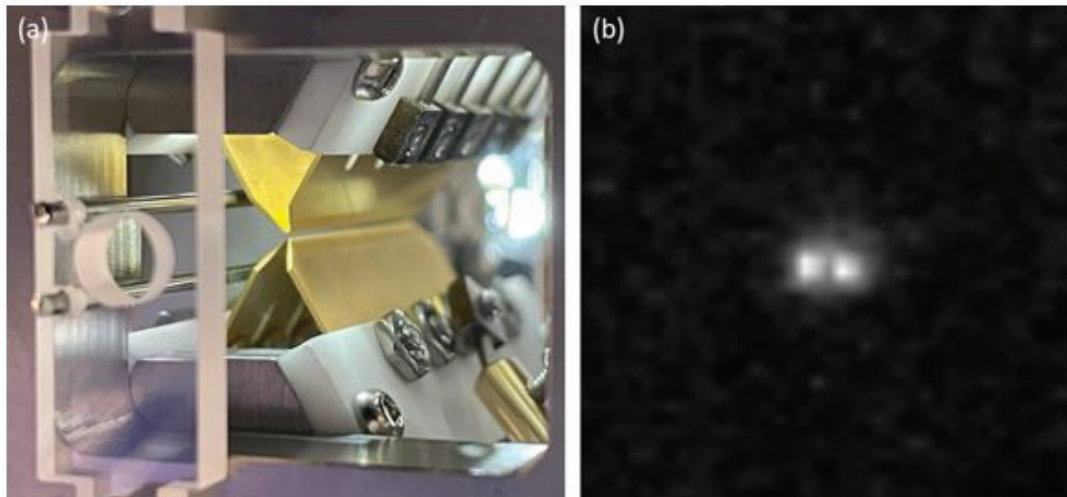
Figure 1: (a) Photograph of our segmented-blade trap. (b) Fluorescence image of two trapped ions.

Presenter name: Jungsoo Hong

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Virtual poster / Vir48: *Trapped ions, Rydberg atoms, cold plasmas* ID266

Progress on the development of Ca$^+$ optical clocks

Authors: Yao Huang[1]; Hua Guan[1]; Kelin Gao[1]

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Here the recent progress on the Ca$^+$ ion optical clocks will be reported: including a cryogenic Ca$^+$ ion clock at the liquid nitrogen environment with evaluated uncertainty of 3×10^{-18}, and a transportable Ca$^+$ ion clock with uncertainty of 1.3×10^{-17} and an uptime of ~85% in a month. the clock stability is greatly improved, with long term stability reaching the 10^{-18} level. The absolute frequency measurement of the clock transition was recently made, with a total uncertainty of 2.8×10^{-16}, this is a factor of 2 improvement comparing to the measurement in 2020. We will also discuss the possibility of making a transportable, room-temperature-based Ca$^+$ ion clocks, with uncertainty at the 10^{-18} level, and also give the prospect on the possible future applications.

Presenter name: Kelin Gao

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https://icapp2022.blogspot.com/2022/06/blog-post.html

Poster session / Tu-79: *Ultrafast, strong-field phys., plasma phys.* ID49

Correlations in the process of strong field ionization

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We apply correlation function analysis for a study of strong field ionization of atoms. We show that the study of the correlations of electron's coordinate and velocity reveals patterns which can be naturally interpreted as manifestations of the electron's barrier exit point (the spatial point where the electron exits the tunneling barrier). This analysis provides an unambiguous definition of the exit point in the tunneling ionization process. The location of the exit point thus determined agrees well with the estimates used in the semiclassical simulations.

In the framework of the standard semi-classical picture of ionization based on the Keldysh theory and its modifications, known as the two-step model, an electron emerges into the continuum with zero or near zero velocity at a certain point in space (the tunnel exit), setting up initial conditions for the subsequent electron motion. An initial value of the coordinate is defined either by the so-called Field Direction Model or (for Coulomb systems) by an estimate based on the use of the parabolic coordinate system, as a point at which the electron exits the barrier. Despite the great deal of success which had the trajectory based calculations employing these initial conditions defining the subsequent electron motion, the notions of the initial conditions are not easy to reconcile with quantum mechanics (QM). We cannot assign direct meaning to the initial electron's coordinates and velocity using the wave-function provided by the solution of the conventional TDSE, such a possibility being excluded by the very basic principles of the QM. What we can do, using the TDSE and the framework of the conventional QM, is to study *correlations* between different observables at different moments of time. We show that study of the correlation function $C(z, t; v, t_m)$, describing correlations between the probabilities to locate electron in particular regions of the coordinate and momentum spaces, reveals patterns which can be naturally interpreted as manifestations of the electron's ionization event, providing information about spatial location of the exit point, where electron exits the tunneling barrier.

Presenter name: Igor Ivanov

Investigation of laser frequency offset on nonlinear conversion in Lyman-alpha laser system

Authors: Rachel Wang· ; Reza Akbari· ; Kirk Madison· ; Takamasa Momose·

Generation of high power 121.6 nm light is vital for efficient laser cooling of antihydrogen. The nanosecond pulsed laser system developed for the ALPHA collaboration at CERN is presented here. It includes a high energy pulsed amplifier at 730 nm, followed by a doubling and subsequent gas phase third harmonic generation stage. We observe an anomalous frequency offset between the 730 nm seed laser input and the amplified light in the first stage. This leads to a frequency shift of the narrowband Lyman-alpha radiation and to a shift-dependent enhancement of the nonlinear conversion process. Simulation of thermal-optical effects in the Ti:Sapphire amplifier crystals predict a similar frequency offset to experimental observation. Cavity alignment and off-resonant locking conditions introduce an additional frequency shift accompanied by an unprecedented increase in nonlinear conversion to 121.6 nm radiation. The forthcoming paper will present supporting theoretical framework and simulation results of this phenomenon.

Presenter name: Rachel Wang