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Book of Abstracts

Contents

Quantum magnetism / 23

Spontaneous Formation of Altermagnetism from Orbital Ordering

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Altermagnetism has emerged as a third type of collinear magnetism. In contrast to standard ferromagnets and antiferromagnets,
altermagnets exhibit extra even-parity wave spin order parameters resulting in a spin-splitting of electronic bands in momentum space. In the hitherto identified altermagnetic candidate materials the anisotropies arise from the local crystallographic symmetry.
Here, we show that altermagnetism can also form as an interaction-induced electronic instability in a lattice without the crystallographic sublattice anisotropy. The antiferromagnet and the altermagnet are then separated by a proper phase transition. We provide a microscopic example of a two-orbital model showing that the coexistence of staggered antiferromagnetic and orbital order can realize robust altermagnetism. We quantify the spin-splitter conductivity as a key experimental observable and discuss material candidates for the interaction-induced realization of altermagnetism.

Quantum magnetism / 30

Reviving Majorana zero modes in the spin-1/2 Kitaev ladder model

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The one-dimensional p-wave superconductor, characterized by boundary Majorana modes, has attracted significant interest owing to its potential application in topological quantum computation. Similarly, spin-1/2 Kitaev ladder systems with bond-dependent Ising interactions, featuring Majorana fermions coupled with Z_2 flux, exhibit boundary Majorana modes when in a topological phase. However, the ground state degeneracy, inherent in these systems, may result in the annihilation of Majorana modes due to the superposition of the degenerate states. To avoid this issue, here we introduce a projective measurement that selects one of the degenerate Z_2 sectors, enabling the revival of Majorana modes. Once the state is selected, we show that the application of the local spin operators on a bond flips the sign of the adjacent Z_2 flux. Repeating such operators enables the system to reach a desired Z_2 flux configuration. The Majorana zero modes can be manipulated and fused by tuning the flux sectors achievable through applying local spin operators. We also discuss the engineering of the Kitaev ladder and open questions for future studies.

31

Higher-Rank Spin Liquids and Spin Nematics from Competing Orders in Pyrochlore Magnets

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Pyrochlore magnets have proven to provide an excellent arena for the realization of a variety of many-body phenomena such as classical and quantum order-by-disorder, as well as spin liquid phases described by emergent gauge field theories. These phenomena arise from the competition between different symmetry-breaking magnetic orders. In this work, we consider a subspace of the most general bilinear nearest-neighbor Hamiltonian on the pyrochlore lattice, parameterized by the local interaction parameter $J_{z\pm}$, where three symmetry-breaking phases converge. We demonstrate that for small values of $|J_{z\pm}|$, a conventional $\mathbf{q} = 0$ ordered phase is selected by a thermal order-by-disorder mechanism. For $|J_{z\pm}|$ above a certain finite threshold, a novel spin-nematic phase is stabilized at low temperatures. Instead of the usual Bragg peaks, the spin-nematic phase features lines of high intensity in the spin structure factor. At intermediate temperatures above the low-temperature orders, a rank-2 U(1) classical spin liquid is realized for all $J_{z\pm} \neq 0$. We fully characterize all phases using classical Monte-Carlo simulations and a self-consistent Gaussian approximation.

Triangular lattice / 36

spin liquid physics in triangular lattice KYbSe2 and NaYbSe2

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I discuss our recent work to study the ground states of triangular delafossite magnets KYbSe2 and NaYbSe2. Using inelastic neutron scattering, we employ Hamiltonian analysis, entanglement witnesses, and comparison to theoretical models to show that KYbSe2 is very close to a quantum spin liquid on the J2/J1 phase diagram. Investigating NaYbSe2 shows that the second neighbor J2 value increases relative to the K compound (shown via heat capacity and inelastic neutron scattering), revealing that chemistry can tune the magnetic interactions, and potentially putting the Na compound into a QSL phase. Measuring the low-temperature NaYbSe2 susceptibility shows evidence of a 2.1 μeV gap. This signals the presence of a gapped QSL state, potentially the Z2 liquid of the proposed RVB phase.

37

Unconventional spin relaxation in strongly correlated kagome systems

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Recent progress in material design enables the study of correlated, low-temperature ordered phases and associated anomalous transports in kagome systems. Famous examples include the giant anomalous Hall effect in noncollinear antiferromagnets Mn_3X ($X =$ Sn, Ge, Ga) [1]. Here, we show that unconventional transport phenomena can arise even in high-temperature disordered kagome systems due to emergent dynamical constraints [2]. To demonstrate this effect, we consider a strong-coupling limit of an extended Hubbard model on the kagome lattice with commensurate fillings. There, the emergent constraints arise from the combined effect of strong interactions and geometric frustration. We numerically study the charge and spin transports by cellular automaton circuits, which encode the constraints exactly and allow us to simulate large system sizes and long-time scales. The charge dynamics show an unconventional relaxation reflecting the constraints, which can be understood by a Gaussian field theory of a scalar height field. Moreover, the system exhibits a hidden spin conservation law on dynamic sublattices, which enables additional slow relaxation pathways for spin excitations. We also demonstrate that unconventional relaxations appear as characteristic spectral features in dynamic structure factors, which can be experimentally measured by inelastic neutron scattering.

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38

An Atlas of Classical Pyrochlore Spin Liquids Daniel

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The pyrochlore lattice magnet has been one of the most fruitful platforms for the experimental and theoretical search for spin liquids. Besides the canonical case of spin ice, works in recent years have identified a variety of new quantum and classical spin liquids from the generic nearest- neighbor anisotropic spin Hamiltonian on the pyrochlore lattice. However, a general framework for the thorough classification and characterization of these exotic states of matter has been lacking, and so is an exhaustive list of all possible spin liquids that this model can support and what is the corresponding structure of their emergent field theory. In this work, we develop such a theoretical framework to allocate interaction parameters stabilizing different classical spin liquids and derive their corresponding effective generalized emerging Gauss's laws at low temperatures. Combining this with Monte Carlo simulations, we systematically identify all classical spin liquids for the general nearest-neighbor anisotropic spin Hamiltonian on the pyrochlore lattice. We uncover new spin liquid models with exotic forms of generalized Gauss's law and multipole conservation laws. Furthermore, we present an atlas of all spin liquid regimes in the phase diagram, which illuminates the global picture of how different classical spin liquids are connected in parameter space and transition into each other. Our work serves as a treasure map for the theoretical study of classical and quantum spin liquids, as well as for the experimental search and rationalization of exotic pyrochlore lattice magnets.

40

Artificial spin ice on the CaVO lattice: a bridge from square to kagome

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Artificial spin ices are arrangements of dipolar-coupled nanomagnets, with magnetic moments that behave like Ising spins as a result of shape anisotropy. They have been successfully implemented as platforms for imaging and controlling phase transitions in systems with longrange interactions [1]. However, the exploration of thermally-activated phase transitions has been mostly focused on two lattices: the square and the kagome. Artificial square ice orders readily into an antiferromagnetic, two-in/two-out ground state, with a transition belonging to the Ising 2D universality class [2]. In contrast, artificial kagome ice is highly frustrated and the predicted phase diagram is richer [3, 4]. Upon lowering the temperature, the system first experiences a crossover from a paramagnetic to a spin liquid state with no long range order, then transitions into a Coulomb phase with charge crystallization. This is an example of magnetic moment fragmentation [5, 6], in which each magnetic moment can be decomposed into the sum of a long-range ordered, divergence-full fragment and a fluctuating, divergence-free fragment which can be elegantly mapped to a dimer model.
We have carried out a comprehensive characterization of the thermodynamics of an artificial spin ice based on the CaVO (also called the square-octagon) lattice, part of the family of Archimedean lattices [7]. We show that the magnetic interactions on the vertex level can be significantly tuned by changing the relative sizes of square and octagonal plaquettes, while preserving the lattice constant and symmetries. This results in a complex phase diagram, with two very different ground states and ordering processes separated by a multicritical region. Each bears strong similarities with either the square or kagome phenomenologies. We map out this phase diagram with Monte-Carlo simulations and magnetic force microscopy of as-grown configurations. Different spin liquid states can be observed, as well as moment fragmentation for some geometries. Finally, we perform temperature and field-dependant magnetometry measurements on a series of lattice geometries, making it possible to detect thermally-active correlated phases without using large-scale instrumentation. Our work paves the way for engineering exotic magnetic properties at the mesoscale. By tuning frustration within a single lattice geometry, we can design artificial systems that exhibit spin liquid and multicritical behaviours - something that, in natural magnetic systems, typically requires extremes of either pressure, field or temperature.

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41

Weak first-order phase transitions in the frustrated square lattice J1 – J2 classical Ising model

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The classical J1 – J2 Ising model on the square lattice is a minimal model of frustrated magnetism whose phase boundaries have remained under scrutiny for decades. Signs of first-order phase transitions have appeared in some studies, but strong evidence remains lacking. The current consensus, based upon the numerical data and theoretical arguments in [S. Jin et al., Phys. Rev. Lett. 108, 045702 (2012)], is that first-order phase transitions are ruled out in the region $g = J2/|J1| > 0.67$. We point out a loophole in the basis for this consensus, and we find strong evidence that the phase boundary is instead weak first order at $0.67 < g < \infty$ such that it asymptotically becomes second order when $g \rightarrow \infty$. We also find strong evidence that the phase boundary is first order in the region $0.5 < g < 0.67$. We establish these results with adiabatic evolution of matrix product states directly in the thermodynamic limit, and with the theory of finite-entanglement scaling. We also find suggestive evidence that when $g \rightarrow 0.5+$, the phase boundary becomes of an anomalous first-order type wherein the correlation length is very large in one of the coexisting phases but very small in the other.

Kitaev magnets / 42

Spin-Phonon Coupling and Phonon Thermal Hall Effect

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We have recently developed first-principles based approach for treating generic spin-phonon interactions in materials with strong spin-orbit coupling (SOC). This allows for estimation of various terms relevant to the phonon thermal Hall effect, acoustic Faraday effect, ultrasound attenuation, and magnon-phonon hybridization. In the example material α-$RuCl_3$, we find that SOC significantly enriches the form of these interactions, and imbues them with chirality that is conducive to generating finite phonon Berry curvatures through coupling of phonons and spins. We show that this leads to a phonon thermal Hall effect that qualitatively reproduces the measured field dependence of κ_{xy} without requiring a field-induced spin liquid. With these tools, we aim to address the thermal Hall effect in magnetic insulators in a material-specific way, identifying potentially key phononic contributions, and their microscopic origin.

44

Evidence of random spin-singlet state in the three-dimensional quantum spin liquid candidate Sr3CuNb2O9

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The disorder is ubiquitous in any quantum many-body system and is usually considered an obstacle to elucidating the underlying physics of complex systems. Still, its presence can often introduce exotic phases of matter that cannot generally be realized in a clean system. Here, we report a detailed experimental and theoretical study of the magnetic properties of the highly disordered material Sr3CuNb2O9, which exhibits random site mixing between Cu and Nb. The magnetic moments (Cu2+) are arranged in a quasicubic (three-dimensional) manner, leading to a high degree of frustration with a Curie-Weiss temperature θCW of about −60 K without any long-range magnetic ordering down to 466 mK. These observations suggest that Sr3CuNb2O9 is a quantum spin liquid (QSL) candidate. More interestingly, the susceptibility (χ = M/μ0H) and Cm/T (Cm is the magnetic part of the heat capacity) follow a power-law behaviour with decreasing temperature. In addition, M(T,μ0H) and Cm(T,μ0H)/T show scaling relationships over a wide range of temperatures and fields. This unusual behaviour with respect to the conventional behaviour of a QSL can be discussed qualitatively as the coexistence of a disorder-induced random spin-singlet (RSS) state and a QSL state. A quantitative description is given by numerical calculations considering a power-law probability distribution P(J) ∝ J−γ (J is the exchange interaction) of random spin singlets. The parameters extracted from the numerical calculations are in excellent agreement with the experimental data. Furthermore, the analytical results are also consistent with the power-law and scaling behaviour of χ and Cm(T,μ0H)/T as a whole. Thus, our comprehensive experimental and theoretical analysis provides evidence of stabilising the RSS state in a three-dimensional lattice.

45

Strange metal and non-Fermi liquids at Lifshitz transition

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Non-Fermi liquids, particularly the universal strange metal, are ubiquitously observed in strongly correlated materials, that includes the high-Tc cuprates, ruthenate oxides and twisted bilayer graphenes. The unprecedent tunablity of these two-dimensional (2D) systems provides access towards the Lifshitz transition where the Fermi surface exhibits van Hove singularity (VHS) saddle points.
More importantly, in almost all cuprates, experimental observations indicate that the critical hole doping rate at which the pseudo-gap vanishes coincides with the Lifshitz transition point. However, the critical phenomenon induced by the VHS are rarely explored.

Here, we study the 2D critical Fermi surface with VHSs coupled with critical bosons via Yukawa interactions.
We show the strange metal behaviors, that includes the linear-in-T resistivity and the Tln(1/T) specific heat, can emerge solely from the inclusion of spatially uniform Yukawa interactions. This is sharply contrast and complementary to the universal theory of strange metal from spatially random Yukawa interactions [Patel, Guo, Esterlis and Sachdev, Science 381, 790-793 (2023)]. This surprising result is attributed to the Galilean invariance breaking at VHS. We systematically carry out diagrammatic calculations to evaluate the optical conductivity at both zero and finite temperature regimes, and deduce persistent strange metal transport behaviors.

Along this line, we further study the non-Fermi liquid behaviors at higher-order VHSs. We show that the cyclotron mass is renormalized away from the bare value violating the Kohn's theorem, which is again attributed to the breaking of Galilean invariance of higher-order dispersions.

Moreover, we also study the critical fluctuating loop current order which is relevant to pseudo-gap termination in cuprate high-Tc superconductors. Exotic non-Fermi liquids behaviors including the strange metal are deduced when the VHSs are coupled with the loop current vector. We show that the conductivity is greatly determined by an anomalous contribution from the bosonic loop current order which is absent in previous studies.

47

$\mathbb{Z}_4$ transitions in quantum loop models on a zig-zag ladder

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We study the nature of quantum phase transitions out of $\mathbb{Z}_4$ ordered phases in quantum loop models on a zig-zag ladder – an effective toy model describing a non-magnetic sector of frustrated spin-1 chain. We report very rich critical behavior that includes a fusion of two Ising transitions, a multicritical Ashkin-Teller point and a remarkably extended interval of a non-conformal chiral transition. Although plaquette states turn out to be essential to realize chiral transitions, we demonstrate that critical regimes can be manipulated by deforming the model as to increase the presence of leg-dimerized states. This can be done to the point where the chiral transition turns into first order, we argue that this is associated with the emergence of a critical chiral end point.

48

Magnetic structure of the rare-earth monosilicate Er2SiO5

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Rare-earth monosilicates R_2SiO_5 (R = rare earth) exhibit a diverse range of chemical, structural, and physical properties that make them highly suitable for applications in gamma and X-ray scintillation detectors [1], as well as in thermal and environmental barrier coatings [2]. Despite their potential, research into the intrinsic properties of
R_2SiO_5 has been limited due to difficulties in synthesizing bulk phase-pure samples [3,4]. Recent progress in crystal growth using the floating zone method has however enabled the fabrication of large, high-quality single crystals, overcoming these drawbacks [5-7]. Although extensive studies have focused on the optical and thermal properties of rare-earth monosilicates [1,2,8,9,10], their magnetic properties remain largely unexplored. The complex network of magnetic rare earth ions in R_2SiO_5 however offers a unique platform for studying frustrated magnetism [7]. In this study, we investigate the magnetic structure of Er_2SiO_5 using high-purity crystals grown in a laser-diode-heated floating zone (LDFZ) furnace [7]. Neutron diffraction experiments were conducted on the ZEBRA instrument at the Paul Scherrer Institute along with magnetization and heat capacity measurements, providing key insights into the frustrated magnetic interactions among Er ions within the complex lattice structure.

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49

Symmetric entangled dimer state in the Shastry-Sutherland magnet Yb2Be2SiO7

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The frustrated Shastry–Sutherland lattice (SSL), with antiferromagnetic intradimer and interdimer Heisenberg exchange, is known to host an antisymmetric singlet ground state when the intradimer exchange is dominant. Rare-earth-based SSL systems with strong spin-orbit coupling offer the opportunity for tuning their magnetic properties by using magnetic anisotropy as a control knob. Here, we present bulk characterization and neutron scattering measurements of the SSL material $Yb_2Be_2SiO_7$. We find that the Yb^{3+} ions can be described by an effective spin-1/2 model at low temperatures and the system does not show signs of magnetic order down to 20 mK. An isolated dimer model with highly anisotropic exchange describes the magnetization, heat capacity, and neutron spectroscopy data well. The symmetric dimer ground state identified for $Yb_2Be_2SiO_7$ shows that strong spin-orbit coupling can induce novel entangled states of matter on the SSL.

51

Ground-State Selection and Braided Ising Spin-Tubes in a new Family of Breathing Kagome Magnets

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The recently discovered family of rare-earth based quantum antiferromagnets R_3BWO_9 have been proposed as proximate spin-liquid candidates, realizing the highly frustrated breathing kagome lattice. We present a thorough experimental investigation on *single crystals* of the R = Pr, Nd members [1-3], including inelastic neutron scattering, neutron diffraction, thermodynamic and magnetometric measurements. Pr_3BWO_9 possesses a disordered ground state with an unusual excitation spectrum, involving a coexistence of sharp spin waves and broad continuum excitations [3]. Nd_3BWO_9 on the other hand orders magnetically at the lowest temperatures, revealing a highly anisotropic $H - T$ phase diagram including various quantum- and multicritical points [1]. Three different fractional magnetization plateaux are realized in applied fields, with distinct propagation vector and ordering pattern depending on the field orientation [2].
We combine these observations with theoretical modeling, showing that it is the *inter*-plane couplings that determine the exotic magnetism of these materials. We derive a simple one-dimensional Ising model composed of twisted triangular spin-tubes, i.e., triple braids of Ising spin chains with nearly-orthogonal anisotropy frames and competing ferro-antiferromagnetic interactions [2]. This model can account for the ground state, excitations and the numerous field-induced fractional magnetization plateau phases in Nd_3BWO_9, as well as the incommensurate magnetic correlations emerging at elevated temperatures [2]. As for Pr_3BWO_9, its non-Kramers nature allows for a small splitting of the lowest quasi-doublet states, resulting in a quantum disordered singlet ground state. It poses an ideal realization of a frustrated transverse-field Ising model, where both spectrum and thermodynamics can be modeled to astounding success [3].

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52

Phonon dynamics in the site-disordered Kitaev spin liquid

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The Kitaev honeycomb model provides a paradigmatic example of an exactly solvable quantum spin liquid (QSL), where spins fractionalize into itinerant Majorana fermions coupled to a static background of $\mathbb{Z}2$ gauge fluxes. This model has attracted significant interest due to its potential experimental realization in spin-orbit Mott insulators like $\alpha-$RuCl3. Among various experimental techniques, ultrasound measurements of sound attenuation have emerged as a promising approach to detect spin fractionalization in these materials. However, deviations from the ideal Kitaev model, often due to disorder, introduce localized modes that dominate the low-energy physics. To investigate these effects, we calculate the sound attenuation coefficient in the site-disordered Kitaev honeycomb model under an applied magnetic field that breaks time-reversal symmetry. Our analysis reveals that quasilocalized modes from quasivacancies impact the phonon self-energy, yet the sound attenuation coefficient maintains its sixfold symmetry and linear temperature dependence at low temperatures, even with disorder. This robustness underscores sound attenuation's reliability as a probe for spin fractionalization. Furthermore, we show that this linear behavior persists under an external field and in the random-flux sector, highlighting the persistent influence of fractionalized excitations, despite disorder.

Other / 54

Edge-driven skyrmion motion under microwave fields

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Magnetic skyrmions are microscopic spin vortices with topological properties. They are stabilized by magnetic frustrations and/or Dzyaloshinskii–Moriya interactions. The topologically protected spin textures make them attractive candidates for information carriers. One potential application is racetrack memory, where skyrmions are created, driven, and detected along magnetic nanostrips.
In this work, we study the skyrmion dynamics along a nanostrip under microwave fields. Crucially, the inversion symmetry is broken when skyrmions are close to the sample boundary. As a result, unidirectional skyrmion motion becomes possible. We demonstrate that skyrmion excitations, such as the counter-clockwise rotation mode, allow controlled skyrmion motion along the strip. While skyrmions are initially attracted to the sample boundary, the short-range repulsive interaction becomes dominant as skyrmions approach the boundary. Furthermore, the repulsive interaction leads to an exponential increase in the skyrmion velocity. Our work provides new insights into the skyrmion dynamics of magnetic nanostrips, which might elucidate a pathway for applying frustrated magnets to electronic applications.

55

Charge ordering and spontaneous topological Hall effect in bilayer skyrmion crystals

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Magnetic skyrmion crystals with zero net skyrmion charge and zero topological Hall response are interesting candidate phases which can occur at a vanishing magnetic field in centrosymmetric systems. We study a minimal bilayer model of skyrmion crystals having opposite chirality and topological charge in the two layers, and show that it can host nearly flat electronic bands with quasi-uniform Berry curvature and quantum metric. Using Hartree-Fock theory, we show that weak to moderate short-range electron interactions induce two distinct types of symmetry breaking patterns depending on the band dispersion: an intra-unit-cell charge density modulation from Chern band mixing or a layer-imbalanced phase with a nonzero ferroelectric polarization. Both phases break inversion symmetry leading to a spontaneous and large net topological Hall effect, with the phase diagram tunable by external electric fields. Our results may be relevant to centrosymmetric skyrmion materials such as Gd_2PdSi_3 and $Gd_3Ru_4Al_{12}$ as well as artificially engineered heterostructures. We also discuss its relation to recent work on twisted transition metal dichalcogenide bilayers.

56

AC Elastocaloric Effect Study of α-RuCl3

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α-RuCl3 has attracted a great amount of attention as a prime candidate that may host a Kitaev quantum spin liquid state on the honeycomb lattice. A pending question in the field is whether there exists a quantum critical region in proximity to the phase transition from the symmetry breaking zigzag antiferromagnetic phase to the putative field-induced topological quantum spin liquid phase. Leveraging the magnetoelastic coupling of the material, we apply in-plane AC uniaxial strain to study the elastocaloric effect in high-quality α-RuCl3 single crystals. The measurement is of thermodynamic nature and allows us to directly extract the Grüneisen ratio of the system, which is expected to diverge and changes sign near a quantum critical point. We will present the phase diagram mapped out by the elastocaloric effect, along with uniaxial Grüneisen ratio as a function of magnetic field and temperature, and discuss the thermodynamic implications for the field-induced quantum phase transitions.

Triangular lattice / 57

Dynamics of Critical Dirac Spin Liquids

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Quantum fluctuations can inhibit long-range ordering in frustrated magnets and potentially lead to quantum spin liquid (QSL) phases. A prime example is the gapless Dirac quantum spin liquid (DSL) with an emergent U(1) gauge field, which can be described at low energies in terms of quantum electrodynamics in 2+1 dimension QED_3. Despite the availability of several promising triangular lattice candidate materials and recent advances in numerical methods the description of their dynamical response is an outstanding challenge. In this talk I will discuss our recent theory for the dynamical spin structure factor of the triangular lattice J_1-J_2 model. We not only find good agreement between recent experiments and rigorous numerics but argue that our self-consistent parton mean field theory, which includes fluctuations leading to spinon bound states, is a powerful and general tool for understanding the response of other types of QSLs and their instabilities.

58

Ferrimagnetism from triple-q order in Na2Co2TeO6

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The candidate Kitaev magnet $Na_2Co_2TeO_6$ exhibits a characteristic ferrimagnetic response at low temperatures, with a finite residual magnetization that changes sign at a compensation point located at around half the ordering temperature. We argue that the behavior can be naturally understood to arise in this material as a consequence of a noncollinear triple-**q** magnetic ground state. Using large-scale classical Monte Carlo simulations, we study the finite-temperature response of the pertinent honeycomb Heisenberg-Kitaev-Γ-Γ' model in weak training fields. Our model features all symmetry-allowed nearest-neighbor exchange interactions, as well as sublattice-dependent next-nearest-neighbor interactions, consistent with the reported crystal structure of the material. We also consider a six-spin ring exchange perturbation, which allows us to tune between the two different magnetic long-range orders that have been suggested for this material in the literature, namely, a collinear single-**q** zigzag state and a noncollinear triple-**q** state. We demonstrate that the experimentally-observed ferrimagnetic response of $Na_2Co_2TeO_6$ can be well described within our modeling if the magnetic ground state features noncollinear triple-**q** order. The observation of a compensation point, where the residual magnetization reverses sign, suggests a sublattice g-factor anisotropy, with a larger out-of-plane g-factor on the sublattice with stronger antiferromagnetic intrasublattice exchange. By contrast, a classical Heisenberg-Kitaev-Γ-Γ'-type model with collinear zigzag ground state is insufficient even in principle to describe the observed behavior. Our results illustrate the unconventional physics of noncollinear magnetic long-range orders hosted by frustrated magnets with bond-dependent interactions.

Other / 60

XY model with competing higher-order terms

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We study critical behavior of the generalized classical XY model that includes in the Hamiltonian competing higher-order terms (HOT) with alternating signs and exponentially decreasing intensity. It is found that critical properties of such a model strongly depend on whether the number of HOT is odd or even. Inclusion of any odd number of HOT results in two consecutive phase transitions to distinct ferromagnetic quasi-long-range order phases. On the other hand, even number of HOT leads to two phase transitions only if the decay of the HOT intensities is relatively slow. Then the high-temperature transition to the ferromagnetic phase is followed by another transition to a peculiar competition-induced canted ferromagnetic phase. In the limit of an infinite number of HOT only one phase transition is confirmed, and under the conditions of fierce competition between the even and odd terms the transition temperature can be suppressed practically to zero.

61

Magnetic Phase Diagrams and Dimensionality of Magnetic Interactions in Rouaite, $Cu_2(OH)_3(NO_3)$, with a Distorted Triangular Lattice

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Spinon-magnon mixing was recently reported in botallackite $Cu_2(OH)_3Br$ with a uniaxially compressed triangular lattice of Cu^{2+} quantum spins [1]. Its nitrate analogue rouaite, $Cu_2(OH)_3(NO_3)$, has a highly analogous crystal structure and might be expected to exhibit similar physics. We grew cm-scale single crystals of rouaite hydrothermally, and achieved >90% deuteration to allow neutron scattering studies of its magnetic order. We report rouaite's magnetic phase diagrams for $H \parallel a$, b, and [001]. The lowest-temperature magnetic state comprises alternating ferro- and antiferromagnetic chains, similar to botallackite but with different canting, leading to a cycloidal arrangment of net moments. The higher-temperature phase is an approximately helical modulation of this cycloid. In our inelastic neutron spectra, the hierarchy of exchange interactions indicates that rouaite is quasi-one-dimensional but we do not observe spinon continua, possibly indicating that the material is magnetically more two-dimensional than botallackite.

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63

Higher-Order Susceptibilities in Extended Kitaev Models Computed Via Krylov-Space Based Methods

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Recently, it was proposed that techniques measuring higher-order response functions, such as two-dimensional coherent spectroscopy (2DCS) could provide more insights into the excitations of a system. However, calculating non-linear response functions can be computationally intensive. We introduce an efficient Lanczos-based approach to compute higher-order susceptibilities, such as $\chi^2(\omega_t, \omega_\tau)$ and $\chi^3(\omega_t, \omega_\tau)$ directly in the frequency domain, avoiding computationally expensive, explicit numerical time evolution. We apply this method on extended Kitaev models relevant in the context of α-RuCl\textsubscript{3} and investigate their non-linear response. M.M., D.K. and R.V. gratefully acknowledge funding by the DFG(German Research Foundation): TRR 288 – 422213477.

64

Magnetic glass state in the Gd2ScNbO7 pyrochlore with possible XY correlations

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Gadolinium pyrochlores have long held the interest of the condensed matter community due to the number of unusual ground states that are observed. Many new mixed B-site Gadolinium pyrochlores, of the form $Gd_2BB'O_7$, also have new surprises. The mixed B-site pyrochlore Gd_2ScNbO_7 has been synthesized and characterized through a variety of techniques, including x-ray diffraction, magnetic susceptibility, muon spin relaxation, heat capacity and neutron scattering. Despite a Curie–Weiss temperature of −3.93(3) K, indicating net antiferromagnetic interactions, no signs of long ranged magnetic ordering are found down to T = 0.3 K. Instead, a disordered magnetic state emerges with a small correlation length of 2.1(1) Å of single tetrahedra. A Reverse Monte Carlo (RMC) analysis of the polarized neutron scattering data reveals short-range antiferromagnetic order with possible emergent XY spin correlations. Muon spin relaxation, and AC susceptibility measurements confirm that the magnetization condenses into a glass, with 10 % of the potential entropy missing in the specific heat. This magnetic ground state is similar to what is observed in $Gd_2Sn_2O_7$ just above the ordering temperature, without the eventual long-range ordering at low temperature.

66

Role of interlayer spin interactions in α-$RuCl_3$

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$\alpha-\mathrm{RuCl_3}$ has attracted significant attention as a prime candidate for the spin-1/2 Kitaev spin liquid in two-dimensional honeycomb lattices. Although its ground state is magnetically ordered, the order is suppressed under a moderate in-plane magnetic field. The intermediate regime of the field has exotic behaviours, some of which are claimed to originate from a Kitaev spin liquid. When resolving the debates on these behaviours, the interlayer interactions of the full three-dimensional model for $\alpha-\mathrm{RuCl_3}$ have been ignored, as they are small. However, near the transitions, the small interlayer interactions may play an important role. Here, we consider the $R\bar{3}$ and the $C2/m$ structures and first investigate the effects of interlayer coupling on the transition temperatures using the classical Monte Carlo simulations.
Focusing on the $R\bar{3}$ structure, we then study the effects of interlayer interactions on the phase diagrams under the in-plane magnetic fields. A series of intermediate phases emerges due to interlayer interactions. Our findings provide new insights into the exotic behaviours and sample dependence reported in $\alpha-\mathrm{RuCl_3}$.

67

Magnetization plateaus in a S = 1/2 perfect kagome antiferromagnet under ultrahigh magnetic fields up to 120 T

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Geometrical frustration in quantum spin systems is one of the key issues in condensed matter physics because the synergy of frustration and quantum fluctuations can give rise to unique spin states such as quantum spin liquid states. For example, the S = 1/2 kagome antiferromagnet $ZnCu_3(OH)_6Cl_2$ exhibits strong antiferromagnetic interactions of about J = 170 K between Cu^{2+} ions on kagome lattice, whereas no magnetic ordering is observed down to 50 mK [1]. The T-linear term in the heat capacity [2] and the continuum of excitations observed in inelastic neutron scattering measurements [3] suggest that $ZnCu_3(OH)_6Cl_2$ can realize a gapless spin liquid state, although NMR studies have reported a coexistence of a gapless disordered and random singlet states [4]. This discrepancy may arise from intrinsic disorder due to the similar ionic radii of magnetic Cu^{2+} and nonmagnetic Zn^{2+} ions, leaving the ground state of the kagome system an open question. To pin down the inherent ground state, materials with an ideal, disorder-free kagome network have been highly anticipated. Recently, $YCu_3(OD)_{6.5}Br_{2.5}$ (abbreviated as YCu_3), was reported as a promising candidate for a quantum kagome antiferromagnet [5]. YCu_3 is composed of a two-dimensional perfect kagome layer with no antisite disorder between Cu^{2+} and Y^{3+} ions. In this study, magnetization data for YCu_3 up to 120 T were obtained using a single-turn coil technique. The low-field data (below 60 T) show good agreement with the previous data measured by a non-destructive method; the 1/9 magnetization plateau was observed. Furthermore, the successive magnetization plateaus corresponding to 3/9 and 5/9 of the saturation magnetization were verified around 63 T and 100 T, respectively. While the 3/9 plateau is consistent with the regular S = 1/2 kagome model calculation, the 5/9 plateau appears at a lower magnetic field than calculated. In the presentation, we will discuss the implications of the observed magnetization plateaus.

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68

Anyon polarons as a window into competing phases of the Kitaev honeycomb model under a Zeeman field

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We compute the spectra of anyon quasiparticles in all three superselection sectors of the Kitaev model (i.e., visons, fermions and bosons), perturbed by a Zeeman field away from its exactly solvable limit, to gain insights on the competition of its non-abelian spin liquid with other nearby phases, such as the mysterious intermediate state observed in the antiferromagnetic model. Both for the ferro- and antiferro-magnetic models we find that the fermions and visons become gapless at nearly identical critical Zeeman couplings. In the ferromagnetic model this is consistent with a direct transition into a polarized state. In the anti-ferromagnetic model this implies that previous theories of the intermediate phase viewed as a spin liquid with a different fermion Chern number are inadequate, as they presume that the vison gap does not close. In the antiferromagnetic model we also find that a bosonic quasiparticle becomes gapless at nearly the same critical field as the fermions and visons. This boson carries the quantum numbers of an anti-ferromagnetic order parameter, suggesting that the intermediate phase has spontaneously broken symmetry with this order.

69

Ground-state degeneracy and magneto-thermodynamics of the spin-½ Heisenberg antiferromagnet on the diamond-decorated square lattice

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The spin-½ Heisenberg antiferromagnet on the diamond-decorated square lattice is a highly frustrated quantum spin system that exhibits rich physical phenomena. In the presence of a magnetic field, it displays various quantum phases including the Lieb-Mattis ferrimagnetic, dimer-tetramer, monomer-dimer, and spin-canted phases, in addition to the trivial fully saturated state [1]. We investigate the thermodynamic properties of this model using several complementary analytical and numerical methods such as exact diagonalization up to systems of 40 spins, an effective monomer-dimer description, sign-problem-free quantum Monte Carlo simulations for up to 180 spins, and a decoupling approximation. In this contribution, we focus on the parameter region favoring the dimer-tetramer phase [2]. This ground state can be represented by a classical hard-dimer model on the square lattice and retains a macroscopic degeneracy even under a magnetic field. However, the description of the low-temperature thermodynamics close to the boundary between the macroscopically degenerate dimer-tetramer and the non-degenerate monomer-dimer phases requires an extended classical monomer-dimer lattice-gas model. In the vicinity of the dimer-tetramer phase, we detect an enhanced magnetocaloric effect promoting an efficient cooling to absolute zero temperature under adiabatic demagnetization.

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70

Spin-1/2 Heisenberg diamond-like decorated honeycomb lattice in a magnetic field

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The spin-1/2 quantum Heisenberg model on the two-dimensional diamond-like decorated honeycomb lattice is a highly frustrated magnet exhibiting rich phenomena. Its ground-state phase diagram includes, in addition to the fully polarized state, a monomer-dimer phase, a Lieb-Mattis type ferrimagnetic phase, a spin-canted phase with a continuous increase of magnetization in a magnetic field, and a macroscopically degenerate dimer-tetramer phase with finite residual entropy.

Moreover, we consider the effects of distortions that enhance the couplings within the vertical dimers or along the zig-zag chains of the lattice structure. This leads to the emergence of new ground states, corresponding to additional magnetization plateaus. While the isotropic version of the spin-1/2 quantum Heisenberg model exhibits a macroscopically degenerate dimer-tetramer phase, a small distortion can either completely lift the degeneracy, resulting in a dimer-tetramer crystal (DTC), or produce a dimer-tetramer liquid (DTL) phase with significant degeneracy, but zero residual entropy. Based on a mapping of the original quantum spin model onto a hard-dimer model on the hexagonal lattice, we predict a thermal phase transition between the DTC and DTL phases that belongs to the Kasteleyn universality class. This scenario is assessed by a numerical treatment of the full quantum spin model.

71

Spin-charge separation and resonant valence bond spin liquid in a frustrated doped Mott insulator

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Ever since Anderson's groundbreaking ideas of the resonant valence bond (RVB) liquid and spin-charge separation [1-3], there have been extensive efforts to demonstrate the existence of an RVB liquid in realistic systems. Here, we present a concise, realistic, and elegant solution to this longstanding problem by demonstrating that an RVB spin liquid, exhibiting spin-charge separation, emerges as the ground state of doped Mott insulators on corner-sharing tetrahedral lattices with frustrated hopping near half-filling – a manifestation of the counter-Nagaoka effect. We confirm numerically that this result holds for finite-size systems, finite dopant density, and small exchange interactions. While much attention has been devoted to the emergence of new states from geometrically frustrated interactions, our work demonstrates that kinetic energy frustration in doped Mott insulators may be pivotal to stabilise robust, topologically ordered states in real materials [4]. We end by identifying some families of pyrochlore compounds as suitable frameworks to experimentally test our predictions and suggest how it may be possible to manifest the elusive RVB state for the first time in these materials.

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73

Shedding light on emergent quantum electrodynamics in $Ce_2Zr_2O_7$

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Quantum spin ice is a three-dimensional quantum spin liquid with an emergent compact $U(1)$ gauge structure that provides a lattice realization of quantum electrodynamics. It supports gapless photon-like modes as well as electric and magnetic monopoles of the emergent gauge theory, commonly referred to as spinons and visons, respectively. There is increasing experimental support for the claim that the dipolar-octupolar compound $Ce_2Zr_2O_7$ is a material realization of quantum spin ice. The lowest lying doublet of the magnetically active Ce^{3+} ions forming a pyrochlore lattice can be described by pseudospin-1/2 with two components that transform as dipoles and one as an octupolar moment. We theoretically analyze new polarized neutron scattering measurements on $Ce_2Zr_2O_7$ with Gaussian quantum electrodynamics and gauge mean-field theory. Our modeling allows for a critical examination of competing scenarios for the microscopic interactions and provides evidence for the presence of spinons and emergent photon excitations. Those conclusions are supported by a cubic scaling of the low-temperature heat capacity, consistent with the presence of linearly dispersing gapless bosonic modes. Our work lends further support to the identification of $Ce_2Zr_2O_7$ as a long-sought-after experimental realization of a three-dimensional quantum spin liquid.

74

Generic magnetic field dependence of thermal conductivity in magnetic insulators via hybridization of acoustic phonons and spin-flip excitations

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Magnetic insulators provide excellent playgrounds to realize a range of exciting spin models, some of which predict exotic spin ground states and thermal transport properties have been taking center stage in probing the spin excitations. Despite the fact that acoustic phonons make the major contribution to heat conduction in a crystalline system, their interplay with magnetic excitations is often viewed as peripheral to the physics of interest, for instance as an inconvenient source of scattering or decoherence. Here, we present a comprehensive study on the longitudinal magneto-thermal transport in a paramagnetic effective spin-1/2 magnetic insulator CsYbSe2. We introduce a minimal model requiring only Zeeman splitting and magnetoelastic coupling, and use it to argue that hybridized excitations – formed from acoustic phonons and localized spin-flip-excitations across the Zeeman gap of the crystal electric field ground doublet – are responsible for non-monotonic field dependence of longitudinal thermal conductivity. Beyond highlighting a starring role for phonons, our results raise the prospect of universal magneto-thermal transport phenomena in magnetic insulators that originate from simple features shared across many systems.

75

Density-Matrix Mean-Field Theory

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Understanding ordered states in proximity to spin liquid phases requires efficient theoretical tools that incorporate quantum fluctuations. We present Density-Matrix Mean-Field Theory (DMMFT), a novel framework that extends conventional mean-field approaches by systematically including quantum fluctuations through reduced density matrices. Applying DMMFT to the antiferromagnetic Heisenberg model on a triangular lattice, we demonstrate its ability to quantitatively capture the renormalization of order parameters induced by quantum fluctuations. Furthermore, we show that DMMFT accurately identifies ordered topological ground states in the Affleck-Kennedy-Lieb-Tasaki model, even in the absence of symmetry-breaking local observables. This approach offers a powerful and unbiased method for investigating frustrated magnets in high spatial dimensions ($d \geq 2$), providing new insights into quantum ordered phases and their complex behavior.

76

Classical signatures of quenched and dynamical disorder

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In the last number of decades, significant resources have been dedicated to the search for quantum disordered phases of matter including quantum spin liquids. This search has been hampered by the presence of other forms of disorder including quenched structural disorder which can drive a spin-glass transition, or fluctuations which can pick out a unique ground state leading to order by disorder. The problem is further complicated by the apparent non-specificity of the signatures of truly quantum disorder driven phenomena, such as diffuse excitations and continua, which can be difficult to distinguish from classical processes.
In this talk, I will discuss how classical disorder can give rise to features in neutron scattering spectra which may be misinterpreted as being quantum-mechanical in origin. Examples will be given that demonstrate both the consequences of quenched disorder and large classical ground state degeneracies on the dynamics of spin systems. Using the recently developed KPM method for Linear Spin Wave Theory, calculations of the neutron scattering spectra will be presented for several experimentally motivated models. These results both expand current analytical results beyond the dilute disorder limit and demonstrate the new feasibility of testing for classical origins for continua and diffuse phenomena observed in neutron scattering measurements.

77

Anisotropic Spin Ice on a Breathing Pyrochlore Lattice

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Spin ice systems have long captivated researchers due to their exotic magnetic properties and interesting emergent excitations. Recently, breathing pyrochlore compounds have been identified as a platform for studying novel phases, including fracton physics and distinct quantum spin liquids. Our study explores a spin ice model on a breathing pyrochlore lattice, introducing sublattice-dependent anisotropic interactions that we argue to be realizable experimentally, for example, through uniaxial strain. We theoretically uncover a rich phase diagram by varying the strain and show how these anisotropic constraints reduce the ground state degeneracy across the different phases. Our numerical simulations reveal that, at low temperatures, the models undergo a crossover into a constrained spin ice manifold, characterized by an entropy density that falls below the celebrated Pauling entropy associated with conventional spin ice. Moreover, we observe glassy dynamics in spin correlations when probing the out-of-equilibrium behavior, suggesting slow relaxation and memory effects. This model provides a new perspective on spin ice physics, offering a potentially robust platform for studying fracton phenomena, including mobile excitations on subdimensional manifolds. Furthermore, it opens avenues for the experimental exploration of constrained magnetism and emergent glassy dynamics.

78

Thermal transport and magneto-thermodynamics in frustrated magnets

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We will review experimental studies documenting the thermoelectric and thermal counterparts of the anomalous Hall effect. Like their electric counterpart, the anomalous Nernst and the anomalous thermal Hall effects are set by the Berry spectrum of the magnetic solid. Correlations between the amplitude of these three anomalous transverse transport coefficients have been observed as expected. Onsager reciprocity imposes relations between their amplitude in different configurations.
Magnetostriction refers to a change in lattice parameter induced by magnetic field and arises when the elastic energy is field-dependent. Maxwell relations imply concomitance between linear magnetostriction and piezomagnetism to be concomitant. We will review experiments which confirm this expectation.
Magnetic torque is a probe of the angle dependence of magnetic energy. We will review experiments employing this technique to detect the field-induced distortion of spin texture in topological magnets.

79

Stability of Quantum Spin Liquids in Weak Mott Insulators with a Spin-Orbit Coupling

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The weak Mott insulating regime of the triangular lattice Hubbard model exhibits a rich magnetic phase diagram as a result of the ring exchange interaction in the spin Hamiltonian [1,2]. These phases include the Kalmeyer-Laughlin type chiral spin liquid (CSL) and a valence bond solid (VBS). However, the robustness of these exotic phases in the presence of a weak spin-orbit coupling (SOC) has remained unexplored.

In this work [3], we use infinite density matrix renormalization group (iDMRG) to determine the stability of the CSL and VBS phases of the triangular lattice Hubbard model in presence of a weak SOC. We calculate the effective spin model for the spin-orbit coupled triangular lattice Hubbard model in the weak Mott insulting regime, including all SOC-mediated spin-bilinear and ring-exchange interactions. We then construct a simplified spin model keeping only the most relevant SOC-mediated spin interactions which captures the essential physics. Using iDMRG on this simplified spin model, we show that the CSL and VBS phases of the triangular lattice Hubbard model can be stabilized in the presence of a weak SOC. We found that the stabilization results from a compensation between the Dzyaloshinskii-Moriya interaction (D_z) and a SOC-mediated ring-exchange interaction (J_{r_1}). We also present additional qualitative arguments to intuitively understand the compensation mechanism in the iDMRG quantum phase diagrams. The mechanism for stabilization presented in this work can potentially be useful for the experimental realization of quantum spin liquids.

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81

Magnetic Field Response of Dipolar-Octupolar Quantum Spin Ice

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Recent experiments have shown promising evidence for π-flux quantum spin ice (QSI) phases in dipolar-octupolar pyrochlore systems $Ce_2(Zr,Sn,Hf)_2O_7$. However, since no single experimental signature can unambiguously confirm a QSI phase, a multifaceted experimental approach is essential for definitive characterization. Notably, neutron scattering studies of spin correlations in $Ce_2Zr_2O_7$ under magnetic fields provide valuable insights [1]. Due to the structure of the pyrochlore lattice, magnetic fields of different directions couple differently to different tetrahedron sites. Therefore, by investigating with different field directions, we can build a comprehensive experimental profile. At present, however, corresponding theoretical studies have been lacking.

As such, we will report on our theoretical study of dipolar-octupolar QSI under magnetic fields oriented along [110], [111], and [001] using gauge mean field theory. We will highlight magnetic phase diagrams, including the emergence of a staggered flux phase—characterized by π flux on half the plaquettes and 0 flux on the others—under a [110] field. Additionally, we will explore the distinct evolution of equal-time and dynamical spin structure factors as functions of magnetic field strength and direction, providing insights into experimental observations and potential signatures of QSI.

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83

Resonating valence bond physics in Rydberg atom arrays

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Rydberg atom arrays have emerged as a highly controllable platform and are being used to simulate spin systems. Following recent proposals [1,2] to realize a spin liquid in this artificial platform, we perform numerical simulations for both thermodynamics and ground state physics for an appropriate model. As the parameter range in which we investigate the model can host classical or quantum spin liquids, as well as a quantum paramagnet, we need to have a sophisticated algorithm which we have developed specifically for this model [3]. We investigate the stability of a resonating valence bond (RVB) like state in the presence of the interactions present for Rydberg atom arrays and determine the possibility of having a ground state which has confined defects, such that the topological nature of the RVB state is still maintained, thus making it useful for topological quantum computing.

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Quantum magnetism / 84

Frustrated Magnetism in S=1/2 chain compounds

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In this talk, we discuss two S=1/2 compounds, cuprate and vanadate with spin chain geometries and study the effect of frustration on the magnetic properties by employing first-principles density functional theory (DFT) approach coupled with many-body techniques.
In the first case, Cs2CuAl4O8, having zeolite-like network structure was studied [1]. The DFT-derived 1D spin model features a combination of alternating ferromagnetic-antiferromagnetic interactions, together with the presence of both nearest- and next-nearest-neighbor interactions, making it an unprecedented case. Motivated by the intricacy of the derived spin model, we examined the ground-state properties of this model in the parameter space of exchange interactions, which shows the possibility of driving quantum phase transition between gapped and gapless spin excitation.
In the second example,[2] we study the role of interchain interactions, multimagnon condensation, and strain effect in the chain compound NaVOPO4. The frustrating nature of interchain interactions is found to host a disorder phase with a finite spin gap. The predominant manifestation of interchain interactions in the disorder phase happens in the stabilization of a multimagnon condensed phase upon gap closing by application of an external magnetic field. We further explore the effect of tensile uniaxial strain, which is found to drive the system from a gapful to a gapless ground state.

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85

Exploring Unconventional Magnetism and Structural Changes in the Copper-Based Square Lattice $(CsCl)_2Cu(VO_3)_2$

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We synthesized and studied the structural, magnetic, and thermodynamic properties of single-crystalline $(CsCl)_2Cu(VO_3)_2$, a material featuring Cu-Cl square sheets interlinked by non-magnetic vanadate chains. Copper-based ($S = \frac{1}{2}$) square lattices are of significant interest due to their potential link to high-T_c superconductivity. From our investigations, employing x-ray diffraction, bulk susceptibility, specific heat, ESR, and ^{133}Cs NMR, we observed a structural transition from tetragonal to orthorhombic symmetry at ~140 K, along with magnetic ordering transitions at 2.7 K and 1.5 K. These magnetic transitions are suppressed by an external field of ~2 kOe. ^{133}Cs NMR and ESR measurements suggest short-ranged correlations emerging around 8 K. The ^{133}Cs spin-lattice relaxation rate $1/T_1$ follows a gapped behavior, with an activation energy of ~10 K, and this gap increases with the applied magnetic field. These findings reveal unusual magnetic behavior in $(CsCl)_2Cu(VO_3)_2$, potentially offering new insights into quantum magnetic phenomena in copper-based systems.

86

Emergent Dirac spinons in a kagome lattice antiferromagnet

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Emergent quasiparticles with a Dirac dispersion in condensed matter systems can be described by the Dirac equation for relativistic electrons. For example, electrons with a Dirac dispersion have been intensively studied in electronic systems such as graphene and topological insulators. However, charge is not a prerequisite for Dirac fermions, and the emergence of Dirac fermions without a charge degree of freedom has been theoretically predicted to be realized in Dirac quantum spin liquids. These quasiparticles carry a spin of 1/2 but are charge-neutral and called spinons. We report the spin excitations of a kagome antiferromagnet, YCu3(OD)6Br2[Br0.33(OD)0.67], are conical with a spin continuum inside, which is consistent with the convolution of two Dirac spinons. The predictions of a Dirac spin liquid model with a spinon velocity obtained from spectral measurements agree with the sample's low-temperature specific heat. Our results provide spectral evidence for a Dirac quantum spin liquid state emerging in this kagome lattice antiferromagnet. However, the locations of the conical spin excitations differ from those calculated by the nearest-neighbor Heisenberg model, suggesting the Dirac spinons have an unexpected origin.

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87

Phases and Phase transitions in pressurized SrCu2(BO3)2

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In the field of correlated electron materials, the relation between the resonating spin singlet and antiferromagnetic states has long been an attractive topic for understanding of the interesting macroscopic quantum phenomena, such as the ones emerging from magnetic frustrated materials, antiferromagnets and high-temperature superconductors. SrCu2(BO3)2 is a well-known quantum magnet, and it is theoretically expected to be the candidate of correlated electron material for clarifying the existence of a pressure-induced deconfined quantum critical point (DQCP), featured by a continuous quantum phase transition, between the plaquette-singlet (PS) valence bond solid phase and the antiferromagnetic (AF) phase. However, the real nature of the transition is yet to be identified experimentally due to the technical challenge. Here we show the experimental results for the first time, through the state-of-the-art high-pressure heat capacity measurement, that the PS-AF phase transition of the pressurized SrCu2(BO3)2 at zero field is clearly a first-order one. Our result clarifies the more than two-decade long debates about this key issue, and resonates with the recent quantum entanglement understanding that the theoretically predicted DQCPs in representative lattice models are actually a first-order transition. We also find that the transition temperatures of the PS and AF phase meet at the same pressure-temperature point, which signifies a bi-critical point as those observed in Fe-based superconductor and heavy-fermion compound and constitutes the first experimental discovery of the pressure-induced bi-critical point in frustrated magnets. Our results provide fresh information for understanding the evolution among different spin states of correlated electron materials under pressure.

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88

Spin dynamics of easy-plane Dirac spin liquid in a frustrated honeycomb XY model: Application to honeycomb cobaltates

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Recent work has shown that the honeycomb lattice spin-$1/2$ J_1-J_3 XY model, with nearest-neighbor ferromagnetic exchange J_1 and frustration induced by third-neighbor antiferromagnetic exchange J_3, may be relevant to a wide range of cobaltate materials. We have suggested that an easy-plane Dirac spin liquid (DSL) is an energetically competitive candidate for the ground state of this model at intermediate frustration. We extend our previous Gutzwiller projected variational Monte Carlo (VMC) study of the easy-plane DSL to include competing spiral and double zig-zag orders and find that these can slightly lower the energy of the DSL due to weak ordering tendency, supporting the idea that the DSL is a 'parent' state for the diverse magnetic orders observed in these materials. Within VMC, the ordered state is found to be easily polarized by a weak in-plane magnetic field as observed in experiments. To study spin dynamics of the DSL, we formulate a modified parton theory for such frustrated spin models, and explore the potential instabilities the DSL due to residual spinon interactions within a random phase approximation (RPA), both at zero magnetic field and in a nonzero in-plane field. The broken symmetry states which emerge in the vicinity of this Dirac spin liquid include ferromagnetic, zig-zag, and incommensurate spiral orders. We calculate the dynamical spin response of the easy-plane DSL, including RPA corrections, near the boundary of the ordered states, and present results for THz spectroscopy and inelastic neutron scattering, at zero field as well as in an in-plane magnetic field, and discuss experimental implications.

90

Quantum criticality and multipartite entanglement via finite-temperature spin dynamics

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S=1/2 triangular-lattice Heisenberg magnets have attracted much attention as promising candidates to exhibit highly-entangled quantum state of matter, quantum spin liquid states. The recent inelastic neutron scattering experiment revealed that one of the triangular-lattice candidate materials, $KYbSe_2$, clearly showed the quantum criticality beyond the spin wave prediction in their neutron spectrums, and showed the presence of multipartite entanglement by the estimated quantum Fisher information density [1].
Motivated by these results, we have numerically investigated quantum criticality and multipartite entanglement via finite-temperature spin dynamics of the S=1/2 J_1-J_2 triangular-lattice Heisenberg antiferromagnetic model. Our state of art quantum typicality method allows us to compute finite-temperature spin dynamics without any bias to our model Hamiltonian and our computational results succeed in capturing the consistent multipartitness of the quantum entanglement and critical exponent to those of $KYbSe_2$. Along with these computational results and comparisons with the experiments, we plan to show the latest insights into the differences from a randomness-relevant quantum state.

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91

Magnetism and quantum spin liquid in multipolar moment materials

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This is a tutorial lecture on theory of novel magnetic properties and quantum spin liquid in magnetic materials with multipolar moments. Higher rank multipolar moments such as quadrupolar and octupolar moments of magnetic ions often arise in crystalline electric field (CEF) environment. These moments couple to external magnetic field, neutron spin, and lattice strain in very interesting ways. These peculiar couplings offer novel ways to detect elementary excitations in quantum spin liquid and magnetically ordered phases in quantum magnets. We will explain relevant theoretical ideas and make connection to existing and future experiments.

92

The Phase Diagram of Pyrochlore Magnets

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I present a comprehensive picture of the structure of the phase diagram for the pyrochlore pseudo-spin Hamiltonian with all symmetry-allowed nearest-neighbor interactions in the classical large-S limit. I present three primary insights. First, I demonstrate how to unify the classification of ground states in terms of irreducible representations of the tetrahedral point group with the organization of spins into multipole tensors appearing in the description of tensor spin liquids. Second, I present a complete visualization of the phase diagram which illustrates all of the phases, phase boundaries, and triple intersections of phases, exposing four distinct triple lines which all intersect at the Heisenberg anti-ferromagnet. Lastly, I demonstrate the presence of an additional 1-dimensional "diabolical locus" in the phase diagram, about which the ground state spin configuration can wind non-trivially when adiabatically transported; the phase diagram is foliated into surfaces of constant canting angle which all intersect on this locus. With the complete picture of the phase diagram in hand, I comment on how a wide variety of previously-studied phenomena, from spin liquids to order-by-disorder, arise at different places in the phase diagram and can be understood in a more unified perspective. Time permitting, I will comment on how these methods can be extended to other geometries such as the octochlore lattice realized in anti-perovskite materials.

93

Quantum criticality and dimensional reduction in the frustrated sawtooth chain compound atacamite

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We present evidence for the presence of a field-induced quantum critical point (QCP) at 21.9(1) T (**H** || *c* axis) in the frustrated quantum magnet atacamite $Cu_2Cl(OH)_3$, a mineral which we have recently identified as a material realization of sawtooth chains [J ~ 336 K (basal-basal), J' ~ 102 K (basal-apical)] [1]. Residual interchain couplings lead to long-range antiferromagnetic order in atacamite below T_N = 8.9(1) K [1]. Through extensive high-field studies of the heat capacity, we were able to map the entropy landscape of atacamite up to 35 T [2]. It features highly distorted isentropes indicative of quantum criticality in the material. By further combining macroscopic and microscopic high-field measurement techniques, we provide evidence for the QCP at 21.9(1) T to separate field regions with and without long-range magnetic order, but far away from full polarization of the material [2]. Underpinned by numerical results we propose this behavior to be related to an effective dimensional reduction of the material, where the chains decouple into independent subunits [2]. We interpret this behavior as a special type of dimensional reduction caused by the interchain network.

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94

Raman spectroscopic signatures of magnetic fluctuations in Kagome planes of Pr2Zr2O7 under H || [111]

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The exotic properties of multipolar quantum spin ice candidate $Pr_2Zr_2O_7$ are determined by the coupling of spin, orbital, and lattice degrees of freedom. Some of these interactions can be followed through the line shape of crystal field excitations which are detected by high resolution spectroscopy. Using Raman scattering spectroscopy we explore crystal field excitations spectra of Pr^{3+} as a function of temperature down to 2 K, and as a function of magnetic field applied in [100] and [111] directions.
We demonstrate vibronic interactions of crystal field levels of Pr^{3+} with phonons, prominent for excited states. We identify an unconventional temperature behavior of a splitting of the Pr^{3+} non-Kramers ground state doublet and suggest a static or dynamic deviation of Pr^{3+} from the ideal position as the origin of the effect.

In magnetic field H || [100] crystal field excitations spectra of Pr^{3+} in this material can be fully understood within conventional Zeeman splitting, in contrast to H || [111]. With magnetic field applied in H || [111] direction, magnetic moments of pyrochlores are known to split into triangular lattice planes of moments aligned with the field and Kagome planes which can show Kagome ice behavior. We demonstrate that Zeeman splitting can explain only the crystal field spectra of the moments aligned parallel to the [111] magnetic field. Crystal field spectra of Pr^{3+} in Kagome planes show evidence of fluctuations, without reaching a polarized state in magnetic field up to H=14 T.

95

Field-Induced Ordered Phases in Anisotropic Spin-1/2 Kitaev Chains

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Motivated by intense research on two-dimensional spin-1/2 Kitaev materials, Kitaev spin chains and ladders, though geometrically limited, have been studied for their numerical simplicity and insights into extended Kitaev models. The phase diagrams under the magnetic field were also explored for these quasi-one dimensional models. For an isotropic Kitaev chain, it was found that a magnetic field polarizes the ground state except along the symmetric field angle, where the chain is found to remain gapless up to a critical field strength where it enters an intriguing soliton phase before reaching the polarized state at higher field strengths. Here we study an anisotropic Kitaev chain under a magnetic field using the density matrix renormalization group technique. Unlike the isotropic chain, the ground state has a macroscopic degeneracy with a finite gap in the absence of the magnetic field. When the field is aligned parallel to the weak bond, a polarized state is found. On the other hand, when it is aligned parallel to the strong bond, a four-site ordered phase arises. In a certain angle of the field, another ordered phase characterized by a uniform chirality emerges. We employ a perturbation theory to understand such field-induced ordered phases, and find an effective low energy model with transverse Ising and Dzyaloshinskii-Moriya interactions between the unit cells enabled by the external field. A connection to the two-dimensional limit and open questions are also presented.

96

Unlocking Exotic Magnetism: Insights from Triangular and Square Lattice Systems

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This discussion explores the intriguing domain of frustrated magnets, focusing on triangular lattice systems, which are potential hosts for quantum spin liquid states, and square lattice systems, which may exhibit both quantum spin liquids and novel field-induced spin configurations. By presenting recent findings from thermodynamic studies and neutron scattering experiments on rare-earth-based single-crystal compounds with these lattice geometries, we aim to shed light on the fundamental physics driving their exotic properties.

97

A Frustrated Antipolar Analogue to the Classical Spin Liquid in $EuAl_{12}O_{19}$

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The ground-state of the S = ½ Ising Triangular Lattice AntiFerroMagnet (**ITLAFM**) is the go-to example of a frustrated magnet, and was solved analytically by Wannier over 70 years ago 1. In the absence of strong quantum fluctuations, this ground-state is called a classical spin liquid with a large number of energy-degenerate spin configurations that share the minimum energy. It is expected to have spin-dynamics governed by Arrhenius behavior, with topologically protected strings which can be broken upon nucleation of spinons [2] Despite interest in investigating this type of system experimentally, model magnetic materials are hard to come by, with S = 1/2 spins or $S_{effective}$ = 1/2 spins typically deviating from the Ising limit or displaying significant quantum fluctuations.

The rare-earth hexaaluminates with the magnetoplumbite structure are a promising family of triangular lattice magnets thanks to well separated triangular layers of magnetic ions. I will present our investigations of the compound $EuAl_{12}O_{19}$. In this compound, ferromagnetic interactions drive the material to ferromagnetism with a T_C = 1.3 K. [3]

Instead, we find the sought-after classic-liquid physics of the ITLAFM ground-state not within its magnetic lattice, but within a lattice of antiferroelectrically coupled electric dipoles. The material contains a triangular lattice of *dynamically disordered*, but antiferroelectrically correlated, charge displacive dipoles built from Al^{3+} ions sitting off-centre within their bipyramid oxygen cages. Electric dipoles have an advantage over spins that they can be intrinsically Ising, and we label this model instead the Ising Triangular Lattice AntiFerroElectric (**ITLAFE**). I will present our recently published structural, spectroscopic, and thermodynamic measurements on $EuAl_{12}O_{19}$, comparing the observed properties to those expected for the ITLAFM. [4]
By this contribution, I will show to the attendees of HFM, that analogues of highly frustrated magnets can be realized on lattices of electric dipoles and that their study leads to the discovery of uncommon dielectric phases.

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98

Magnetic skyrmion materials

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Recently, there has been considerable interest in the physics of magnetic skyrmions due to their huge potential for use in spintronic devices, such as in racetrack memories and logic devices. Magnetic skyrmions are topological magnetic spin structures originally identified in the B20 class of materials. More recently, skyrmions have been found and investigated in other non-centrosymmetric classes of materials and in centrosymmetric intermetallics. To make headway in experiments to understand the basic physics of these skyrmion materials, high quality single crystals are essential. This has motivated us to embark upon a study of several classes of skyrmion materials and to explore a wide composition range of each of the family of compounds. The materials investigated range from centrosymmetric intermetallics such as Gd2PdSi3, GdRu2Si2, magnetic layered van der Waals materials such as Fe3GeTe2, to a large family of intercalated transition metal dichalcogenides (TMDCs) and other frustrated and topological magnets.
In this talk, I will present an overview of the materials characteristics of several of the above materials including the challenges in the synthesis of these materials using a variety of techniques at Warwick. Investigations of the effects of substitution and the resulting structural order/disorder as well as magnetic frustration on the existence of the skyrmion phase in these crystals sheds light on the origin and the tuning of the skyrmion lattices. The study of their important structure–property correlations is vital to the understanding of these materials for possible future device applications.

99

Designing the Light in Quantum Spin Ice

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Quantum spin ice (QSI) is a lattice spin-model realization of full-fledged quantum electrodynamics, including photons, electric charges, and magnetic monopoles. As one of the most interesting quantum spin liquids, a significant amount of experimental and theoretical investigation has been done in this field. I will present an overview of the quantum spin ice physics and also discuss our recent ongoing work 1 on how, in the so-called dipole-octupole QSI [2-5], one can experimentally have clean control of the dynamics of its emergent QED, including the transition between different symmetry-enriched phases, tuning the dispersion of photons and fine-structure constants, etc. One of the most straightforward experiments can achieve this: turning on the external magnetic field in the right direction.

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100

Analysis of the $\mathrm{Kitaev}-\Gamma$ Model Using the Schwinger Boson Approach

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Quantum spin liquid states are characterized by the absence of long-range order even at absolute zero temperature due to significant quantum fluctuations. These states have been suggested to exhibit unique characteristics, such as fractionalized excitations and topological degeneracy in their ground states. In 2006, Kitaev proposed an exactly solvable model whose ground state is a quantum spin liquid with excitations carried by fractionalized Majorana fermions 1. These particles have been proposed for applications in topological quantum computing, which has attracted growing attention to quantum spin liquids.

However, analyzing the finite-temperature dynamics of disordered phases is challenging due to the absence of order. While the $S = 1/2$ Kitaev model is exactly solvable with fermionic excitations, the $S = 1$ Kitaev model is not exactly solvable, and the excitations of this model are suggested to be bosonic [2]. Thus, the Schwinger boson approach [3,4], which is widely used for analyzing disordered phases, is considered appropriate for this analysis. Although Γ interactions have been reported to stabilize the quantum spin liquid state 5, many aspects of their finite-temperature behavior remain unexplored in terms of bosonic excitations. In this study, we investgate the $S = 1$ $\mathrm{Kitaev}-\Gamma$ model using the Schwinger boson approach. We apply the mean-field approximation to an interacting bosonic model obtained in the Schwinger boson representation. We examine the characteristics of quantum spin liquid states realized in this model at both zero and finite temperatures. In the presentation, we will also present the results of the dynamical structure factors $S(\boldsymbol{q}, \omega)$.

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101

Stability of algebraic spin liquids coupled to quantum phonons

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Quantum fluctuations can inhibit long-range ordering in frustrated magnets and potentially lead to quantum spin liquid (QSL) phases. A prime example are gapless "Dirac" QSLs with emergent U(1) gauge fields which may emerge on triangular-lattice J_1-J_2 Heisenberg models. Despite several promising candidate materials, however, a complicating factor for their realisation is the presence of other degrees of freedom. Here, we predict that the U(1) Dirac QSL exhibits a spin-Peierls instability to valence bond solid order upon coupling to classical lattice distortions. We investigate the stability of realistic systems using both field-theoretical tools and variational Monte Carlo, and find strong evidence that emergent monopoles drive the spin-lattice transition. Beyond the static lattice approximation, we study the coupling of a QSL to dynamical "quantum" phonons and predict the regime of stability against spin-Peierls ordering, finding that the DSL ground state might still be achievable in 2D candidate materials. We make the connection to the well known spin-Peierls instability in 1D, and extend our results to a wider class of deconfined U(1) gauge theories, such as deconfined quantum critical points.

103

SCGA for Spin-1 Magnets

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When considering the classical limit of quantum magnets, it is customary to consider individual spins as O(3) vectors. This works surprisingly well for spin-$\frac{1}{2}$ magnets, even at a semi-classical level. However, O(3) vectors fail to describe many of the properties of higher-spin moments. In particular, they cannot describe states with on-site quadrupole moments, as seen in magnetic insulators [1-3], Fe-based superconductors [4] and cold atoms 5. For these problems, the classical limit must be taken in a different way that accounts for the fact that spin-1 moments can support both dipolar and quadrupolar moments.

Recently, we developed a simple semi-classical method for calculating the dynamics of spin-1 magnets [6]. This method is based on a treatment of quantum spin-1 moments within the algebra u(3) [1,6], allowing to treat both dipolar and quadrupolar moments on an equal footing and to describe their time evolution. In this work, we extend our u(3) description of spin-1 moments to a method called Self-Consistent Gaussian Approximation (SCGA) which assumes spins to be classical in the sense that each component is treated as an independent real variable. Originally, the SCGA is based on an O(3)-vector (dipolar) description of spins [7-8] and provides an efficient route to access classical thermodynamic and ground state properties for disordered phases such as spin liquids. Here I show how the SCGA scheme can be naturally generalized to the u(3) framework in order to describe a spin-1 moment [9].

We illustrate our new method by comparison with high temperature classical Monte Carlo (MC) simulation also obtained within the u(3) framework for the spin-1 bilinear-biquadratic model on the triangular lattice. Namely we show that since the u(3) generators capture both dipolar and quadrupolar degrees of freedom, the u(3) based SCGA method provides a robust description of correlations in spin-1 materials [9], as shown in Figure 1.

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104

Quantum-interference-induced pairing in bosonic doped antiferromagnets

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The pairing mechanism in doped antiferromagnets is essential for understanding high-temperature superconductivity. We investigate the pairing mechanism in bosonic doped antiferromagnets via large-scale density matrix renormalization group calculations of the bosonic t-J model. We discover a pair density wave (PDW) coexists with the antiferromagnetic (AFM) order, forming a "supersolid" at small doping. The pairing is attributed to a hidden many-body Berry phase that introduces the sole "sign problem" into this bosonic model and imposes quantum phase frustration to the spin-charge interference pattern. Only via tightly pairing of doped holes, can such frustration be most effectively erased in an AFM background. By contrast, the pairing vanishes as the Berry phase is trivialized in the ferromagnetic condensate at larger doping or switched off into the Bose-Hubbard model at large U. The present pairing mechanism—distinct from the conventional mechanisms based on Fermi surface instabilities—may provide a different perspective and new insights for understanding the complex nature of doped Mott insulators and is promising to be probed on qudit-based quantum simulators such as ultracold Rydberg atom arrays.

106

Continuum excitations in a triangular-lattice spin supersolid

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The ground state of the quantum spin-½ triangular lattice XXZ easy axis antiferromagnets has been predicted theoretically to be a spin supersolid. We present thermodynamic and neutron scattering studies of a nearly Ising triangular lattice antiferromagnet $K_2Co(SeO_3)_2$ which has a supersolid ground state 1. It exhibits a quasi-two-dimensional magnetic order with a non-collinear "Y" spin structure. The magnetic excitation spectrum has a dual character. It features a broad, gapless continuum and a gapped pseudo-Goldstone excitation at low energy, as well as gapped continuum at high energy. The former is associated with the transverse XY spin components and may arise from a proximate quantum spin liquid state. In modest magnetic fields applied along the easy axis, the continuum excitations show distinctive evolution in the supersolid phase, until a field-induced quantum critical point above which the system enters a 1/3 magnetization plateau state with a collinear up-up-down spin structure. The broad continuum disappears and only sharp spin wave excitations remain. We will compare these results with recent theoretical calculations.

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109

Tunable Magnetism in Triangular Lattice Metal-Organic Frameworks

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Metal Organic Frameworks (MOFs), compounds consisting of metal ions connected by organic ligands, offer a possibility for tunable magnetic interactions, creating an ideal space to explore exotic magnetism in real materials. Two isostructural MOFs, Co-BIF and Ni-BIF, containing triangular lattices of Ni^{2+} and Co^{2+} ions connected by a boron trisimidazolate ligand, have been studied by DC and AC magnetization measurements. Co-BIF does not order at measured temperatures (above 400 mK) due to weak superexchange and displays a temperature-dependent spin state due to thermally populated crystal field levels. Ni-BIF demonstrates cluster spin-glass behavior and large ferromagnetic exchange, attributed to disordered radical ligands. These results demonstrate the unique magnetic tuning capabilities of organic ligands and the realization of a frustrated triangular lattice in a MOF.

110

Magnetic phase diagram and dynamics of a distorted triangular lattice antiferromagnet Cs_2RuO_4

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The celebrated family of distorted triangular lattice systems Cs_2MX_4 (M = Cu, Co, X = Br, Cl) gained much attention in the field of quantum magnetism, with recent advancements in Cs_2CoBr_4 [1-3]. We report single crystal bulk properties and neutron spectroscopy measurements of another member, Cs_2RuO_4. Unlike the Cu and Co-based counterparts, its magnetism stems from a S = 1 4d transition metal ion Ru^{6+}. It has stronger spin-orbit coupling and potentially features bond-dependent anisotropies in the spirit of the Kitaev model. We present thermodynamic measurements to map out an intriguing $H - T$ phase diagram and investigate the role of anisotropy. We observed magnetic order at T_N = 5 K and a spin-flop-like transition accompanied by a gap closing and reopening, reminiscent of a quantum critical point. Additionally, inelastic neutron scattering measurements in zero-field show a rich and complex 2D dispersion in the distorted triangular plane. Our findings further expand the explored parameter space within the anisotropic triangular lattice antiferromagnet paradigm.

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111

Kinetic Energy Frustration as New Paradigm for Correlated Metals

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Since Anderson's seminal proposal of a resonating valence bond (RVB) ground state in triangular Heisenberg magnets, geometric frustration has become a key paradigm in modern physics, driving the discovery of novel states of matter in quantum magnets. Its application to the exchange interactions governing the physics of Mott insulators has uncovered a wealth of emergent phenomena, which have been a central focus of this conference series.

In a more recent seminal work, Jan Haerter and Sriram Shastry demonstrated that kinetic energy frustration gives rise to effective antiferromagnetic interactions in slightly doped triangular Mott insulators. I will argue that this result represents just the tip of an iceberg of emergent phenomena, encompassing polaron physics, unconventional pairing, and metallic RVB spin liquids exhibiting spin-charge separation—all driven by kinetic energy frustration. Moreover, we will explore how the metallic RVB liquid induced by this "counter-Nagaoka" effect emerges as an exact ground state in slightly doped Mott insulators on corner-sharing tetrahedral lattices.

113

Spin-Peierls Transition in the frustrated spinels ZnCr2O4 and MgCr2O4

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The chromium spinels MgCr2O4 and ZnCr2O4 are prime examples of the highly frustrated pyrochlore lattice antiferromagnet. Experiment has carefully established that both materials, upon cooling, distort to lower symmetry and order magnetically.
In this talk, we will introduce both materials and study the nature of the transition by a combination of density-functional-theory based energy mapping and classical Monte Carlo simulations. We will first computationally establish precise Heisenberg Hamiltonian parameters for the high temperature cubic and the low temperature tetragonal and orthorhombic structures of both spinels. We will then investigate the respective ordering temperatures of high symmetry and low symmetry structures. Comparing our results with experimental facts, we find that our simulations are consistent with a type of spin-Peierls mechanism, adapted to three dimensions, where the structural distortion is mediated by a magnetic energy gain due to a lower degree of frustration. To conclude we will discuss our understanding of the nature of the low-temperature magnetic order in these spinels.

114

Engineering Pinch Lines in Classical Spin Systems: A Novel Route to Exotic Emergent Electromagnetism

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In recent years, numerous works have advanced the classification of classical spin liquids, proposing theoretical systems that exhibit truly exotic features 1. Among these are multifold pinch points observed in structure factors, signaling emergent Coulomb physics that extends beyond the familiar spin-ice paradigm [2]. Instead of divergenceless vectors, these systems exhibit tensor-based constraints, leading to the emergence of fractonic charges, exotic quasiparticles with subdimensional mobility. Another notable feature is the emergence of pinch lines, where pinch points persist across all planes, along a given line in reciprocal space, offering a one-dimensional extension of the pinch point concept [3]. However, the occurrence of pinch lines in classical spin systems remains rare, and previously studied systems have only displayed conventional two-fold pinch points along these lines.

In this work, we introduce a novel and straightforward recipe for designing 3D classical spin systems that host pinch lines [4]. This method allows for the generation of a diverse array of systems with such features. In particular, we demonstrate the existence of a new class of pinch lines in which the structure of the pinch points continuously evolves along the line, a phenomenon that has not been observed in any prior theoretical models. This finding proposes an illustration of the potential coexistence of multiple realizations of generalized electromagnetism within a single system.

Our approach not only expands the range of emergent electromagnetism accessible in spin systems but also provides a practical tool for identifying simple systems with these remarkable properties. The simplicity of our method opens exciting opportunities for the realization of pinch lines and their experimental detection, paving the way for further exploration of these exotic phases in classical spin liquids.\\

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115

Exotic quantum features of a spin-1 Heisenberg diamond chain in a magnetic field

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The ground-state phase diagram, magnetization curves, low-temperature thermodynamic and magnetocaloric properties of a quantum spin-1 Heisenberg diamond chain are studied in a magnetic field using several complementary analytical and numerical methods including variational method, theory of localized magnons, exact diagonalization, and the density matrix renormalization group (DMRG). Our exploration reveals that the spin-1 Heisenberg diamond chain exhibits in a magnetic field several intriguing quantum phases such as the uniform and cluster-based Haldane phase, Lieb-Mattis ferrimagnetic phase, Tomonaga-Luttinger quantum spin liquid, as well as, bound-magnon crystal phase. These quantum states are reflected in exotic quantum features of this quantum spin chain as for instance in a presence of intermediate magnetization plateaus in low-temperature magnetization curves, multipeak dependencies of magnetic susceptibility and specific heat, the enhanced magnetocaloric effect, etc. Specifically, we also analyze the performance of a quantum Stirling cycle comprised of isomagnetic heating and cooling alongside isothermal strokes, which may reach under certain conditions highest possible efficiency of the Carnot cycle. The studied model is developed for providing a deeper understanding into the magnetic behavior of the polymeric nickel-based compound
[Ni3(OH)2(O2C−C2H2−CO2)(H2O)4].2H2O. The present work was financially supported by Slovak Research and Development Agency under the contract No. APVV-20-0150.

116

Energy scale separation of Wannier and spin super-solid physics in the triangular antiferromagnet $K_2Co(SeO_3)_2$

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We present a detailed investigation of the spin supersolid phase in the triangular lattice XXZ easy-axis antiferromagnet $K_2Co(SeO_3)_2$, using a combination of ultra-high-resolution inelastic neutron scattering, thermodynamic measurements, and Quantum Monte Carlo numerical simulations. Our study reveals Berezinskii-Kosterlitz-Thouless (BKT) transitions signaling the emergence of Ising and supersolid order, alongside the experimental recovery of Wannier entropy above the supersolid phase.

At low temperatures and zero field, neutron scattering results show a broad continuum of magnetic excitations, with no discrete coherent magnon modes resolved within an experimental resolution of 23 μeV. A pseudo-Goldstone mode with a small energy gap of 0.06 meV is also detected. In applied magnetic fields, these excitations evolve into coherent spin waves, with distinct behaviors observed in the Goldstone and pseudo-Goldstone sectors.

This work highlights the unique thermodynamics and spin dynamics of the spin supersolid phase, offering quantitative agreement between experimental data and quantum Monte Carlo simulations. The results underscore $K_2Co(SeO_3)_2$ as an ideal platform for exploring supersolid phenomena and the complex interplay of quantum and thermal fluctuations in anisotropic antiferromagnets.

117

Elucidating the local physics of disordered QSL systems using NMR and inverse Laplace transform (ILT) 1/T1 analysis

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One of the main challenges in experimentally identifying a quantum spin liquid (QSL) state is in understanding the influence of disorder. Chemical and structural imperfections existing in many QSL candidate materials often lead to a magnetically inhomogeneous ground state, which cannot be understood from sample-averaged measurements alone.

This highlights the importance of using nuclear magnetic resonance (NMR) in the search for QSLs. NMR can locally probe the spin susceptibility χspin (separate from defect contributions) and low-energy spin fluctuations at the NMR frequency via the Knight shift K and the nuclear spin-lattice relaxation rate 1/T1, respectively. Analogous to how variations in local χspin are reflected in the distribution of Knight shifts which make up the NMR lineshape, multiple environments with qualitatively distinct local spin dynamics can contribute to the nuclear magnetization curve M(t) in a 1/T1 relaxation measurement. The 1/T1 distribution which makes up M(t) is equal to its inverse Laplace transform (ILT), and can be represented as a probability density function P(1/T1). This prompted us to develop a program for computing P(1/T1) from the measured M(t) data, which primarily uses Tikhonov regularization in order to limit the instability of numerically inverting data with finite noise 1. In contrast to traditional 1/T1 analysis, which typically fits M(t) with a stretched exponential function to obtain an approximate spatial average of the 1/T1 distribution, our approach of calculating P(1/T1) can delineate the behavior of multiple distinct 1/T1 components, and hence preserve vital information on the position-by-position distribution of local spin dynamics.

In this presentation, we discuss our NMR results on the Kitaev honeycomb iridates Cu2IrO3 [2] and Ag3LiIr2O6 [3] and the kagome Heisenberg antiferromagnets ZnCu3(OD)6FBr (Zn-barlowite) and ZnCu3(OD)6Cl2 (Herbertsmithite) [4-7]. In the materials known to exhibit a disordered QSL ground state, our use of ILT 1/T1 analysis provides crucial insight into the nature of their low-energy spin excitations, such as evidence of spin singlets with spatially inhomogeneous energy gaps observed in Zn-barlowite and Herbertsmithite. We will also showcase how ILT can be used to generate two-dimensional maps for visualizing the correlations between local 1/T1 and Knight shift. In our 19F NMR study on Zn-barlowite, this technique helped to evidence the emergence of spin-polarized domains induced by interlayer Cu2+ defects.

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119

μSR and NMR measurements on the Ti-based kagome material (CH3NH3)2NaTi3F12 : a new Quantum Spin Liquid candidate.

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Quantum Spin Liquids (QSL) are peculiar magnetic systems where strong quantum fluctuations and frustration prevent the system from ordering even at 0 K, despite strong antiferromagnetic interactions. The kagome lattice, consisting of triangles connected by their vertices, dressed with S=1/2 spins, coupled with a nearest-neighbour, isotropic, antiferromagnetic, Heisenberg interaction, is believed to be one of the best configurations in which to find a QSL. However, all the kagome QSL candidates that have been discovered so far differ slightly from the ideal theoretical case due to the presence of magnetic impurities or an anisotropic distortion of the kagome lattice.

This work has been focused on the study of (CH3NH3)2NaTi3F12, referred to as 1-Ti, in which S=1/2 titanium ions occupy a perfect Kagome lattice and interact through the fluorine ions. In 1-Ti, kagome planes are separated by the Na ions and randomly oriented methylammonium molecules. These randomly oriented molecules likely induce a certain degree of randomness that is different from the substitutional disorder present in other kagome QSL candidates. Preliminary thermodynamic measurements performed by Jiang et al. 1 showed a Curie-Weiss temperature of -139.5 K, indicating strong antiferromagnetic interactions between the titanium ions but showed no signs of magnetic order down to 0.1K.

Here we present a subsequent investigation of this material using two local probe techniques: muon spin rotation (μSR) and nuclear magnetic resonance (NMR). Our zero-field μSR results show the formation of F-μ-F complexes, indicating that the muon is well coupled to the kagome planes. We observe a lack of magnetic order down to 32 mK and non-Redfield spin dynamics at low temperature which could come from a distribution of magnetic interactions caused by the disordered methylammonium units. We also performed 19F NMR experiments down to 1.7 K, also showing no indications of magnetic order. The NMR spin-lattice relaxation rate 1/T1 shows a power law temperature-dependence at low temperatures with a surprisingly shallow exponent α=0.14, suggesting the presence of highly unconventional spin dynamics.

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120

Kitaev interaction and unusual spin dynamics in iodine-baesd van der Waals triangular antiferromagnets

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The Kitaev model, a honeycomb network of spins with bond-dependent anisotropic interactions, is a rare example that gives the quantum spin liquid state as an exact solution. Unfortunately, most Kitaev model candidate materials eventually order magnetically due to inevitable non-Kitaev interactions. On the other hand, their bond-dependent exchange anisotropy manifests in unusual spin dynamics. It has recently been suggested that bond-dependent anisotropy can stabilize exotic magnetic phases on the geometrically frustrated triangular lattice. However, few materials have been identified with simultaneous geometric frustration and bond-dependent anisotropy. In this talk, I will present spin dynamics of iodine-based van der Waals triangular antiferromagnet CoI_2 and NiI_2. We found evidence of finite bond-dependent anisotropy in both compounds using inelastic neutron scattering. From the paramagnetic scattering and observed magnetic structure, we conclude that the Kitaev interaction plays an essential role in explaining. Moreover, momentum and energy-resolved inelastic neutron scattering measurements show substantial magnon decay and level repulsion in CoI_2. In the case of NiI_2, we found evidence of higher-order skyrmion crystal at the intermediate temperature regime (60 K < T < 75 K). Our results provide the basis for future studies of the interplay between Kitaev magnetism and geometric frustration.

121

What have we learned about the magnetic interactions in α-RuCl3 from neutron scattering?

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It has been almost 10 years since the first neutron scattering results from α-RuCl3 were published starting in 2015 (see e.g. [1-3]). This was about a year after α-RuCl3 was first described as a candidate material to realize the exactly solvable Kitaev model on a honeycomb lattice [4], as a related compound to the iridates Na2IrO3 and Li2IrO3. As of now we have however learned that none of these materials is a good realization of the Kitaev model. The model consists of bond directional nearest-neighbor magnetic interactions and since the interaction in neighboring spins connects orthogonal components, the model cannot generate long-range magnetic order and the ground state is a quantum spin liquid. The observation of collinear AFM magnetic order in α-RuCl3 through neutron scattering immediately implies that the real material has additional magnetic couplings and the 3D ordering wavevector shows that interplane couplings are present. Inelastic neutron scattering (INS) has further revealed sharp modes expected for conventional magnon excitations superimposed on a broad continuum compatible with the presence of the fractionalized excitations. Neutron scattering has also shown that the AFM order is suppressed by intermediate magnetic fields before a high-field ordered phase is entered. The minimal viable model that accounts for these observations includes up to 3rd neighbor couplings in the honeycomb plane and up to 2nd neighbor couplings perpendicular to the layers.
We will present new INS data together with models thereof that shed light on the spin excitations of this system indicating complex magnetic interactions. The data agrees with a pronounced anisotropy of the magnetic interaction but at the same time disagrees with a simple or strongly dominant Kitaev coupling. The comparison to 3D models reveals how interlayer interactions affect the magnetic excitations.

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122

Magnetic-field induced quantum critical 2D Bose gas in the honeycomb antiferromagnet YbCl3

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Bose-Einstein condensation (BEC) is a quantum phenomenon, where a macroscopic number of bosons occupy the lowest energy state and acquire coherence at low temperatures. It manifests itself not only in superfluid 4He and dilute atomic gases but also in quantum magnets1. In three-dimensional (3D) antiferromagnets, an XY-type long-range ordering (LRO) near a magnetic-field-induced transition to a fully polarized state (FP) has been successfully described as a BEC in the last few decades. An attractive extension of the BEC in 3D magnets is to make their two-dimensional (2D) analogue. In a strictly 2D system, BEC cannot take place at a finite temperature due to the presence of a finite density of states at zero energy, but instead, a Berezinskii-Kosterlitz-Thouless (BKT) transition may emerge. In a realistic quasi-2D magnet consisting of stacked 2D magnets, a small but finite interlayer coupling stabilizes marginal LRO and BEC, but such that 2D physics is still expected to dominate. A few systems were reported to show such 2D-limit BEC, but at very high magnetic fields that are difficult to access.
YbCl3 is a pseudo-spin 1/2 honeycomb Heisenberg antiferromagnet with intra-layer coupling of J ~ 5 K and exhibits a transition to a FP state at an in-plane saturation field Hs = 5.93 T [2-4]. Here, we demonstrate that the LRO right below Hs is a BEC but close to the 2D-limit, marginally stabilized by an extremely small interlayer coupling J⊥ of the order of 10-5J 5. At the quantum critical point Hs, we capture 2D-limit quantum fluctuations as the formation of a highly mobile, interacting 2D Bose gas in the dilute limit. A much-reduced effective boson-boson repulsion compared with that of a prototypical 3D system indicates the presence of a logarithmic renormalization of interaction, which is unique to 2D. Thus, the old candidate for a Kitaev quantum spin liquid, YbCl3, is now established as an ideal arena for a quantum critical BEC in the 2D limit.

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123

Two-Dimensional Triplon Confinement in the Quantum Dimer Magnet Yb2Si2O7

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Quantum dimer magnets represent a textbook example of quantum magnetism, where nearest-neighbor spins entangle to form spin singlets (dimers). The excitations of the quantum dimer magnet are a triplet of $S_{textnormaltot}$ = 1 states, referred to as triplons. An applied magnetic field causes the lowest energy triplet state ($S_{textnormalz}$ = 1) to be driven to degeneracy with the singlet ground state, resulting in Bose-Einstein condensation (BEC) of the triplons. Typically, the magnetic field induced BEC state for quantum dimer magnets presents as a symmetric dome in the field vs. temperature phase diagram and the system can be effectively mapped to a BEC of triplons in the vicinity of the transitions into and out of the dome.
In this talk, I will discuss $Yb_2Si_2O_7$ which exhibits a monoclinic lattice that forms distorted honeycomb layers of magnetic Yb^{3+} ions that eludes magnetic order down to 50 mK, entering a quantum dimer magnet state. In $Yb_2Si_2O_7$, an asymmetric dome was observed in the phase diagram for fields applied along the c-axis and the critical fields to enter the BEC are significantly smaller than those of other quantum dimer systems. Theoretical explanations of the asymmetric dome in the phase diagram have differed, particularly focusing on possible anisotropy in the exchange interactions and g-tensor. Here I will present new inelastic neutron scattering measurements for a field applied along the b-axis that aim to quantify the strength and anisotropy of the magnetic exchange interactions. We have combined multiple measurements of the field polarized spinwaves along different crystallographic directions and linear spinwave theory to fit the magnetic exchange interactions in $Yb_2Si_2O_7$. These fits provide strong evidence that the magnetic exchange is predominantly Heisenberg-like and that the triplons are confined to the honeycomb layers. This provides promise that $Yb_2Si_2O_7$ can be an intriguing playground for exploring BEC physics and further develop our understanding of the quantum phases possible with rare-earth ions.

125

Novel insight into Tb2Ti2O7 Flavor modes and mixed dipolar-quadrupolar phases

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Tb2Ti2O7 has remained an enigma in condensed matter physics, and more specifically in the field of frustrated magnetism, for more than twenty-five years 1. This material evades long-range order down to temperature as low as 20 mK and its ground state exhibits puzzling diffuse magnetic scattering [2,3]. Its low energy spin dynamics includes, on the one hand, an exciton located at about E = 1.5 meV, which shows a significant dispersion [4]; on the other hand, Tb2Ti2O7 also hosts exotic low energy collective dynamics (≈ 0.3 meV), which is believed to be hybrid dipolar-quadrupolar excitations [5,6].

Using polarized inelastic neutron scattering measurements, I will present a review of the characteristics of these low-energy modes, including their dispersion and evolution of spectral weight in the Brillouin zone. I will then describe RPA simulations, based on a Hamiltonian, which includes both dipolar and quadrupolar couplings [7], yielding spin dynamics, which compare quite well with those data. The best set of couplings suggest that Tb2Ti2O7 is one of the very rare examples of quantum spin ice, yet very close to several ordered phases, especially a planar antiferromagnetic dipolar phase and purely quadrupolar ones [8,9].

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126

Magnetic field induced deformation of the spin density wave microphases in Ca3Co2O6

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The frustrated triangular Ising magnet Ca3Co2O6 has long been known for an intriguing combination of extremely slow spin dynamics and peculiar magnetic orders, such as the evenly-spaced non-equilibrium metamagnetic magnetization steps and the long-wavelength spin density wave (SDW) order, the latter of which is essentially an emergent crystal of solitons 1. Recently, an elaborate field-cooling protocol to bypass the low-field SDW phase was proposed to overcome the extraordinarily long timescale of spin relaxation that impeded previous experimental studies in equilibrium [2], which may point to a deep connection between the low-temperature slow relaxation and the cooling process passing through the low-field SDW phase. As the first step to elucidate the conjectured connection, we investigate the magnetic field-induced deformation of the SDW state and incommensurate-commensurate transitions, thereby mapping out the equilibrium in-field phase diagram for a realistic three-dimensional lattice spin model by using Monte Carlo simulations [3], which is in an excellent agreement with recent experiments by Hardy et al. (Phys. Rev. B 110, 144443, 2024). We also discuss Ginzburg-Landau theory that includes several Umklapp terms as well as an effective sine-Gordon model, which can qualitatively explain the observed magnetic field-induced deformation of the SDW microphases.

127

Raman Circular Dichroism of Chiral Quantum Spin Liquids

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We investigate the Raman circular dichroism (RCD) of chiral Quantum spin liquids as a probe of the topological properties of fractionalised spin excitations. Starting from the Loudon Fleury formalism we show that the scattering Intensity is directly related to the light matter coupling formalism of spinon bands. We reveal that the RCD signal arises as a result of the Berry curvature and Quantum geometry contributions. We show application to different model quantum spin liquids.

128

Single Crystal Diffuse Neutron Scattering Study of the Dipole-Octupole Quantum Spin Ice Candidate $Ce_2Zr_2O_7$: No Apparent Octupolar Correlations Above T = 0.05 K

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The insulating pyrochlore $Ce_2Zr_2O_7$ has attracted much attention as a quantum spin ice candidate with dipole-octupole character that permits spin ice phases based not only on magnetic dipole moments but also allows for even-more-exotic octupole-based spin ice phases. This work focuses on low-temperature neutron diffraction measurements on single crystal $Ce_2Zr_2O_7$ with Q-coverage both at low Q where the magnetic form factor for dipoles is near maximal and at high Q covering the region where the magnetic form factor for Ce^{3+} octupoles is near maximal. This study was motivated by recent powder neutron diffraction studies of other Ce-based dipole-octupole pyrochlores, $Ce_2Sn_2O_7$ and $Ce_2Hf_2O_7$, which each showed temperature-dependent diffuse diffraction at high Q that was interpreted as arising from octupolar correlations. Our measurements use an optimized single crystal diffuse scattering instrument that allows us to screen against strong single crystal Bragg scattering in $Ce_2Zr_2O_7$. The temperature-difference neutron diffraction reveals a low-Q peak consistent with dipolar spin ice correlations. For larger Q, the temperature-difference neutron diffraction shows an alternation between positive and negative net intensity. These features are qualitatively consistent with the corresponding numerical-linked-cluster (NLC) calculations using pseudospin interaction parameters reported for $Ce_2Zr_2O_7$, $Ce_2Sn_2O_7$, or $Ce_2Hf_2O_7$. Importantly, neither the measured data nor any of the NLC calculations show increased scattering at high Q resulting from octupolar correlations. We conclude that at the lowest attainable temperatures for our measurement ($T = 0.05$ K), octupolar correlations are not present in $Ce_2Zr_2O_7$ on the level of our observation threshold of $\sim 0.1\%$ of the low-Q dipole scattering.

131

Quantum spin liquid synthesis through microwave-assisted solid-state synthesis (MASS)

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Quantum spin liquid (QSL) candidates[1,2] are an exciting class of frustrated magnetic materials, characterised by strongly correlated magnetic moments upon magnetically frustrated lattices.[2,3] The synthesis of QSL candidates is challenging, as the introduction of lattice defects can generate additional exchange interactions, leading to sample dependant magnetic properties.[4] We report a new method of reproducibly synthesising significantly high quality solid-state materials by application of microwave-assisted solid-state synthesis (MASS). This method often yields exceptionally non-defective solid-state materials on a short & long-range, with superior materials properties at as little as 5% the time required for a traditional furnace synthesis.

To demonstrate the potential of the MASS synthesis approach, here we present a new study of the QSL candidate material, ZnV_2O_4. ZnV_2O_4 is a frustrated spinel with S = 1 V^{3+} ions arranged on a pyrochlore lattice (Fig. 1(a)).[5] Competing antiferromagnetic interactions and orbital degrees of freedom have led to a complex and highly debated magneto-structural behaviour across a variety of different samples in the literature.[5–7] We highlight the influence of the synthesis route taken for this material by demonstrating distinct differences in the structural and magnetic behaviours of samples prepared via a typical 24-hour furnace synthesis and a novel 12-minute MASS synthesis. While furnace prepared samples undergo a structural transition upon cooling, highly crystalline microwave assisted samples retain the undistorted cubic pyrochlore lattice to low temperatures (Fig. 1(b,c)). We show the possible emergence of a QSL ground state in microwave-assisted samples, the temperature-independent spin fluctuations persisting to at least 1.5 K , as evidenced by a comprehensive inelastic neutron scattering study (Fig. 1(d)).

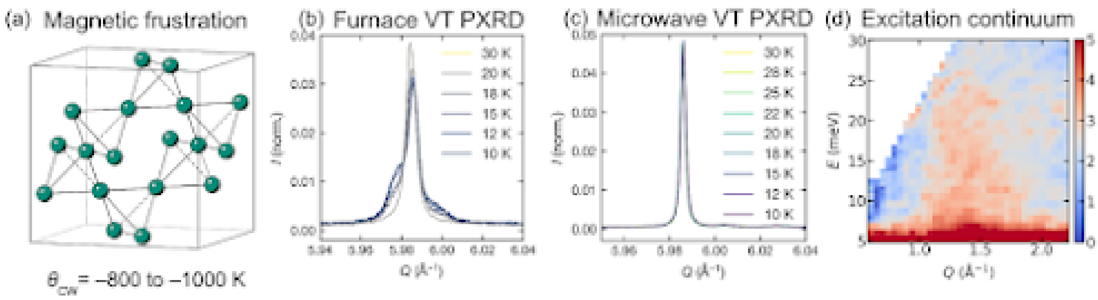

Figure 1: Image

Figure 1. a) Corner-sharing tetrahedra make up the vanadium frustrated pyrochlore sub-lattice. (b) High-resolution powder X-ray diffraction (HR-PXRD) showing the presence of a cubic to tetragonal ($I4_1/amd$) phase transition at T < 30 K in a furnace synthesised ZnV2O4 sample (c) HR-PXRD showing the absence of any structural transition in a MASS-synthesised sample down to T = 10 K. (d) INS

data collected on PANTHER at T = 1.5 K, E_i = 90 meV showing the excitation continuum extending to high energy in a MASS-synthesised sample.

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132

Collinear Altermagnets and their Landau Theories

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Collinear altermagnetism corresponds to compensated magnetic order exhibiting alternating and anisotropic spin-splitting of electronic bands, due to distinctive magneto-crystalline symmetries. These systems have attracted interest because of their potential for spintronics applications. We provide a general Landau theory that encompasses all three-dimensional altermagnets, assuming the magnetic order does not enlarge the unit cell. We identify all crystal structures admitting altermagnetism, and reduce to a smaller set of possible Landau theories characterized both with and without spin-orbit coupling (SOC). In the zero SOC limit we determine the possible local multipolar orders that are tied to the spin splitting of the band structure. Importantly, we clarify the bridge between "ideal" SO-free altermagnets and real altermagnets with SOC, and we distinguish the measurable properties and response functions of SOC altermagnets from collinear Néel antiferromagnets.

133

Microscopic Roadmap to a Yao-Lee Spin-Orbital Liquid

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The exactly solvable spin-1/2 Kitaev model on a honeycomb lattice has drawn significant interest, as it offers a pathway to realizing the long-sought after quantum spin liquid. Building upon the Kitaev model, Yao and Lee introduced another exactly solvable model on an unusual star lattice featuring non-abelian spinons. The additional pseudospin degrees of freedom in this model could provide greater stability against perturbations, making this model appealing. However, a mechanism to realize such an interaction in a standard honeycomb lattice remains unknown. Here we provide a microscopic theory to obtain the Yao-Lee model on a honeycomb lattice by utilizing strong spin-orbit coupling of anions edge-shared between two eg ions in the exchange processes. This mechanism leads to the desired bond-dependent interaction among spins rather than orbitals, unique to our model, implying that the orbitals fractionalize into gapless Majorana fermions and fermionic octupolar excitations emerge. Since the conventional Kugel-Khomskii interaction also appears, we examine the phase diagram including these interactions using classical Monte Carlo simulations and exact diagonalization techniques. Our findings reveal a broad region of disordered states that break rotational symmetry in the bond energy, suggesting intriguing behavior reminiscent of a spin-orbital liquid.

134

1/5 and 1/3 magnetization plateaux in the spin 1/2 chain system YbAlO

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Quasi-one-dimensional magnets can host an ordered longitudinal spin-density wave state (LSDW) in magnetic field at low temperature, when longitudinal correlations are strengthened by Ising anisotropies. In the S = 1/2 Heisenberg antiferromagnet $YbAlO_3$ this happens via Ising-like interchain interactions. Here, we report the first experimental observation of magnetization plateaux at 1/5 and 1/3 of the saturation value via thermal transport and magnetostriction measurements in YbAlO3. We can understand the occurance and stability of the plateau
states based on ferromagnetic interchain interactions in $YbAlO_3$. We also report a sharp, step-like increase of the magnetostriction, indicating a first-order phase transition of unknown origin in the high-field phase just below the saturation. The phase diagram including the new features is presented in the figure.

135

Spin-wave excitations in triangular-lattice antiferromagnets near the Ising limit

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Recent experiments on $K_2Co(SeO_3)_2$ [1, 2] and $NdTa_7O_{19}$ [3] have stimulated an extensive interest in the low-temperature properties and the low-energy excitations of the triangular $S = 1/2$ XXZ model in the limit of strong easy-axis (Ising-like) anisotropy. Motivated by the recent experimental findings, this presentation will report on a theoretical analysis of spin-wave excitations in the 1/3-plateau and in the supersolid phase of the nearest-neighbour XXZ model near the Ising limit. In the "up-up-down" 1/3-plateau phase, stabilized by a c-axis oriented field, the limit of strong magnetic anisotropy $\alpha = J_{xy}/J_{zz} \ll 1$ allows one to rigorously study the magnon excitations by a systematic expansion in α. We show that the linear-spin wave (LSWT) approximation, although exact at leading order in α, severely misses the coefficients of the higher-order corrections in α. We argue that this quantitative failure of LSWT is at the origin of the discrepancies between the linear-spin wave theory predictions and the inelastic-neutron scattering spectrum observed in $K_2Co(SeO_3)_2$ in Ref. 1. In the zero-field supersolid phase, we show that the non-linear spin-wave (large-S) expansion, for small α, can be systematically reduced to an effective bosonic theory with quartic interactions on the honeycomb lattice. The presentation will discuss the results which we obtained by analyzing this effective model and the connections with the experimental results on the supersolid state of triangular XXZ materials.

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137

Single Crystal Heat Capacity Study of the Dipole-Octupole Quantum Spin Ice Candidates $Ce_2Hf_2O_7$ and $Ce_2Sn_2O_7$ down to $T \sim 0.02$ K

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The insulating magnetic pyrochlores $Ce_2Zr_2O_7$, $Ce_2Hf_2O_7$, and $Ce_2Sn_2O_7$ have gained attention as quantum spin ice candidates with dipole-octupole character that arises from the crystal electric field ground state doublet for the Ce^{3+} Kramers ion in these materials. This dipole-octupole character permits both spin ice phases based on magnetic dipoles and those based on more-exotic octupoles. An important issue relevant to previous studies on Ce-based pyrochlores is that the energy scale of the underlying XYZ Hamiltonian is on order of 1 K or less, and it is difficult to perform equilibrium measurements below $T \sim 0.1$ K. Because of this, previous heat capacity measurements do not provide full coverage of the Schottky-like peak at low temperature for any of these three systems, let alone allow for study of the true quantum ground state regime. This work focuses on new magnetic heat capacity measurements on high quality single crystals of $Ce_2Hf_2O_7$ and $Ce_2Sn_2O_7$ to a base temperature of $T \sim 0.02$ K, a factor of three lower than those previously reported for any of the dipole-octupole pyrochlores.

138

Quantum Spin Solids, Supersolids and Liquids in 2D Frustrated Magnets in magnetic field

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Frustrated spin-systems have traditionally proven challenging to understand, owing to scarcity of controlled methods for their analyses. By contrast, under strong magnetic fields, certain aspects of spin systems admit simpler description. For instance, it is well known that the saturation transition into the field-polarized phase maps onto the BEC condensation of hardcore bosons. However, frustrations provide an additional tuning parameter allowing a scenario where this conventional outcome breaks down. In particular, by studying a representative J_1-J_2-J_3 model on the square lattice, we establish (i) transitions that go beyond the BEC universality class, with new critical exponents, and (ii) find analytical and numerical evidence of the exotic Bose metal – a compressible state with power-law correlations, which in the language of spins translates into an algebraic spin liquid [1].
Another example of exotic physics in an applied field is supplied by the supersolid – an emergent state of matter originally conjectured to exist in ^{4}He, where both the global U(1) symmetry of the order parameter and the translation symmetry are spontaneously broken. Motivated by the very recent experimental evidence for the supersolid state in a triangular lattice magnet from the inelastic neutron scattering data on $K_2Co(SeO_3)_2$ [3, 4], we perform projected entangled-pair state (iPEPS) simulations of the XXZ spin-1/2 model with strong easy-axis exchange anisotropy [2]. We find two phases with supersolid characteristics: the low-field "Y"-phase and the high-field ($B \geq 20$T) "Ψ"-phase. While many methods have been developed to target the ground states of frustrated magnets, few methods capable of computing the excitation spectra exist. We have developed the iPEPS-bases excitation ansatz, following Ref. [5] and computed the dynamical spin structure factor which agrees very well with the experimental neutron scattering data in the "Y" phase, corroborating its interpretations as a supersolid.
The results of this work have appeared in print in Refs. [1] and [2].

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140

Quantum Spin Ice in Confined Geometries: Pyrochlore Thin Films

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Quantum spin liquid (QSL) phases are known to host a range of fascinating phenomena, including lack of long-range order down to zero temperature, emergent gauge fields and fractionalized excitations. A particularly realistic and well-studied example is "quantum spin ice" (QSI) which realizes a three-dimensional $U(1)$ QSL with a well-defined photon excitation and deconfined magnetic and electric charges [1]. In this work, we study the effect of confined geometry on QSI in experimentally relevant thin film geometries. Classical spin ice (CSI) thin films have been shown to display much of the same physics as bulk CSI, but can realize $U(1)$ or Z_2 classical spin liquid phases depending on the boundary conditions [2]. To explore this physics in QSI films, we consider the effect of orphan bonds at the boundaries on the effective Hamiltonian in the QSI phase. We find that the boundaries can extend or relax the bulk constraints, allowing new "string-like" operators that terminate at the surfaces. These operators not only connect the top and bottom surfaces to each other, but also can be localized near a single boundary. To determine the effects of these new terms on the low-energy effective theory we adopt a semiclassical expansion [3] that can naturally incorporate the emergent photon. We find that these string-like operators can open a gap in the photon spectrum and in some cases reduce the $U(1)$ spin liquid to a Z_2 QSL, echoing the classical result. Findings for [001] and [111] pyrochlore thin film geometries and dependence on thickness will be discussed.

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141

Emergent θ-term in a Coulomb Quantum Spin Liquid

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Pyrochlore quantum spin ice (QSI) hosts a Coulomb spin liquid phase, whose low-energy physics is captured by an emergent U(1) gauge theory. When both time-reversal and inversion symmetries are broken, symmetry considerations allow the emergent electric and magnetic fields to exhibit an axionic θ-term coupling, which we find can lead to a magnetoelectric response of the QSI sample to applied external electromagnetic fields. We use symmetry analysis to find the simplest microscopic QSI Hamiltonian on the pyrochlore that generates a θ-term in the effective description and thereby estimate the scale of the θ-response. Despite the large collection of single-spin and nearest-neighbor two-body terms permitted when time-reversal and inversion are broken, we show that generically next-nearest-neighbor terms are required to generate an effective θ-term.

143

Giant anisotropy of the magnetoresistance in few-layer α-RuCl3 tunnel junctions

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The magnetic insulator α-RuCl3 is proximate to a quantum spin liquid (QSL) described by the Kitaev model. A promising route to realizing a true Kitaev QSL in α-RuCl3 is to reduce its dimensionality via mechanical exfoliation. In addition to enhancing magnetic fluctuations, exfoliating α-RuCl3 opens the door to manipulating its magnetic state by coupling it to other two-dimensional materials. However, measuring the magnetic properties of such small samples represents a great technical challenge. Moreover, to harness the technological potential of this predicted Kitaev QSL phase and its non-Abelian anyonic excitations, an electrical probing technique is highly desirable but limited by the insulating nature of the material.

Here, we present angle-dependent tunneling magnetoresistance (TMR) measurements on ultrathin α-RuCl3 crystals with various layer numbers (Fig. 1) to probe their magnetic, electronic and crystal structure [1]. We observe a giant change in resistance – as large as ~ 2500 % – when the magnetic field rotates either within or out of the α-RuCl3 plane. This is a manifestation of the anisotropic spin interactions arising from the strong spin-orbit cou-pling in this material. Using TMR as a probe, we track the magnetic phase diagram of α-RuCl3 as a function of temperature, applied magnetic field and its angle relative to the crystallographic axes. Our results show that few-layer α-RuCl3 hosts a zigzag antiferromagnetic order with a Néel temperature of ~ 14 K, higher than the ~ 7 K measured in bulk samples with a rhombohedral stacking. We explain this surprising result by showing that exfoliated flakes maintain a monoclinic structure at low temperature, while bulk α-RuCl3 is believed to undergo a monoclinic-to-rhombohedral phase transition. This conclusion is supported by our scanning transmission microscopy study of isolated flakes. Our study provides a deeper understanding of how the magnetic properties of α-RuCl3 depend on its stacking order and layer number, which helps lay the groundwork for the van der Waals engineering of exotic magnetic phases such as QSLs.

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144

50 years of $BaCo_2(AsO_4)_2$

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$BaCo_2(AsO_4)_2$ was discovered 50 years ago. It was among a group of several transition-metal compounds that attracted interest in quantum magnetism due to their low-coordination honeycomb lattice of magnetic ions and easy-plane anisotropy. Its ground state and very low in-plane critical fields remain an enigma. Initially, it was suspected to realize magnetic vortices related to BKT physics. Recently, it was proposed as a strong candidate for the realization of the Kitaev model, only to be demoted back to the easy-plane ferro-antiferromagnet shortly thereafter. We present a combination of neutron-scattering, analytical, and DMRG results to shed new light on this puzzling compound, with the goal of finally settling the most puzzling questions about its true model description.

145

Compass-model physics on the hyperhoneycomb lattice in the extreme spin-orbit regime

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The physics of spin-orbit entangled magnetic moments of 4d and 5d transition metal ions on a honeycomb lattice has been much explored in search for unconventional magnetic orders or quantum spin liquids expected for compass spin models, where different bonds in the lattice favour different orientations for the magnetic moments. Realizing such physics with rare-earth ions is a promising route to achieve exotic ground states in the extreme spin orbit limit, however this regime has remained experimentally largely unexplored due to major challenges in materials synthesis. Here we report successful synthesis of powders and single crystals of β-Na2PrO3, with 4f1 Pr4+ jeff=1/2 magnetic moments arranged on a hyperhoneycomb lattice with the same threefold coordination as the planar honeycomb. We find a strongly noncollinear magnetic order with highly dispersive gapped excitations that we argue arise from frustration between bond-dependent, anisotropic off-diagonal exchanges, a compass quantum spin model not explored experimentally so far. Our results show that rare-earth ions on threefold coordinated lattices offer a platform for the exploration of quantum compass spin models in the extreme spin orbit regime, with qualitatively distinct physics from that of 4d and 5d Kitaev materials.

146

Spin vorticity phase on the octochlore lattice with J1-J2-J2' Ising interactions

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Investigating the physical properties of classical spin liquids continues to be an exciting avenue in frustrated magnetism. These phases fall beyond the Landau-Ginzburg-Wilson paradigm, exhibiting massive degeneracy in their ground state and fractionalized excitations that emerge as point-like topological defects. Instead of an order parameter, classical spin liquid phases have defining local constraints and, in the coarse-grained approximation, characteristic emergent gauge fields. The well-studied spin ice, in this context, is defined by a local zero divergence constraint and exhibits a U(1) gauge structure.

Chung and Gingras recently proposed a novel classical spin liquid, the spin-vorticity phase, arising from the condition of local curl-free plaquettes. Remarkably, in this phase the emergent gauge theory has a rank-2 antisymmetric U(1) structure and the excitations correspond to one-dimensional charged strings 1.

Here, we adopt this formalism for the octochlore lattice of corner-sharing octahedra, which has been shown to host a Coulomb phase with spin textures of dipolar and quadrupolar components 2. On the octochlore lattice, the vorticity is defined as the circulation of the spins on the void square plaquettes between the octahedra. The spin vorticity Hamiltonian of this lattice can be written in the constrainer form involving only first and second neighbor Ising interactions and thus is less fine-tuned than the original pyrochlore spin vorticity model 1.

Using Monte Carlo simulations and self-consistent gaussian approximation, we find evidence of the spin vorticity phase, which prevails in a larger parameter space beyond the special point where the Hamiltonian reduces to the square of the constraint. We explore the phase diagram as the function of the two types of second neighbor interactions and discuss the characteristic spin structure factor and residual entropy for the spin vorticity phase. We propose material candidates that could potentially host this exotic new spin liquid.

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147

Investigation of isotropic magnetism in a Heisenberg-type, pseudo-honeycomb Co-dimer AFM $K_7Co_6Te_{11}O_{46}H_{29+}$

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In the pursuit of a material hosting a true quantum spin liquid (QSL) state, the exploration of novel structure types offers the potential to overcome intrinsic limitations of some of the best-studied lattice geometries. This is particularly useful in attempts to stabilize non-geometric frustration, such as in the case of the Kitaev QSL.

Here we expand on our previous report of $K_7Co_6Te_{11}O_{46}H_{29+}$ (KCoTeOH), a Zemannite-type, novel antiferromagnet (AFM) possessing structural elements of both triangular dimer and honeycomb cobaltate systems. Through extensive bulk and local probe characterization of the material's magnetic ground state, a largely isotropic, Heisenberg-type magnetic response is observed, despite the presence of dimerized chains of S_{eff} = 1/2 Co^{2+} cations that would typically result in dominant Ising-type interactions. We also present evidence for a small fraction of the Co^{2+} moment remaining fluctuating below the AFM ordering transition observed in bulk magnetic susceptibility measurements, suggesting the coexistence of two magnetic phases in the "ordered" state, down to at least T = 1.8 K. This work highlights the potential of unconventional hydroflux synthesis methods in the stabilization of novel magnetic materials possessing novel and potentially more frustrated lattice geometries.

148

Skyrmions of Frustrated Quantum Dimer Systems

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Magnetic skyrmions are topologically protected solitons observed in various classes of real magnets. In two-dimensional systems, where the target space of local magnetization values is the two-sphere S^2, skyrmion textures are classified by the homotopy classes of two-loops S^2 in S^2: $\Pi_2(S^2) \cong Z$. Here, we demonstrate that more general topological skyrmion textures emerge in the classical limit of quantum dimer systems, where the phase space of the relevant classical theory is CP^{N-1} (with $N = 4$ for the case of interest), because the relevant second homotopy group, $\Pi_2(\mathrm{CP}^{N-1}) \cong Z$ for $N \geq 2$, remains unchanged. Building on the framework established by Zhang et al. (2022), we consider a classical limit based on SU(4) coherent states, which preserve intra-dimer entanglement. We show that the zero-temperature phase diagram of frustrated spin-dimer systems on a bilayer triangular lattice with weak inter-dimer coupling includes two magnetic-field-induced CP^3 skyrmion crystal phases.

149

On the origin of spin nematic order in Sr_2IrO_4

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Quantum spin nematics, a quantum analog of liquid crystals, can be thought of as an intermediate state between magnetically ordered, and spin-liquid phases. To date spin nematics have mostly been discussed in the context of spin-1 magnets with strong biquadratic interactions, or spin-1/2 frustrated ferromagnets in high magnetic field. Recent experiments suggest that a spin-nematic may also be found at high temperatures in the strongly spin-orbit-coupled antiferromagnet Sr_2IrO_4. However the mechanism for stabilizing this spin-nematic state remains mysterious. Here we explore the conditions needed for spin-nematic order to arise in Sr_2IrO_4, using a combination of symmetry analysis and large-scale numerical simulation.

151

Spin-1 moments on the pyrochlore lattice

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Pyrochlore magnets continue to provide a rich source of inspiration, offering a steady stream of novel ordered and spin liquid phases. To date, however, most theoretical studies have focused on (psuedo-)spin-1/2 moments with anisotropic interactions, representative of rare-earth magnets with strong spin-orbit coupling. Relatively little is known about what happens for spin-1 transition metal ions such as Ni2+, where spin-orbit coupling plays a smaller role.

Here we explore what can be learned by applying recently-developed simulation techniques for spin-1 moments to the pyrochlore lattice. We uncover a wide variety of different ordered and spin liquid phases, many of them not previously reported in the literature, and discuss their implications for experiment. These results suggest that spin-1 pyrochlore magnets represent another exciting new frontier in frustrated magnetism.

152

Quantum spin supersolid as a precursory Dirac spin liquid in a triangular lattice antiferromagnet

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Based on the recent experiments on the triangular lattice antiferromagnet Na2BaCo(PO4)2, we propose the easy-axis XXZ spin-1/2 model on the triangular lattice, that exhibits a quantum spin supersolid, to be a precursory Dirac spin liquid. Despite the presence of a three-sublattice magnetic order as a spin supersolid, we suggest that this system is close to a Dirac spin liquid by exploring its spectroscopic response. The physical consequence is examined from the spectroscopic response, and we establish the continuous spectra near the M point in addition to the K point excitation from the spinon continuum on top of the three-sublattice order. Moreover, the satellite peaks were predicted at the mid-points connecting the Γ and K points. This proposal offers a plausible understanding of the recent inelastic neutron scattering measurement in Na2BaCo(PO4)2 and could inspire further research in relevant models and materials, such as K2Co(SeO3)2 and Rb2Co(SeO3)2, and even more anisotropic magnets like PrMgAl11O19.

153

Signature of classical spin liquid state in a highly frustrated S = 1 Kagome lattice antiferromagnet (CH3NH3)2NaV3F12

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Kagome lattice antiferromagnets offer promising platforms for realizing highly entangled quantum states, such as quantum spin liquids (QSLs). While s=1/2 kagome antiferromagnets are widely recognized as a potential QSL hosts, their s=1 counterparts are theorized to exhibit trimer crystals, valence bond phases, or gapped classical spin liquid states, awaiting experimental verification. In real V3+ and Ni2+-based kagome antiferromagnets, unavoidable perturbations, such as single-ion anisotropy and higher-order biquadratic interactions, add further complexity, leaving their impact on the predicted ground state in s=1 Heisenberg kagome antiferromagnets an open question.
In this presentation, we address the crystal structure, thermodynamic properties, and spin dynamics of (CH3NH3)2NaV3F13, where V3+ ions form a nearly perfect two-dimensional kagome lattice in the ab-plane. Magnetic susceptibility measurements above 150 K yield orientation-dependent Curie-Weiss temperatures, temperatures θ_CW^∥= -58 K and θ_CW^⊥= ⊠120 K. High-field magnetization data reveal a weak kink corresponding to the one-third magnetization plateau and a spin-flop-like transition near 2 T, alluding to the essential roles of single-ion anisotropy and additional interactions in this s=1 kagome lattice system. Specific heat measurements indicate the presence of weak magnetic order around 4 K, supported by µSR and 23Na NMR results. Below 4 K, the magnetic specific heat follows a power-law dependence down to 73 mK, indicative of gapless excitations. µSR shows persistent spin fluctuations down to 30 mK, with no signs of conventional long-range magnetic order. This coexistence of weak spin freezing and gapless excitations is further corroborated by the temperature dependence of the 23Na NMR spin-lattice relaxation rate. These observations suggest that CH3NH3)2NaV3F13 exhibits a unique interplay between weak magnetic order and classical spin liquid behavior at zero field. Singularly, the application of a moderate magnetic field quenches the weak magnetic order, raising the possibility of a field-induced classical spin liquid state.

155

Monopoles, Dirac strings and Magnetic Noise in Model Spin Ice

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Using the fragmentation [1,2] procedure on the dumbbell model of spin ice 3, it is shown that the deconfined magnetic monopoles are topologically constrained by classical Dirac strings defined in the space-time of particle trajectories. The consequences of the topological constraints are addressed for real Dirac monopoles and their strings and the Stanford experiment for Dirac monopole detection [4] is reconstructed in model spin ice. The experimental setup is used to study magnetic noise experiments in a simulation with stochastic dynamics. It is shown that the noise from the monopoles and their constraining strings can be separated and that the correlated signal over long times comes largely from the constraining strings rather than from the monopoles themselves.

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156

Signatures of quartic modes in magnetically ordered spin systems

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Classical magnetically ordered spin systems feature spin wave excitations which correspond to collective harmonic oscillations and are thus well captured by linear spin wave theory. However, this standard scenario breaks down in the case of softer excitations like quartic modes which can be regarded as an intermediate case between harmonic and zero modes. We argue that quartic modes appear naturally in magnetically ordered systems with several possible symmetry related ordering wave vectors. Specifically, if one of these wave vectors is selected by spontaneous symmetry breaking, a quartic mode arises from perturbing the spin state with another ordering wave vector. At zero temperature this quartic perturbation gives rise to a gapless spin wave branch in the spin structure factor. At finite temperatures, our analytical investigations of a simple phenomenological model together with classical molecular dynamics simulations indicate a finite, fluctuation-induced gap whose size scales with a characteristic exponent of 1/4 as a function of temperature. We demonstrate that this scaling behavior is independent of system details such as dimensionality and can thus be used as a characteristic signature to detect quartic modes in experiments.

158

Investigating Cl covalency in alpha-RuCl3

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Alpha-RuCl3 has been the leading material in the search for Kitaev quantum spin liquids due to its quasi-2D nature and large spin-orbit coupling. However, the Kitaev model alone is insufficient to describe the magnetism in the material. Additional off-diagonal terms and Heisenberg interactions are known to be necessary, but a full understanding of the Hamiltonian remains incomplete. Thus far, research has focused largely on the Ru spin structure, ignoring covalency of the Ru-Cl bonds. There has however been some suggestion of covalency in the material being important. Third neighbour interactions have been added to the Hamiltonian to stabilize magnetism in the material, arising from long range hopping with strong hybridization. A recent Resonant Inelastic X-ray Scattering (RIXS) study shows spectra best explained with non-local excitations, emphasizing the importance of electron itinerancy 1.In our previous Resonant Elastic X-ray Scattering (REXS) measurements at the Ru L3-edge, azimuthal angle dependence of the Bragg peaks was used to determine the Ru moment direction [2,3]. We have carried out further REXS measurements at the Cl K-edge, observing resonant enhancement of the magnetic Bragg peaks with a different azimuthal dependence to Ru L3, indicating presence of magnetic moment on the Cl site. The temperature dependence of the resonant Bragg peaks match those of the Ru edge suggesting a similar magnetic origin. Our measurements provide evidence of the importance of Cl covalency to magnetism in RuCl3.

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160

Vison crystallisation in inversion symmetry broken quantum spin ice

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Recent excitement in the quantum spin ice (QSI) community has come from the experimental discovery of pseudospin-$\frac{1}{2}$ breathing pyrochlores, including $Ba_3Yb_2Zn_5O_{11}$, in which inversion symmetry is broken by the 'up' and 'down' tetrahedra taking different physical sizes. We show here that the often-neglected $J_{z\pm}$ coupling between Kramers ions, in combination with the breathing nature of the lattice, can produce an imaginary ring flip term.
This can lead to an unconventional "$U(1)_{\pi/2}$ phase", corresponding to a maximally dense packing of visons on the lattice. The coherent, emergent QED dynamics of conventional QSI persist in this phase in a manner reminiscent of fragmentation in spinon crystals.
We characterize the excitations of the system within the enlarged QSI phase diagram, showing that the imaginary ring flip acts both as a chemical potential for visons and as an effective three-photon vertex akin to strong light-matter coupling. The novel coupling causes a structured high-energy continuum to emerge in the dynamical spin susceptibility, which is naturally interpreted as three photon up-conversion in a nonlinear optical crystal.

161

Perfectly hidden order and $\mathbb{Z}_2$ confinement transition in a fully packed monopole liquid

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Pyrochlore spin ice in a [100] field famously realises a Kasteleyn transition in which the field-polarised state breaks down by a sudden proliferation of strings of flipped spins that span the full system. In this talk, I will discuss a variant of this phenomenon in an alternative version of spin ice, whose degenerate ground states are densely packed monopole configurations. Here, an applied [111] field results in a thermodynamic transition, as indicated by, e.g., specific heat; however, *no local order parameter* distinguishes the two phases, unlike the standard Kasteleyn transition.

I will show that the transition is in fact a $\mathbb{Z}_2$ topological one, driven by the deconfinement of loops of flipped spins. Short loops are allowed in the monopole-liquid ground state manifold, even in very high fields; as the field is lowered, these loops get longer and longer, until loops of all sizes, including system-spanning ones, proliferate at the transition. While this is not captured by the magnetisation, it has clear signatures in topological and string order parameters, establishing the system as a rare example of perfectly hidden order in a 3-dimensional classical model.

We describe the transition in terms of a bosonic field theory with a pairing term, as well as a Kramers-Wannier duality to a 3D Ising model, which establishes its $\mathbb{Z}_2$ nature and explains why the system shows critical scaling expected near a 3D Ising transition instead of the "3/2-order" kink associated with the Kasteleyn transition. Remarkably, however, the magnetic response scales with the critical exponent not of the susceptibility, but of the *specific heat*, which may serve as a clear diagnostic of this transition into perfectly hidden order in experimental realisations.

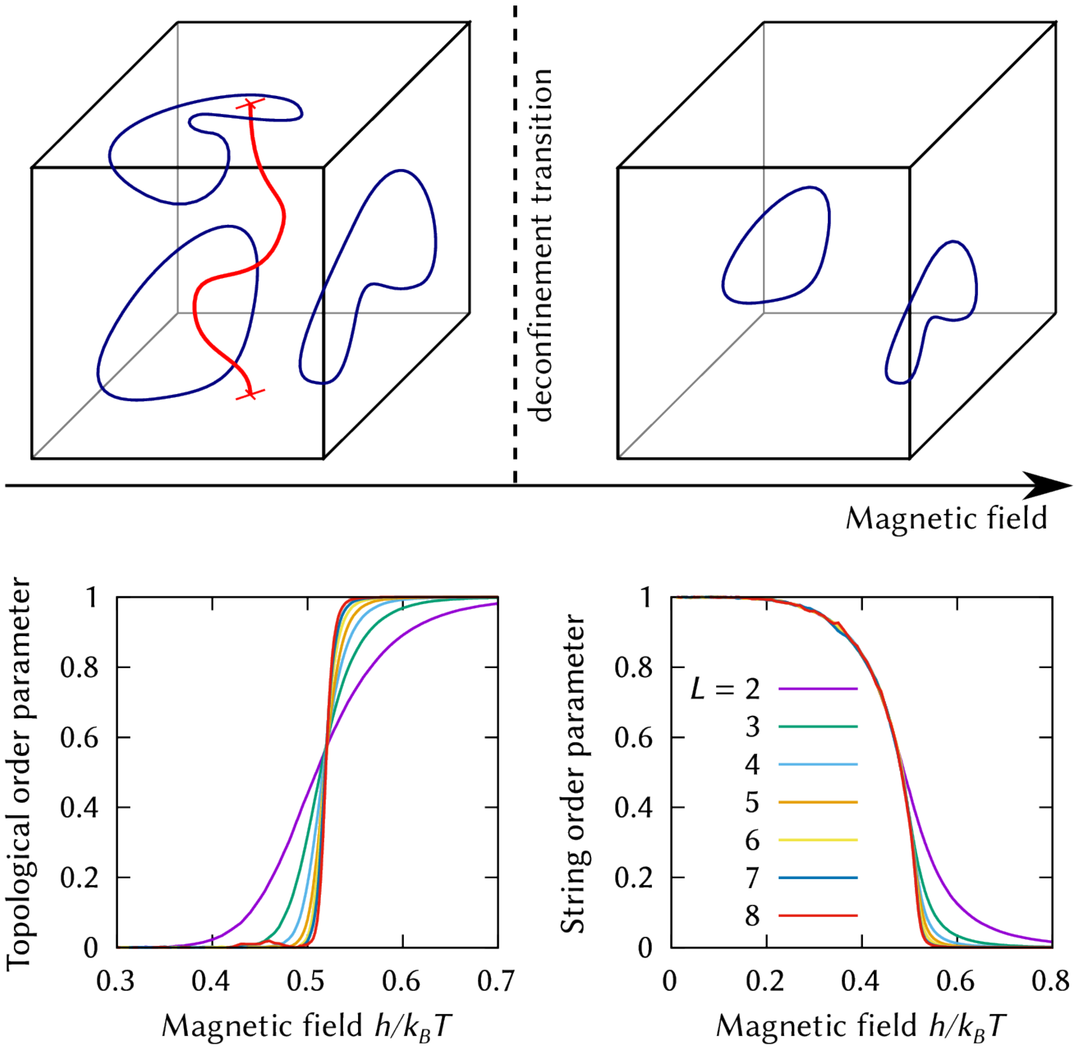

Figure 2: Kasteleyn

162

Exploring the Anisotropic Shastry-Sutherland Model by Strain Tuning of $SrCu_2(BO_3)_2$

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The Shastry-Sutherland model is a hallmark of frustrated magnetism and is realized by $SrCu_2(BO_3)_2$, where competing intra-dimer and inter-dimer interactions J and J' stabilize a dimerized ground state. The Shastry-Sutherland model can be generalized to an anisotropic model with two sets of inequivalent couplings J_1, J_2 and J'_1, J'_2. This model is predicted to host novel ground states [1] and may address the debate [2] on the nature of the plaquette phase of $SrCu_2(BO_3)_2$. Experimentally, anisotropic strains break the lattice symmetry of $SrCu_2(BO_3)_2$ and may therefore be used to tune the anisotropy in the Shastry-Sutherland model. We use the AC elastocaloric effect, a thermodynamic probe of strain-tuned quantum materials [3], to map out the entropic landscape of $SrCu_2(BO_3)_2$ under large anistropic strains. By comparing the results under [100] and [110] strain, we disentangle the effects of symmetry-breaking and symmetry-conserving strains on $SrCu_2(BO_3)_2$. Our phase diagrams reveal features consistent with hydrostatic-pressure studies [4], alongside new effects that may arise from symmetry breaking.

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163

Thermal pure matrix product state in two dimensions: tracking thermal equilibrium from paramagnet down to the Kitaev spin liquid state

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Numerical studies of Quantum many body systems at finite temperature are generically difficult, in particular if one is interested in systems with competing interactions. Methods applied so far have certain caveats: Lanczos based methods rely on the full Hilbert space limiting the accessible size of the system up to N 30 to 40. Quantum Monte Carlo methods, on the other hand, very often suffer from the infamous sign problem.

On general grounds, one considers either of two representations of a thermal state: The Gibbs state of the density operator which is a mixture of an exponential numbers of states and purity zero, whereas the thermal pure quantum (TPQ) state is a single pure wave function with purity one. Using random sampling methods, however, one can also construct various thermal mixed quantum states (TMQ) with a purity in-between 0 and 1 [1].

Here, we present an application of the recent approach to represent a TPQ state using matrix-product state (MPS). Although generally, MPS encodes states satisfying the area law of entanglement, TPQ-MPS has been shown to exhibit a volume law entanglement for a practically useful system size, e.g. N =64 sites [2]. For this, we employ a trick to accommodate larger entanglement than the standard MPS in attaching auxiliary sites on both edges of the MPS chain. These states are not physical but instead constitute an entanglement bath. Starting from the random (infinite temperature) MPS $|\Psi(0)\rangle$ and performing imaginary time evolution, we obtain a nearly pure state that requires few samples while reaching down to T 10^{-2} of the corresponding energy scale.

We extend the TPQ-MPS ansatz to two spatial dimensions by applying the, by now quite common, cylinder geometry: We wrap the lattice onto a cylinder and wind the one-dimensional MPS around using a spiral boundary condition. The system becomes quasi-1D with long range interactions. Thereby, we demonstrate that our method can be applied reasonably well to a non-trivial two dimensional system. Specifically, we reproduce the characteristic double peak structure in the specific heat of the Kitaev Honeycomb model [3], and compare our results to the very accurate, yet quite specialized, method based on treating the lattice-gauge degrees of freedom classically [4] as well as recent tensor-network methods [5]. Applications to other two-dimensional quantum systems will be discussed.

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165

Quadrupoles on the pyrochlore lattice

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Rare earth pyrochlore magnets have been studied in the context of magnetic frustration for many years - a testament to the richness of the physics of these systems. A common feature among this family is the presence of large angular momentum local moments and, as a result, one may expect multipolar couplings to play an important role under certain circumstances. In this presentation, I give an overview of the landscape of multipoles in rare earth pyrochlores before focussing on the quadrupolar couplings and describing features of the physics arising from their interplay with geometric frustration.

166

Magnetic frustration on the Cairo pentagonal lattice; Bi2Fe4O9

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The octahedrally and tetrahedrally coordinated Fe^{3+} (S=5/2) ions in $Bi_2Fe_4O_9$ form a quasi two-dimensional Cairo pentagonal lattice ($Pbam$). Combined with predominantly antiferromagnetic interactions, the unusual nature of the crystal structure gives rise to five dominant super exchange interactions, J_1- J_5 and strong magnetic frustration with $T_N = 245$ K while $\theta_{CW} = -1670$ K 1 in a fairly unexplored geometry. The magnetic structure for $T < T_N$ can be indexed with $k =$ (½, ½, ½) with a noncollinear magnetic structure of Fe_1 and Fe_2 moments, 2 different sites, and an interpenetrating pattern of fourfold spin rotations, a very novel magnetic state. For $T > T_N > \theta_{CW}$ we have probed a diffuse continuum of correlated anisotropic excitations reminiscent of an emergent state observed and characterised in the classical spin liquid h-$YMnO_3$ [2-4].

Previous measurements, on rather small (~0.6 g) single crystals and powdered samples of $Bi_2Fe_4O_9$ in the ordered phase, determined magnetic excitations over a broad energy range, $0 < \Delta E < 90$ meV [2, 3], with some disagreement between the two studies [5,6]. Beauvois measures an ungapped acoustic AF mode while Duc Le reports a gapped mode. As such Beauvois argue that no anisotropy is present while Duc Le indicates an easy-plane single-ion anisotropy. Additionally, the two studies report flat modes at different energies leading to an inconsistent interpretation of exchange interactions.

We have synthesized a 2.35 g, high quality single crystal of $Bi_2Fe_4O_9$ and are re-examining the magnetic excitations across the complete energy scale ($0 < \Delta E < 90$ meV) using multiple neutron spectroscopy instruments; CAMEA and EIGER (PSI), IN20 (ILL) and 4SEASONS (J-PARC). Already at energy transfers below 10 meV, in the ordered phase, we see distinct discrepancies between our data and previous data. Our data show a clear double spin gap that we can assign to the two unique Fe sites with axial and planar anisotropy. Additionally, we have measured inelastic neutron scattering on IN20 with polarization analysis, enabling us to study the nature of the anisotropic fluctuations for the various magnetic modes. The measured excitations have been modelled with linear spin wave theory and we show very good agreement across the broad energy range. We are therefore able to ascertain the Hamiltonian for the system. The thorough mapping of the ordered state magnetic excitations, $T < T_N$, will enable us to perform quantitative analysis of the emergent frustrated state for $T > T_N$.

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167

Long distance quantum coupling and multipole physics in quasiperiodic systems

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The exploration of quantum phenomena in quasi-periodic systems unveils new dimensions of complexity and novelty in condensed matter physics. In this talk, we discuss the mechanisms that enable robust quantum entanglement over macroscopic distances in quasi-periodic systems, highlighting the role of hidden hyperspace geometry. Furthermore, we explores the emergence of unconventional multipolar degrees of freedom and their frustration effect, which originates from the distinctive point group symmetries in quasicrystals under the influence of spin-orbit coupling. This work provides a significant step for studying exotic magnetism in quasi-periodic systems.

168

Finite temperature behaviour of spin-S Kitaev model

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Understanding the thermodynamic properties of quantum frustrated models has been one of the most challenging problems in condensed matter physics. Quantum monte carlo methods have been successful in probing many body physics at finite temperature, however they fail in the presence of frustration. Recently, a tensor network based method called Minimally entangled typical thermal states (METTS) [1,2] has proven effective in simulating the thermodynamic properties of SU(2) symmetric Hamiltonians 3. The method suffers from strong autocorrelation in absence of similar symmetries[4]. Here, we benchmark an improved METTS algorithm for the transverse field Ising models and subsequently use it to gain insights into the spin-S-Kitaev honeycomb model for low dimensional systems.

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169

Pressure induced spin liquid state in the anisotropic kagome Y-kapellasite

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$Y_3Cu_9(OH)_{19}Cl_8$ materializes an anisotropic kagome model with 3 different nearest neighbor interactions, yielding a rich phase diagram 1. Besides two long range ordered phases, this phase diagram features a large spin liquid area, which encompasses the isotropic kagome model. Noticeably the large difference in the Y and Cu radii prevents inter-site mixing and the anisotropic kagome planes are free from magnetic defects. We present a detailed investigation of large, phase pure, single crystals of this compound by neutron scattering, and local µSR and NMR techniques 2. At variance with polycrystalline samples, the study of single crystals gives evidence for subtle structural instabilities at 33 and 13 K and a bulk magnetic transition at 2.1 K, well below the antiferromagnetic 100 K Weiss temperature. The structural instabilities involve the localization of one interlayer proton and, importantly, preserve the kagome planes. At 2.1 K the compound shows a magnetic transition to the coplanar (1/3,1/3) long-range order as predicted theoretically. However, our analysis of the spin-wave excitations yields an estimate of magnetic interactions, which locate the compound closer to the phase boundary to the spin-liquid phase than expected from ab initio calculations. Enhanced quantum fluctuations at this boundary may be responsible for the reduced ordered moment of the Cu2+ and hint at a strong effect of external perturbations. Indeed, in recent µSR experiment under pressure, we could establish that the fragile long range order is suppressed in favor of a fluctuating ground state with a moderate 23 kbar applied pressure. This finding is rationalized by new high pressure diffraction results showing a tendency towards a more isotropic lattice in the same range of applied pressures.

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170

Microscopic origin of partial magnetic order in a metallic host

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Magnetic frustration often leads to unconventional phases of matter that challenge our understanding of quantum effects. While most research in this field has focused on frustrated insulators, metallic systems hold the potential to reveal novel frustrated quantum phenomena. The frustrated metal HoInCu4, characterized by a low density of states at the Fermi level, serves as an ideal model material for advancing our understanding in this area. The material crystallizes in a face-centered cubic lattice, where only a subset of the magnetic moments exhibits long-range antiferromagnetic order. Using neutron scattering techniques, we determined the magnetic exchange interactions in both the paramagnetic and field-polarized states. Our findings show that linear spin-wave theory does not adequately describe the low-energy spin dynamics in the antiferromagnetic phase. We present evidence for a partially ordered state, arising from the interplay between magnetic frustration and quantum fluctuations, in which only half of the moments contribute to the long-range order while the other half remains short-range correlated.

171

Thermal Hall effect of magnons in non-collinear phases on the triangular lattice

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Topologically nontrivial band structures formed by magnetic excitations have been investigated in the context of anisotropic magnets, where the finite Dzyaloshinskii-Moriya interaction [1-3] or a symmetric exchange anisotropy [4] endow the magnons with a complex hopping amplitude, generating finite Berry curvature. Non-coplanar magnetic textures have been explored, in which the emergent U(1) or SU(2) flux of the canting magnetic moments contributes to the desired kinetic term and the resulting anomalous magnon transport [5]. Recently, the thermal Hall effect of magnons arising from a more exotic higher rank SU(3) gauge structure has been put forward in an antiferromagnetic skyrmion lattice phase.

Motivated by these advances, we investigate the origins of finite Berry curvature and magnon Hall effect in the triangular lattice, where the usual U(1) gauge theory - arising, for example, from the DM interaction - is insufficient. We consider isotropic Heisenberg interactions between the first and second neighbor spins, including ring exchange, and map out the phase diagram of this model using variational approaches and exact diagonalization. We discuss the magnon band topology together with the symmetry-allowed Berry curvature multipoles and anomalous transport properties of the emerging phases.

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172

Order-by-disorder: A view from Anderson's tower

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Competing interactions or 'frustration' often leads to an accidental ground state degeneracy that is not a consequence of any global symmetry of the Hamiltonian. Consequently, thermal or quantum fluctuations may lift it, often resulting in an ordered state: a phenomenon known as "order by disorder" (ObD). While ObD is well-understood in spin systems in the semi-classical limit for large system sizes, its behaviour in the finite-size quantum systems typically amenable to simulation is less clear. For order-by-quantum-disorder at zero temperature, we show there are clear, identifiable signatures of ObD in the low-lying tower of states in the exact diagonalization (ED) spectrum, directly related to the Anderson tower of states usually associated with spontaneous symmetry breaking. We provide a phenomenological description of these features in terms of an effective quantum rotor model describing the competition between ObD induced localization of the order parameter and quantum tunnelling between symmetry-related ground states, capturing the cross-over from from the finite to infinite size limits. Using this model we relate the characteristic splittings in the ED spectrum directly to the ObD selection energy, providing a quantitative estimate of the strength of ObD that can be directly compared to semi-classical calculations. We validate these ideas in examples of spin systems that exhibit ObD: a Heisenberg-Kitaev chain, the Heisenberg-compass model on a square lattice, the Heisenberg-Kitaev model on the honeycomb lattice and the nearest-neighbor anisotropic exchange model on the pyrochlore lattice relevant for $Er_2Ti_2O_7$. Even at small system sizes, we find good agreement between semi-classical estimates of the ObD selection and Anderson tower estimates demonstrating the utility of this tool for understanding ObD in quantum magnets.

173

Interplay of frustrated magnetism and topology in delafossite NaCrS2

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The delafossite family $ACrX_2$ (A -alkali or other monovalent metal cations, X= O, S, Se, Te) is a highly compelling class of materials for the study of frustrated magnetism and exotic magnetic phenomena. Their layered structure, with Cr^{3+} ions forming a triangular network stacked in the 3R, 1T or 2H polymorph fashion, is naturally prone to geometric frustration of magnetic interactions. The non-symmorphic symmetry of the crystals and its combination with time reversal allows for nontrivial topologies in magnetic orders and magnon band crossings.
Non-oxygen-based delafossites are more robust to spin-lattice coupling relative to the oxygen-based variants, where this coupling is very strong and structural transitions accompany magnetic order; additionally chalcogenides are much less studied. We present the investigation of the novel delafossite $NaCrS_2$, and compare to previously studied delafossites such as the highly frustrated $AgCrSe_2$, which is known to have incommensurate helimagnetic ordering similar to early reports on $NaCrS_2$, using a wide array of techniques including extensive single crystal neutron, and x-ray diffraction.

174

Sample Thickness Dependence of Structural and Magnetic Properties in α-RuCl3

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α-$RuCl_3$ has experienced significant research interest as a proximate Kitaev quantum spin liquid candidate, even after the realization of antiferromagnetic order at low temperatures 1. The quasi-2D layered system hosts a honeycomb of Ru atoms and undergoes a structural transition from the high-temperature C2/m phase to the low-temperature R$\bar{3}$ phase at ~150K 2. Due to its layered nature, defects dominated by stacking faults give rise to a strong sample dependence. This results in varying structural hysteresis temperature width and magnetic transitions ranging from 6.5 to 14K 3. Magnetic transitions well above 7K have been directly linked to two-layer magnetic stacking and are common in both thin and manually deformed samples [3-5]. Understanding this sample dependence is crucial for measurements of α-RuCl3 requiring small/thin samples. In this work, we measure magnetic susceptibility over a range of sample thicknesses from 350μm to sub-20μm of α-RuCl3 samples with an initial magnetic transition of ~7K. Repeated exfoliation has revealed that sample thickness can be controlled down to at least 30μm without degrading the sample quality, assessed by the presence of higher temperature magnetic transitions. When the structural hysteresis range is widened through excessive cleaving or bending, the emergence of multiple high-temperature magnetic transitions is observed. The study supports the link between two-layer magnetism and the remnant of C2/m structure due to an incomplete structural transition to R$\bar{3}$.

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175

Field-induced spin liquid in the decorated square-kagome antiferromagnet nabokoite $KCu_7TeO_4(SO_4)_5Cl$

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Quantum antiferromagnets realizing the square-kagome lattice are proving to be a promising platform for nontrivial phenomena in frustrated magnetism. We carry out a theoretical analysis of the recently synthesized compound nabokoite $KCu_7TeO_4(SO_4)_5Cl$ based on a density functional theory energy mapping which establishes an unusual Heisenberg Hamiltonian with a hierarchy of couplings that suggests a description in terms of effective spin liquid models. Owing to the decoration of the square-kagome lattice with a seventh Cu site, nabokoite is characterized by highly frustrated square pyramids that are antiferromagnetically coupled in a chiral arrangement. Employing classical Monte Carlo simulations, we can explain the two transitions observed in the low-temperature magnetization curve from the experimental measurements. Remarkably, we show that the low-field phase is only realized when the inter-layer coupling is included. On the other hand, the intermediate-field phase is also found in a purely two-dimensional model and is described by a spin liquid featuring a subextensive degeneracy with a ferrimagnetic component. The subextensive degeneracy occurs due to the possibility of exchanging spins along zig-zag lines, and leaves characteristic needle-like features in the spin structure factor. We show that this phase can be approximated by a checkerboard lattice in a magnetic field. We finally assess the effects of quantum fluctuations in zero fields using the pseudo-Majorana functional renormalization group method and predict the spin structure factor for comparison with future neutron scattering measurements.

177

Performance of Kitaev-Heisenberg-Γ system as quantum Otto engine in small clusters

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In small-sized clusters, we study the four-stroke Otto engine. The clusters consist of a few sites, and there are spin-spin interactions among the sites. In the background of Kitaev interaction, we consider the presence of Heisenberg and Γ interaction, along with a magnetic field. Depending on the parameter values, this engine can operate in four different modes: heat engine, refrigerator, heat accelerator, and heat distributor. We find that these regions are almost independent of cluster size. We investigate in detail how the performance depends on the cluster size and whether the non-Kitaev interactions have any advantage on the engine performance. We notice a significant enhancement of efficiency of a heat engine when competing Kitaev and Heisenberg interactions are present, instead of just the Kitaev one; efficiency decreases when they are of the same sign. The presence of Γ on top of Kitaev interaction has no significant advantage on efficiency. We found that work delivered by the engine depends linearly on the size of the system. We also see that the maximum efficiency delivered by the engine monotonously depends on entanglement entropy in a rotating magnetic field. Finally, we study the engine for larger spin-S and show that the quantum engine can have dimensional advantages/disadvantages. We use standard fermionic mean-field approximation to relate some of our work to thermodynamic limits. We relate the fluctuation of various order parameters to different regions of the quantum Otto engine within mean-field approximation.

178

Isolated Dimer Interactions in Site-stuffed Quantum Dimer Magnet: BiYbGeO5

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The Kitaev honeycomb model has been a cornerstone in the study of quantum spin liquids (QSLs), offering one of the few exactly solvable frameworks for understanding these highly entangled magnetic states. The possibility of observing these exotic states in real materials has driven the search for compounds with honeycomb lattice structures that can approximate the conditions required by the Kitaev model, making it a focal point for studying novel magnetic phenomena and advancing our understanding of quantum materials.

Motivated by the search for materials that exhibit similar physics, we investigate the rare-earth-based compound $BiYbGeO_5$, which features a quasi-2D distorted honeycomb lattice of Yb^{3+} ions. Previous work by Mohanty et.al. shows BiYbGeO5 to be the first known rare-earth-based system to exhibit an isolated quantum dimer magnetic ground state. The interchangeable nature of rare-earth ions in such systems makes them an interesting playground for the effects of disorder on the ground state of basic magnetic quantum states.

To probe its magnetic properties, we performed neutron diffraction experiments down to 30 mK, revealing no signs of long-range magnetic order. Structural refinement of high-resolution diffraction data at 20 K indicates significant site-stuffing of nonmagnetic Bi^{3+} ions onto Yb^{3+} sites, attributed to their similar ionic radii and valency. This stuffing is seen consistently across all measured temperatures (20 K, 900 mK, and 30 mK), highlighting a robust structural modification of the lattice.

To investigate the consequences of this Bi3+ stuffing, we conducted inelastic neutron scattering (INS) measurements, which revealed a flat triplon band at ~0.15 meV, persisting up to 20 K. This corroborates with the previous work done by Mohanty et.al. where the triplon excitations were modeled indirectly using heat capacity and magnetometry studies. We aim to further analyze the INS data to analyze the structure factor and the temperature dependence of these excitations. Our findings establish $BiYbGeO_5$ as an ideal platform for studying the impact of site-stuffing on quantum dimer states and pave the way for future investigations into amorphous analogs.

179

Finite Temperature Phase Diagram of the Dipolar-Octupolar XYZ Model

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Dipolar-octupolar (DO) magnetic pyrochlore oxides offer an exciting platform for studying frustrated magnetism in three dimensions. Owing to their unique symmetry properties, the low-temperature behaviours of DO materials are well-captured by a pseudospin-1/2 description, whose different components transform as dipolar and octupolar moments under crystal symmetries. In particular, these materials have been well-described described by an alluringly simple XYZ Hamiltonian, whose zero-temperature phase diagram has been shown to host both long-range ordered and quantum spin liquid phases. Beyond the idealized zero-temperature limit, finite temperature properties of these materials have been examined for specific material models, often relying on classical simulation and semi-classical calculations. While a few quantum studies focusing on the XXZ lines of the broader parameter space exist, a full unbiased picture of the finite-temperature XYZ phase diagram, including the stability of zero temperature phases against thermal fluctuations and thermally stabilized phases, has yet to be explored.

To extend our understanding of DO materials, we examine the finite-temperature phase diagram of sign-problem free regimes of the XYZ Hamiltonian using the quantum Monte Carlo stochastic series expansion with directed loops. In particular, we identify and precisely characterize thermally-driven phase transitions through various thermodynamic properties with a focus on regimes where successive transitions are observed. As a result, we identify a quantitative dependence of the critical temperatures on model parameters. Furthermore, we compute spin-spin correlations in each thermally stabilized regime, revealing the nature of the magnetic phase. With these data in hand, we connect our study to recent experiments on real cerium- and neodymium-based DO materials where possible.

180

Two-dimensional nonlinear response of frustrated magnets

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Two-dimensional nonlinear (2DNL) coherent optical spectroscopy is of great interest in order to deconvolute excitation continua in correlated magnets, potentially allowing to analyze individual quasiparticles, including those of fractionalized magnets. We discuss the relevant response functions for the coupling of spin systems to electric fields and analyze the 2DNL dynamical susceptibilities for two scenarios of frustrated magnetism, namely for a quantum spin-liquid (QSL) as well as for a case of incommensurate spiral long-range order (ICO). For the former, we consider the Kitaev magnet, which hosts a quantum spin-liquid, featuring fractionalization in terms of mobile Majorana fermions and static flux-visons. We show that the 2DNL response does not only probe characteristic features of both fractional excitations, but also allows to extract single quasiparticle lifetimes from its multi-particle continua. These properties will be discussed over a wide range of temperatures. For the case of 2DNL response from a magnet with ICO, we chose the J_1-J_3 spin-model on the square lattice. Here, some features of the 2DNL spectra are found to be remarkably similar to those of the QSL case. Going beyond a bare quasiparticle approach, we will also comment on the impact of final-state interactions.

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181

SU(N) spin-phonon simulations of Floquet dynamics in spin S>1/2 Mott insulators

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Motivated by ongoing work in pump-probe experiments and terahertz spectroscopy, we develop new SU(N) Monte Carlo and molecular dynamics techniques capable of simultaneously simulating both magnetic and phonon degrees of freedom. Specifically, these simulations enable us to describe a linear quadrupole-phonon coupling, as allowed by symmetry, and through this examine the effect of resonant excitation of phonons on the underlying magnetic order. We apply these simulations to model a paradigmatic example of multipolar Mott insulators in $\mathrm{Ba_2FeSi_2O_7}$, whose equilibrium zero-temperature phase diagram hosts both a quadrupolar paramagnet (QPM) and easy-plane antiferromagnet (AFM). In this work, we investigate the effect of linear and chiral resonant excitation of E_g phonons in both the QPM and AFM phases. Explicitly, we find a number of fascinating effects including the generation of uniform magnetization in both QPM and AFM phases, a non-equilibrium QPM to AFM phase transition, and the gapping of a Nambu-Goldstone mode in the spin-wave dispersion. Our work highlights new directions for detection and control of multipolar orders and presents an exciting tool for the study of spin-phonon dynamics.

182

Spin-glass and quantum spin liquid ground-states in NaCdM2F7 pyrochlore (M = Co2+, Ni2+, Cu2+) and defect-fluorite (M = Mn2+) antiferromagnets

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The family of $A'A"B_2F_7$ pyrochlore fluoride antiferromagnets represents a unique but understudied class of materials containing the three-dimensional frustrated network of corner-sharing tetrahedra. While the rare-earth-based $A_2B_2O_7$ pyrochlore oxide counterparts have long been the main focus of study for their exotic magnetic ground states (spin glass, spin ice, spin liquid, order-by-disorder etc.), studies of these systems require extremely low temperatures due to the weak dipolar interactions between the magnetic 4f ions ($|\theta_{CW}|$ ~ $10^0 - 10^1$ K). Conversely, the $A'A"B_2F_7$ pyrochlore fluorides [1] overcome this limitation by replacing oxygen (O^{2-}) with fluorine (F^{1-}), enabling the stabilization of divalent magnetic 3d-transition-metal ions (from Mn^{2+} to Cu^{2+}) with stronger super-exchange interactions ($|\theta_{CW}|$ ~ $10^1 - 10^2$ K) on the pyrochlore B-site. Charge balancing and structure stability constraints, however, require a mixed occupancy of the pyrochlore A-site by monovalent A'^{+} and divalent $A"^{2+}$ cations, leading to chemical disorder, which eventually introduces magnetic bond disorder due to the $A'^{+}/A"^{2+}$ ionic size mismatch.

First magnetic studies of Na$A"M_2F_7$ ($A"$ = Ca^{2+}, Sr^{2+}; M = Co^{2+}, Ni^{2+}, Mn^{2+}, Fe^{2+}) single-crystal pyrochlores appeared in 2014 by the Cava group [2], reporting strong antiferromagnetic interactions ($|\theta_{CW}|$ ~ 70 − 140 K) with no apparent magnetic transition until a spin-glass transition at T_f ⊠ 2.4 − 3.9 K, indicating a sizable frustration with the frustration index $f = \frac{|\theta_{CW}|}{T_f}$ ranging between 19 − 58. Despite the observed spin freezing invoked by the weak magnetic-bond-disorder, μSR measurements revealed continued dynamics in $NaCaNi_2F_7$ down to milliKelvin temperatures, with low-energy pinch-points in inelastic magnetic neutron scattering hinting important features of a quantum spin liquid ground-state [3].

In our contribution, we report the successful synthesis and magnetic characterisation of novel frustrated NaCdM_2F_7 pyrochlore (M = Co^{2+}, Ni^{2+}, Cu^{2+}) and defect-fluorite (M = Mn^{2+}) antiferromagnets. [4,5] While M = Co^{2+} (J_{eff} = ½), Ni^{2+} (S = 1) and Mn^{2+} ($S = \frac{5}{2}$) indicate a frozen spin-glass ground-state at T_f ⊠ 2 − 4 K by means of AC susceptibility measurements, M = Cu^{2+} (S = ½) shows no magnetic transition in magnetisation or specific heat, with continued spin dynamics down to 50 mK confirmed by μSR and NMR measurements, hinting the realisation of a quantum spin liquid ground-state.

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184

The 3D analogue of the Shastry-Sutherland model

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The Shasrty-Sutherland lattice, a paradigmatic model in frustrated magnetism, has been the source of exciting physics in the past decades, from experimental measurements of magnetisation plateaus to theoretical evidence of spin liquids. We propose here a 3D analogue of the 2D lattice, which can be seen as a $J_1 - J_2$ deformed pyrochlore lattice where the coordination of each site is conserved but the topology is modified. We study the ground states of the model analytically in the classical Ising and Heisenberg regime, where we determine the exact ground states with respect to J_2/J_1 and an external field h. In the quantum Heisenberg regime we find a singlet state as the exact solution in the range $J_2 \geq 2J_1$, similarly to the 2D model, making this a rare example of a 3D quantum system where the exact ground state is known. We continue our analysis numerically for $J_2 < 2J_1$ using Exact Diagonalisation and Neural Quantum States where we will discuss differences in the phase diagrams of the 2D and 3D models.

185

Dynamical Effective Hamiltonian for Second Harmonic Generation in transition-metal dihalide

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Nonlinear spectroscopy opens up the possibility of exploring interesting physical phenomena in light-matter coupled materials. In particular, Second Harmonic Generation (SHG) intensity can identify magnetic order parameters and hidden order phases in studying 2D magnetic materials as suggested by recent studies [1].We formulate quantitative analysis of the SHG intensity in terms of local many-body multiplet states including both polarization and current terms, which is more suitable for Mott insulators than previous DFT-based approaches. We then use our theory to predict the responses of a van der Waals material NiI_2 and link them to the nature of the microscopic properties and magneto-optical coupling.

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186

Disorder-driven ground state in the frustrated antiferromagnet Ho2Zr2O7

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Disorder has been used as a tuning parameter to enhance strongly correlated ground states. The pyrochlore family $A_2B_2O_7$ combines geometrical magnetic frustration and, if the ratio between A^{3+} and B^{4+} ions is small enough, structural disorder, with A and B occupying the same site with a 50% of occupation each. In this work we examined the ground state, spin anisotropy, and spin dynamics of the disordered fluorite $Ho_2Zr_2O_7$ comparing it to structurally ordered pyrochlores. The sample was synthesized using the sol-gel chemical route. Bulk measurements such as AC magnetic susceptibility and specific heat were performed down to 150mK with magnetic fields under 7.5T and frequency up to 5KHz. We additionally measured Inelastic Neutron Diffraction at 7K and Ei=120meV to probe the consequences of the structural disorder in the crystalline electric field (CEF) excitations. No sign of long-range order was found. AC magnetic susceptibility revealed a broad peak around 1K and slow spin dynamics without glassy behavior. Neutron measurements revealed that disorder reduced the 20meV gap to the first excited state observed in $Ho_2Ti_2O_7$.

187

Spin liquid state in the frustrated S=1/2 Heisenberg body centered cubic garnet NaCa2Cu2(VO4)3

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Quantum spin liquid (QSL) state is well established in 1D, but in a sense much restricted compared to all the varieties of QSL predicted for 2D and 3D. While quantum fluctuations generally diminish with increasing dimensionality, there are now several experimental realizations of low connectivity, 3D frustrated lattices to look for such an unconventional state. Rare-earth-based pyrochlores are prominent examples, as they can stabilize exotic magnetic ground states due to strong anisotropic interactions and magnetic moments. However, due to the complex nature of 4f states, identifying the true key ingredients of their low-T physics may be cumbersome.
Here, we focus on a virtually unexplored alternative for studying QSL: the S=1/2 Heisenberg body-centered cubic (bcc) lattice, which was recently shown to possibly harbor a QSL phase 1. The copper-based material, $NaCa_2Cu_2(VO_4)_3$ belongs to the garnet structure family, $X_3Y_5O_{12}$, where the atoms at the Y-site form a bcc lattice with a 2:3 ratio of magnetic to nonmagnetic ions. The combination of possible magnetic frustration from multiple competing exchange paths and the quantum nature of S = ½ Cu spins — naturally prone to strong fluctuations — makes this material an excellent candidate for stabilizing a QSL state.
Combining polarized neutron scattering, bulk measurements and muon spin relaxation data, we reveal that the Cu2+ moments remains highly disordered down to 50 mK, despite the presence of short-range magnetic correlations from 30K. We found that the highly fluctuating low-temperature state is characterized by unconventional dispersive short-lived excitations (Fig. 1), consistent with a scenario of a spin liquid phase driven by magnetic frustration.

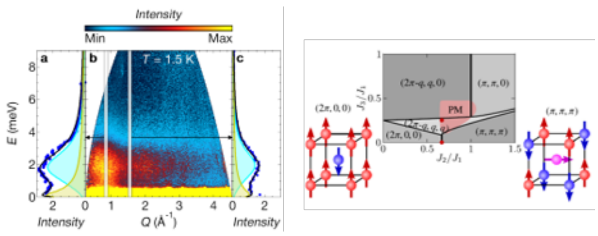

Figure 3: Image

Fig. 1. Left: Inelastic neutron scattering data of $NaCa_2Cu_2(VO_4)_3$ at 1.5K showing a dual response composed of a dispersive inelastic mode and a quasi-static contribution. Right: Phase diagram adapted from [1] with a non-magnetic phase (PM) found with the pseudofermion functional renormalization group technique.

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188

Quantized Kasteleyn transition in a partially ordered Kagome Ising antiferromagnet

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The first neighbour antiferromagnetic Ising model on the Kagome lattice is highly frustrated, resisting order up to zero temperature (Classical Spin Liquid) and hosting a macroscopically degenerate family of ground states. In experimental realizations of this frustrated Ising model, however, residual interactions may select a single ground state and prevent the observation of the Classical Spin Liquid. This is what happens in Kagome out-of-plane artificial spin systems, where long range antiferromagnetic interactions lift the ground-state degeneracy and order the system and low temperatures. On the Kagome lattice the lifting of degeneracy is gradual and, if interactions are truncated at the third nearest-neighbour ($J_1 - J_2 - J_3$ Kagome Ising antiferromagnet), three phases with distinct residual entropies can be stabilized depending on the relative strength of J_2 and J_3.
We report on a novel scenario for phase transition found in the constrained model implementing the $J_1, J_3 \to \infty$ limit of the $J_1 - J_2 - J_3$ Kagome Ising antiferromagnet, whose ground state is partially ordered. In this constrained model we show that the Kasteleyn transition, the condensation of linear defects in a fluctuation-free low-temperature phase, takes an exotic form due to the coexistence of two types of linear defects. The ratio in density of the two kinds of defects is quantized to integer values and the density of either type of defect jumps when this number changes by one, in contrast to the standard case where the density of defects continuously increases as $(T - T_c)^{1/2}$. The consequences of the quantized Kasteleyn transition to the phase diagram of the $J_1 - J_2 - J_3$ Kagome Ising antiferromagnet with finite couplings are explored. We further put forward two other models which host the quantized Kasteleyn transition. The first is a statistical mechanics model of infinite strings with internal degrees of freedom, which admits analytical treatment. The second is a quantum 1D Hubbard model of two fermion species with a spin-dependent interaction.

189

Excitation spectrum of the kagome-like quantum magnet Cu2OSO4

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Compounds characterised by a kagome lattice have been extensively investigated as they represent the archetypal environment to host a spin-liquid ground state [1]. However, if deviations from the perfect kagome lattice are present, such as magnetic interactions beyond the nearest-neighbour or antisymmetric Dzyaloshinskii–Moriya interaction (DMI), the degeneracy can be lifted and result in a long-range magnetic order in the system [2].
Di-copper oxygen sulphate (Cu2OSO4) [3] is one such realisation of a kagome-like lattice of Cu ions in which one of the three corners of the conventional triangle is replaced by a dimer. Therefore, there are two inequivalent Cu sites, namely Cu1 and Cu2. This system can be considered as a playground where significant perturbations to the kagome lattice can help quantify the effects of fluctuations and strong frustration.
Cu2OSO4 displays long-ranged ferrimagnetic order below 20 K. All the Cu magnetic spins point parallel to the kagome plane and the Cu1 moments develop non-collinear antiferromagnetic chains along the crystal b-axis. These chains are connected by Cu2 dimers, which are ferromagnetically coupled. As such, two Cu1 atoms and two Cu2 atoms form an approximately 120° structure with four spins [4]. It is interesting that this
specific ground state is selected, even though the system is far away from an ideal kagome or triangular lattice.
Our preliminary inelastic neutron scattering (INS) measurements on CAMEA (SINQ) display two dispersive modes along the [0K0] direction, within the kagome plane. A sharp dispersion centred at 2 meV and a broad dispersion centred at 8 meV. Interestingly, the minima of the lower sharp mode do not correspond to any Bragg peak position. Our latest INS experiment on IN12 (ILL), where we probed the spectrum perpendicularly to the kagome plane, also revealed that the higher-energy broad mode is actually made of two modes.
Thanks to the data we have collected so far, we managed to developed a spin-wave model that catches most features of the spectrum. It appears that couplings beyond the nearest-neighbour, out-of-plane couplings, DMI and anisotropies on the dominant bonds are needed to describe the dispersion of the magnetic modes. The existence of these anisotropies is supported by DFT calculations [5].
We plan further investigations for the future, also with applied magnetic field, to put further constraints to our model Hamiltonian.

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192

Towards Computing Spin-Phonon Scattering Effects on Phonon Thermal Transport

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It has been suggested that spin-phonon scattering may be responsible for various aspects of thermal transport in layered honeycomb magnets, such as (i) the unexpected thermal Hall effect attributed to chiral phonons, and (ii) strong suppression of longitudinal thermal conductivity in the paramagnetic phase. In this work, we report our preliminary efforts towards modeling these effects from first principles, by combining ab-initio phonons and spin-phonon couplings with semi-classical spin dynamics. We detail, in particular, our modifications to the semi-classical spin dynamics package Sunny to allow computations of higher-order bond-bond correlations, as well as the consequences of spin-phonon scattering for the temperature- and frequency-dependent phonon self-energy in a layered vdW magnet. The results are anticipated to be relevant for longitudinal thermal conductivity, ultrasound attenuation, and Raman scattering experiments.

193

Effective theory for spin-orbital Mott insulators based on first-principles calculation

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Mott insulators exhibit emergent spin and/or orbital degrees of freedom, leading to various intriguing physical phenomena such as multipole orderings and spin liquids. For instance, α-$\mathrm{RuCl_3}$, a spin-orbital Mott insulator, has been proposed as a Kitaev spin liquid candidate due to anisotropic interactions between the localized spins of ruthenium atoms [1]. Recently, a spin liquid state under a 100 T-class out-of-plane magnetic field has been reported [2], and the synthesis and physical properties of halogen-substituted $\mathrm{Ru}X_3$ ($X =$ Br, I) have been actively investigated [3].
Quantitative analysis of such Mott insulators requires addressing both the material's band structure and electron correlations in a multiorbital Hubbard model, which is computationally challenging. To overcome this difficulty, we focus on reducing the problem to a localized effective model. Previously, we constructed methods to construct localized effective models and developed mean-field and classical approaches for their analysis [4].
In this study, we aim to establish a quantitative framework for localized multiorbital electron systems by focusing on $\mathrm{Ru}X_3$ ($X =$ Cl, Br, I) as a case study. First, we construct a multiorbital Hubbard model through first-principles calculations with Quantum ESPRESSO, Wannier90, wan2respack, and RESPACK [5]. Then, we derive a localized effective model using perturbation theory in the strong coupling limit [4]. Furthermore, we determine the low-energy Hamiltonian describing interactions between the localized degrees of freedom and couplings with magnetic fields from first principles, enabling quantitative analysis of the magnetic properties of $\mathrm{Ru}X_3$.
In the presentation, we will discuss the impact of halogen substitution on the effective model, comparing it with previous theoretical studies on $\mathrm{Ru}X_3$ [6]. Additionally, we will present analyses of excitation spectra derived from flavor-wave theory [7], a generalized spin-wave theory, applied to the effective model. This framework provides a comprehensive approach for analyzing systems with orbital degrees of freedom by integrating mean-field, classical, and flavor-wave theories.

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194

Phase Diagram of the Easy-Axis Triangular-Lattice $J_1 - J_2$ Model

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The phase diagram of the $S = 1/2$ easy-axis triangular-lattice $J_1 - J_2$ model is investigated using the density-matrix renormalization group and analytical insights. We find a significant spin-liquid region extending from the Heisenberg limit and residing between the Y phase–known as the magnetic analogue of the "supersolid"–and collinear stripe phase. The order parameters of the supersolid are analyzed and an understanding of the lack of ferromagnetic moment in it is suggested.

195

Nonlinear optical view into phase transitions of an orthorhombic vdW magnet CrSBr

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CrSBr is considered as a special van der Waals magnet due to it low-symmetry crystal field, highly anisotropic electronic bands, yet nearly XY-type spin interactions. Its spin wave gap is around 30GHz, but its magnetic transition temperature is found to be 132K for its bulk and 140K for bilayer. The contrast between small spin wave gap and high critical temperature motives us to quest the nature of the nature of magnetism in the 3D bulk and in the 2D layers of CrSBr. We chose to use second and third harmonic generation (SHG and THG) to probe both the broken symmetries and the spin fluctuations in CrSBr. In this presentation, we will show our experimental results of separated critical temperatures found by SHG and THG in 3D bulk CrSBr, and furthermore, results of additional symmetry breaking phases in 2D bilayer CrSBr under an external magnetic field. As our results cannot be accounted by the known picture of CrSBr magnetism, we will discuss potential reasons of our observations.

196

Vacancy spectroscopy of non-Abelian Kitaev spin liquids

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Spin vacancies in the non-Abelian Kitaev spin liquid are known to harbor Majorana zero modes, potentially enabling topological quantum computing at elevated temperatures. Here, we theoretically study the spectroscopic signatures of Majorana zero modes in a scanning tunneling setup where a non-Abelian Kitaev spin-liquid model with a finite density of spin vacancies forms a tunneling barrier between a tip and a substrate. Our key result is a well-defined peak close to zero bias voltage in the derivative of the tunneling conductance whose voltage and intensity both increase with the density of vacancies. This 'quasi-zero-voltage peak' is the closest analog of the zero-voltage peak observed in topological superconductors, reflecting the fractionalized nature of spin-liquid-based Majorana zero modes. We further highlight a single-fermion Van Hove singularity at a higher voltage that reveals the energy scale of the emergent Majorana fermions in the Kitaev spin liquid.

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197

Low-temperature magnetic ground state in the pyrochlore series Yb2-xNdxTi2O7

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Pyrochlore magnets ($R_2M_2O_7$), where rare-earth ions form a network of corner-sharing tetrahedra, are central to the study of magnetic frustration, and exhibiting intriguing phenomena such as spin ice and spin liquid states. We present a comprehensive investigation of the novel mixed rare-earth pyrochlore system $Yb_{2-x}Nd_xTi_2O_7$ through magnetization, specific heat, neutron scattering, and crystal-field studies. We recently synthesized $Yb_{2-x}Nd_xTi_2O_7$ using the standard solid-state reaction method. AC magnetic susceptibility measurements reveals a peak below 0.5 K consistent with the onset of a long-range magnetic transition. This peak shifts to lower temperatures and broadens with increasing Yb content, suggesting evolving ground magnetic state and spin-spin correlations. Neutron powder diffraction reveals the absence of long-range order down to 0.1 K, in agreement with specific heat results, and suggesting that the ordered magnetic moment of the system must be very small and mostly possessing a dynamic component. Inelastic neutron scattering reveals crystal-field excitations consistent with the anisotropic nature of Yb^{3+} and Nd^{3+} ions. These findings highlight a compelling interplay of frustration and correlations in this series, and makes it an ideal case for exploring long-range order, short-range spin correlations, or glassy magnetic states.

198

Highly frustrated material realizations of the maple leaf lattice

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The Heisenberg quantum antiferromagnet on the maple leaf lattice has been shown to feature highly exotic phases. It would be very interesting to find material realizations of this lattice. Here, we extract and analyze the Hamiltonians of two promising minerals, bluebellite and spangolite.
In a first study [1], we determine the magnetic Hamiltonian of the copper mineral bluebellite using density-functional theory based energy mapping. Due to significant distortion of the spin-1/2 maple leaf lattice, we find two of the five distinct nearest-neighbor couplings to be ferromagnetic. The solution of this Hamiltonian with density matrix renormalization group calculations points us to the surprising insight that this particular imperfect maple leaf lattice, due to the strongly ferromagnetic Cu^{2+} dimer, realizes an effective $S = 1$ breathing kagome Hamiltonian. Analysis of the effective model within a bond-operator formalism then allows us to identify a valence bond solid ground state and extract thermodynamic quantities using a low-energy bosonic mean-field theory.
In a second study [2], we investigate spangolite with DFT energy mapping and find a spatially anisotropic spin-1/2 Heisenberg model featuring five symmetry inequivalent couplings with ferromagnetic bonds on hexagons and antiferromagnetic triangular bonds. Experimental measurements had found a non-magnetic ground state at $T \sim 8$ K with magnetization properties dominated by dimerisation. We demonstrate the validity of the proposed Hamiltonian by tensor network calculations which can assess both the nature of the ground state as well as low-temperature thermodynamics. We provide theoretical support for a dimerized ground state by calculating the static spin structure factor. We further predict the emergence of magnetisation plateaus at high values of an external magnetic field and study their melting with increasing temperature.
A common feature of both maple leaf minerals are distortions of the lattice that lead to different patterns of ferromagnetic and antiferromagnetic couplings. While the ideal maple leaf antiferromagnetic remains elusive, the physics of the distorted Hamiltonians is very rich.

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201

Enhanced dynamics in disordered non-Kramers spin ice Ho2(Ti1−x-Hfx)2O7 : toward the Coulomb quantum spin liquid state

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$Dy_2Ti_2O_7$ [1] and $Ho_2Ti_2O_7$ [2] classical spin ice compounds have been extensively studied over the past 30 years. Their excitations, described as emergent magnetic monopoles, exhibit very slow dynamics at low temperature, which manifests by a freezing and a strong irreversibility in Zero Field Cooled - Field Cooled (ZFC-FC) magnetization measurements [3]. It has been proposed that in spin ices made of non-Kramers magnetic ions, *i.e.* where J is an integer so that the ground-state crystal electric field (CEF) is a non-protected doublet, such as $Ho_2Ti_2O_7$, non-magnetic disorder induces quantum fluctuations that can push the system toward a Quantum Spin Liquid phase (QSL). This phase is characterized, *inter alia*, by a much faster dynamics [4,5].

We present a study performed on $Ho_2Ti_2O_7$, where non magnetic disorder is introduced through a controlled substitution of Ti^{4+} ions by Hf^{4+} ions, with substitution rate from 0 to 40%. X-ray and neutron diffraction show that the crystal structure and the spin ice correlations are preserved up to at least 30% (See Figure 1a) and that the introduction of disorder results in an oxygen depletion of the Ho^{3+} coordination shells, so-called Frenkel pair defects, that locally break the CEF symmetry. As a result, a broadening of the CEF levels is observed in inelastic neutron scattering. Nevertheless, DC magnetic measurements indicate that the Ising nature of the single-ion ground state remains. Interestingly, AC susceptibility and Neutron Spin Echo (NSE) reveal a faster dynamics below 30 K as the substitution rate grows (See Figure 1b). In addition, ZFC-FC measurements show that the freezing temperature is lowered. This speeding up of the dynamics strongly suggests that disorder indeed enables quantum fluctuations in the system. This opens the way to the stabilization of a Coulomb QSL phase at lower temperature.

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202

Spin-S Kitaev-Heisenberg model on the honeycomb lattice: A high-order treatment via the many-body coupled cluster method

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We study the spin-S Kitaev-Heisenberg model on the honeycomb lattice for S = 1/2, 1, and 3/2, by using the coupled cluster method (CCM) of microscopic quantum many-body theory. This system is one of the earliest extensions of the Kitaev model and is believed to contain two extended spin liquid phases for any value of the spin quantum number S. We show that the CCM delivers accurate estimates for the phase boundaries of these spin liquid phases, as well as other transition points in the phase diagram. Moreover, we find evidence of two unexpected narrow phases for S = 1/2, one sandwiched between the zigzag and ferromagnetic phases and the other between the Néel and the stripy phases. The results establish the CCM as a versatile numerical technique that can capture the strong quantum-mechanical fluctuations that are inherently present in generalized Kitaev models with competing bond-dependent anisotropies.

204

New quantum Monte-Carlo algorithm for the XXZ model on the pyrochlore lattice

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In this work, we explore new features of the nearest-neighbor spin-1/2
pyrochlore XXZ model with antiferromagnetic longitudinal exchange interactions via a newly developed quantum Monte-Carlo (QMC) algorithm. This numerical method is based on the worm algorithm for continuous-time path-integral QMC. We investigate the possible phases of this model at weak ferromagnetic transverse exchange coupling, studying, in particular, the crossover between classical and quantum spin ice (QSI) and the phase transition between QSI and the 3D XY ferromagnetically ordered phase. Some underexplored observables, such as the transverse spin susceptibility, are used to explain the latter. We also retrieve both the $\langle \hat{S}_z \hat{S}_z \rangle$ and the $\langle \hat{S}_+ \hat{S}_- \rangle$ equal-time spin correlators in the spin-flip and non spin-flip channels pointing to previously undetected characteristics that clarify the underlying physics both in the liquid and ordered phases. Finally, we reinterpret the $\langle \hat{S}_+ \hat{S}_- \rangle$ correlator in terms of the correlation length per unit cell and make use of this quantity for the first time to detect the transition between QSI and the XY ordered phase.

205

A sizable planar thermal Hall effect in the fully spin-polarized state of the honeycomb magnet: Na3Co2SbO6

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The planar thermal Hall effect (THE) in magnetic insulators has been widely studied and remains a topic of controversy regarding its underlying mechanism. Arguably the most renowned example of planar THE was reported in candidate Kitaev material- α-$RuCl_3$. However, its origin remains under intense debate with proposed mechanisms including Majorana edge modes 1, topological magnons 2, and phonons 3. While issues such as sample dependence due to stacking faults and the proximity to a possible quantum spin liquid phase have hindered a definitive conclusion, studies using simpler systems are desired to make a clear argument on the origin. Here, we found that $Na_3Co_2SbO_6$ (NCSO) acts as the ideal reference system to α-$RuCl_3$ as it shares a similar lattice and magnetic ground state [4-6]. However, under applied magnetic fields, NCSO quickly reaches a field-polarized regime, excluding the possibility of Kitaev physics or the presence of Majorana edge modes. Even so, we observe a sizable planar thermal Hall signal (κ_{xy}) in NCSO, comparable to that of α-$RuCl_3$ with the same field angle anisotropy [7]. Under high magnetic fields, we observe a near saturation of κ_{xy}, in contrast to the linearly increasing magnetic gap. Additionally, κ_{xy} is suppressed at the lowest temperatures, indicating a bosonic origin. While topological magnons yield a finite THE, the experimentally observed magnitude of κ_{xy} is much larger than the theoretical prediction [8]. In this work, we combine these experimental signatures and constraints and propose the possible magnon-phonon drag as the underlying mechanism in which mobile phonons enhance THE driven by topological magnons.

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207

U(1) Dirac spin liquid in a magnetic field: emergent gauge fluxes and dynamical signatures

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Quantum spin liquids are exotic states of matter where spins fractionalize into spinons coupled to emergent gauge fields. A particularly fascinating example is the U(1) Dirac spin liquid (DSL). Its low-energy theory, emergent quantum electrodynamics (QED_3), is believed to flow to a strongly coupled conformal fixed point. Motivated by recent numerical evidence for its realization in microscopic models of frustrated magnets as well as the identification of several candidate materials, we revisit the problem of the U(1) DSL in a Zeeman magnetic field, which has been suggested to exhibit antiferromagnetic ordering. We observe the Zeeman field B to induce an internal orbital field b, proportional to B, which results in the formation of relativistic Landau levels for fermionic spinons of the theory.

We investigate experimentally observable phenomena associated with this deformation of the underlying conformal field theory. Using a combination of field-theoretic analysis and sign-problem-free Monte Carlo simulations of a U(1) lattice gauge theory, we detail signatures in the dynamical spin-structure factor and discuss observables that may be unique to such field-induced state. In experiments, these may allow one to infer the presence of an underlying DSL at zero field.

208

Quantum spin liquid on the surface

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The classification of various topological phases has attracted much interests in recent years. It is known that some 2D quantum spin liquids can only be realized on the surface of a 3D system. But the material's realization of such quantum spin liquids is still lacking.

Here we suggest that 1T-TaS2 can realize a surface spin liquid. This material was found to be a band insulator, with dimerized layers held together by van der Waals force. The dimerized structure makes it analogous to the SSH model, which means that there are two types of surface termination. We found that the type-II surface, which terminates in the middle of the dimer, supports metallic surface state when strongly correlated effect is ignored. When the strong Coulomb interaction between the electrons is taken into consideration, the type-II surface can realize a surface spin liquid.

We also designed an experimental method to detect the surface spin liquid. Specifically, the spin correlation function of the surface spin liquid can be detected by ARPES, provided that the surface spin liquid is coupled to a dilute electron gas.

209

Variational wave functions and Monte Carlo approaches for frustrated spin models

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We discuss the core principles of the variational Monte Carlo method for frustrated S=1/2 spin models. In particular, we focus on the construction based upon the fermionic (Abrikosov) representation and the Gutzwiller projector. This kind of states are particularly effective for describing quantum spin liquids (as proposed for frustrated square, triangular, and kagome lattices). We highlight key technical aspects of Monte Carlo sampling, focusing on the types of computations that can be performed within the variational Monte Carlo framework. Time permitting, we will present a selection of relevant applications.

210

The emergence of a Spin-Liquid Phase in the Shastry-Sutherland Model from a neural-network wave function

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We introduce a variational Ansatz for two-dimensional frustrated magnets by leveraging the power of representation learning, illustrating its efficacy by studying the ground-state phase diagram of the Shastry-Sutherland model. With highly accurate numerical simulations, we provide strong evidence for the stabilization of a spin-liquid between the plaquette and antiferromagnetic phases. In addition, a direct calculation of the triplet excitation at the Γ point provides compelling evidence for a gapless spin liquid. Our findings underscore the potential of Neural-Network Quantum States as a valuable tool for probing uncharted phases of matter, and open up new possibilities for establishing the properties of many-body systems.

211

Field-induced gapless state in an anisotropic S = ½ kagome antiferromagnet: a specific heat and ultrasound study.

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Quantum spin liquids (QSL) are long sought exotic states of matter, with no long-range magnetic order even at T=0K, macroscopic entanglement and emergent fractionalized excitations [1]. In 2D, the S=1/2 nearest-neighbourg Heisenberg antiferromagnet on the kagome lattice is one of the simplest frustrated models that may stabilise a QSL ground state.

Numerical studies predicted that this system could exhibit a series of field-induced phases associated to magnetization plateaus (for M equal to 1/9, 1/3, 5/9 and 7/9 of the saturation value) [2], with a possible QSL state on the first plateau.

The Y-Kapellasite, $Y_3Cu_9(OH)_{19}Cl_8$, is an original variant of this model. In zero [3] but magnetization measurements have revealed the presence of a first plateau with an intriguingly 1/6-value, in the 17-25T field range [4].

The nature of the magnetic state within this plateau remains unknown so far. To shed light on this issue we have investigated the thermodynamic properties of this system down to 0.3K and up to 36T, for several field orientations, combining specific heat and ultrasound measurements. This allowed us to determine detailed T-B phase diagrams and disclose the presence of intriguing gapless excitations in the plateau regime.

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212

Thermal transport properties of the one-third magnetization plateau phase in Kagome antiferromagnet In-Kapellasite

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The spin-1/2 Kagome antiferromagnet has attracted attentions as a fascinating quantum spin system. Due to the quantum fluctuation induced by magnetic frustration, exotic magnetic states such as quantum spin liquid, topological order, and magnon crystal are expected to appear. The magnetic states under an external magnetic field are of particular interest. It has been reported that a series of spin-gapped phases appear with showing magnetization plateaus. These gapped phases are assigned to magnon crystals or topological orders in theoretical studies, whereas they have not been adequately verified in experimental studies.
In this presentation, we present experimental results of our thermal transport measurements on a Kagome antiferromagnet In-Kapellasite $InCu_3(OH_6)Cl_3$ which hosts a one-third magnetization plateau phase. Although the In-Kapellasite undergoes an antiferromagnetic transition at 2 K in zero external magnetic field, the magnetization exhibits a one-third plateau around 10 T. We measured magnetic-field dependence of the longitudinal and the transverse thermal conductivities and found that the thermal conductivities show anomalies at the lower critical field of the one-third plateau phase. From the experimental data, we discuss the thermal transport properties of the plateau phase.

213

Bulk-loop correspondence and pinch point singularity: a spin ice metal study

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Pinch point is a singularity of magnetic structure factor discovered in spin ice. In this contribution, we clarify its quantum geometric aspect based on the flat band description 1. We focus on the two topologically distinct classes of flat band wavefunction: the compact localized state (CLS), and the non-contractible loop state (NLS). We establish their simple mathematical relationship, showing that different Bloch NLSs can be derived as momentum derivatives of a Bloch CLS, depending on the approaching direction toward the singular point. The idea can be extended to higher-order topological phases, where this concept leads to interesting fractionalization of loops states.
This CLS-NLS correspondence helps visualize the pinch point as an interference pattern among NLSs. We demonstrate this mechanism in an electron model defined on a pyrochlore lattice, which was originally introduced to address the trimerized charge order of CsW2O6 [2, 3]. The standard flat band state of pyrochlore lattice at the top of the energy bands are well known, and when introducing the spin-orbit interaction (λ), we have another flat band at the band bottom. For the system with partially filled flat band ground state, we analyze the spectrum of inverse photoemission spectroscopy to access the hole excitation, and show that the spectrum, exhibits the pinch point singularity. Remarkably, not only the singularity but the entire spectrum turns out to be analytically identical to the magnetic structure factor of spin ice, which can be called a "spin ice metal" [4]. The bulk-loop correspondence holds, meaning that the identification of the NLS offers a rare example, where topological information can be identified through experimental observables.

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216

Musr study of Zn-averievite (ZnxCu2-x)Cu3V2O10(CsCl): towards a new spin liquid

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The frustrated mineral averievite Cu5V2O10(CsCl) possesses a quite different structure as compared to herbertsmithite and the other Cu-based kagome spin liquid candidates (barlowite, claringbullite, brochantite…). The kagome layers are indeed separated by two triangular layers, instead of one in herbertsmithite, which reinforces the 2D character (see Fig. 1). Besides, the absence of hydroxyl groups suggests that it may be a potential candidate for charge doping and that the deviations to the perfect Heisenberg model (e.g. magnetic anisotropies) are likely different.
The pristine averievite is known to order magnetically at 24 K due to Cu2+ magnetic interlayers but these can be replaced selectively by non-magnetic Zn2+ in Zn-averievite (ZnxCu2-x)Cu3V2O10(CsCl), thus magnetically decoupling the kagome layers. This gives access to an idealized kagome system as well as a tuning parameter to control the three-dimensionality. While only x<1.25 compounds are by now reported in the literature [1,2,3], we were able to produce samples with x=2.
We present a MuSR study for x ranging from 0 to 2. While we confirm the existence of long-range magnetic order in the parent compound (x=0) below 24 K, we clearly show that only a full substitution of inter-plane copper ions (i.e. x=2) leads to a quantum-disordered ground state. The experiments performed on the partially substituted material (x=1) uncover that the transformation proceeds through an intermediate frozen disordered ground state. The end compound x=2 thus opens a new avenue to study Kagome Quantum Spin Liquids (QSL). We will discuss our findings with respect to other existing Cu-based kagome spin liquid candidates.

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217

Magnon thermal Hall effect via higher rank gauge fields

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The magnon thermal Hall effect was first discussed over a decade ago and initially observed in noncentrosymmetric ferromagnets with Dzyaloshinskii-Moriya interactions or noncoplanar magnetic orderings. These effects are described using U(1) gauge fields, manifesting as fictitious uniform magnetic fluxes acting on magnons to bend their trajectories. This gauge field also arises from slowly varying magnetic configurations of skyrmions.
However, in antiferromagnetic systems with edge-shared geometries, this picture breaks down because the U(1) gauge fields on neighboring plaquettes cancel each other out, thereby strictly forbidding the thermal Hall effect due to symmetry arguments.
Interestingly, certain antiferromagnets exhibit topological magnon properties, such as nonreciprocity in the square-lattice antiferromagnet $Ba_2MnGe_2O_7$, which suggests the existence of spin-split magnon bands. The antiferromagnetic skyrmionic lattice phase in $MnSc_2S_4$ displays a thermal Hall effect, forming three distinct skyrmions on three magnetic sublattices within the triangular (111) plane.
Here, we theoretically demonstrate that antiferromagnets can indeed host thermal Hall effects and topological magnons, dressed with emergent higher-rank gauge fields. In this framework, antiferromagnets with $n = 2$ or 3 magnetic sublattices support n species of magnons. While the U(1) gauge field formed within each sublattice cancels out by themselves, the magnetic exchange interactions between sublattice spins couple these fields to produce higher-rank gauge fields. Consequently, in the square-lattice antiferromagnet, canted spins with slightly noncoplanar structures give rise to SU(2) magnons, and in the three-sublattice skyrmionic lattice, the off-plane spatially varying textures generate SU(3) magnons.
Our spin-wave analysis with support from this high-rank gauge field framework, quantitatively explains the experimental observations. Additionally, we predict other scenarios, such as high-field magnetization phases, where the thermal Hall effect may become active, providing insights into the broader applicability of gauge physics.

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218

Angle-resolved torque magnetometry of epitaxial $Pr_2Hf_2O_7$ thin films

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Angle-resolved torque magnetometry informs the spin-spin interactions of frustrated magnets including classical spin ice pyrochlores 1 and Kitaev candidates [2-3]. Moreover, growing frustrated magnetic thin films on a lattice mismatched substrate can change magnetic interactions due to the strained lattice constant.

Epitaxial thin films of the quantum spin ice candidate $Pr_2Hf_2O_7$ are grown on yttria-stabilized zirconia and lanthanum aluminate substrates using pulsed laser deposition. The choice of substrates controls the epitaxy and the growth conditions influence the microstrain of the thin films, which are characterized using parallel-beam x-ray diffraction. Measurements of the angle-resolved torque magnetometry of these films reveal a rich magnetic phase diagram with strong temperature and field dependences. The angle-resolved torque magnetometry is used to evaluate various aspects of the $Pr_2Hf_2O_7$ thin film phase including crystal structure constraints and the relative strengths of various spin ice states at temperatures from 2 K to 50 K and fields up to 9 T.

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221

Pseudofermion functional renormalization group study of dipolar-octupolar pyrochlore magnets

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Motivated by recent experiments on $Ce_2Zr_2O_7$ that reveal a dynamic, liquid-like ground state, we study the nearest neighbor XYZ Hamiltonian of dipolar-octupolar pyrochlore magnets with the pseudofermion functional renormalization group (PFFRG), which is numerically implemented by the SpinParser software. Taking the interaction between the octupolar components to be dominant and antiferromagnetic, we map out the phase diagram demarcating the quantum disordered and magnetically ordered states. We identify four distinct phases, namely the 0-flux and π-flux quantum spin ices, and the all-in-all-out magnetic orders along the local z and x axes. We further use the static two-spin correlations output by the PFFRG algorithm to compute the polarized neutron scattering cross-sections, which are able to capture several qualitative features observed experimentally, in the materially relevant parameter regime that stabilizes the π-flux quantum spin ice. Our results provide support for a quantum spin liquid ground state in $Ce_2Zr_2O_7$.

225

Magnetic properties investigation on the inverse spinel single crystals

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The general formula of oxide spinel is AB2O4, and the distribution configuration is represented as (A1−xBx)(B2−xAx)O4. Normal spinel have x=0, whereas inverse spinel have x=1; any distribution is possible between the extremes. Inverse spinel structure is a common class of cubic symmetry, space group Fd3¯m, with a frustrated corner sharing tetrahedral network of B-site atoms [1,2]. In the case of the M2TiO4 (M=Mg, Co, Fe, Mn and Zn) system, the electronic state of Ti in M2TiO4 is not diamagnetic Ti4+ but primarily magnetic Ti3+, resulting in the configuration [M2+][M3+Ti3+]O4. The magnetic properties of an inverse spinel compounds are strongly dependent on the distribution of the different cations among (A) and [B] sites. In the case of Co2SnO4, the cation distribution on the sites are A (Co2+1.0) and B (Co2+1.0Sn4+1.0) respectively.

The nature of the magnetic ordering in this compound was reported to be quite complicated in which the ordering of longitudinal spin components at 41K was proposed to be followed by freezing of the transverse spin components occurring at spin−glass transition temperature TSG ⊠ 39.1K. It was proposed that this semi-spin−glass (SSG) state co-existing with longitudinal ferrrimagnetic ordering occurs because of the magnetic frustration caused by the presence of diamagnetic Sn4+ on the B-site [4]. However, in the case of Co2SnO4 there is near complete effective balance of the antiferromagnetically coupled Co2+ moments at the 'A' and 'B' sites leading to negligible values below compensation temperature due to non-magnetic Sn contribution [4].

We have grown single crystals of several inverse spinel compounds using floating-zone and flux techniques. To investigate the static magnetic structure of both sublattices,
both below and above the compensating temperatures, we have used neutron scattering technique and to study the magnetic dynamics around the phase transition, we used muons.

In this presentation, we report how the crystal structure effects the magnetic structure of the M2TiO4 (M=Mg, Mn, Co and Fe) M2TiO4 single crystals.

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226

Magnetic frustration in octahedral lattices: from antiperovskites to fcc antiferromagnets

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Geometrically frustrated magnets typically consist of either triangular or tetrahedral blocks of magnetic ions. A novel frustration motif is provided by octahedral blocks. Magnetic ions form a lattice of corner-sharing octahedra in antiperovskites and Mn_3X intermetallics, while an edge-shared octahedral network appers for the J_1-J_2 spin model on a face-centered cubic (fcc) lattice for a special ratio of two exchanges $J_2/J_1 = 1/2$. We illustrate an emergent complex behavior of octahedral antiferromagnets by studying two examples. The first example concerns the $120°$ antiferromagnet $MnPt_3$, which exhibits a double transition in zero field with a partially ordered intermediate phase. We explain the observed behavior by considering an interplay of a local anisotropy with magnetic frustration in octahedral blocks. The second example is related to the magnetization process of the classical J_1-J_2 fcc antiferromagnet. Up to eight different phases are found in an external magnetic field including two fractional magnetization plateaus at $M/M_{\rm sat} = 1/3$ and $2/3$.

228

Investigating the origin of zero moment layers in $K_3Er(VO_4)_2$

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Spin-1/2 antiferromagnetic triangular lattice models are paradigms of geometrical frustration, revealing very different ground states and quantum effects depending on the nature of anisotropies in the model. The rare-earth delafossite materials, forming a perfect triangular lattice, are prime candidates for hosting quantum spin liquid states, however, imperfect triangular lattice materials may also show intriguing phases. Previous work on rare-earth double vanadate glaserite material $K_3Er(VO_4)_2$, a quasi-two-dimensional (2D) isosceles triangular antiferromagnet, has uncovered a unique ordered ground state comprised of layers of antiferromagnetic b-aligned moments alternating with layers of zero moment. Magnetic susceptibility data suggests that Er^{3+} takes on a strong XY single-ion anisotropy in $K_3Er(VO_4)_2$, leading to vanishing moments when pseudospins are oriented along c. I will present my recent undertaking to further uncover the nature of single-ion anisotropy in $K_3Er(VO_4)_2$ through half-polarized neutron diffraction, crystal field measurements, and diffuse scattering analysis.

229

Experimental studies of three-dimensional lattices of corner-sharing triangles

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Frustration in three-dimensional lattices is most well-studied on the pyrochlore lattice which consist of corner-sharing tetrahedra, where each magnetic ion participates in two tetrahedra. Lattices of corner-sharing triangles also have the potential for strong geometrical frustration. The most commonly-studied system is the hyperkagome lattice where each site participates in two triangles. For example the hyperkagome lattice is found in the Garnet structure (space group $Ia\bar{3}d$ on the 24c Wyckoff position). The hyperkagome lattice is also associated with the space group $P4_132$ on the 12d Wyckoff site. Here besides participating in the two triangles of the hyperkaome lattice each magnetic ions also participates in another inequivalent triangle so that there are in fact three triangles at each site although one is different from the other two. Finally a lattice which consists of three equivalent corner-sharing triangles at each lattice site is the trillium lattice with space group $P2_13$ and magnetic ions on the 4a. This presentation will show example materials from these different types of corner-sharing triangular lattices and discuss their magnetic properties.

230

Dynamic Jahn-Teller effect and a multi-polar order in 5d1 double-perovskites

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In 5d1 double-perovskites magnetic ions sit on a frustrated three-dimensional network derived from a face-centred cubic structure. The interactions comprise ferro- and antiferromagnetic coupling of magnetic dipoles, as well as a coupling of charge quadrupoles [1]. A prominent example of such a system is Ba2MgReO6, which exhibits a magnetic dipole transition at Tm=18K and a charge quadrupolar transition at Tq=33K [2]. Recently we have shown [3] that an additional energy scale must be taken into account, dictated by the Jahn-Teller instability of a spin-orbit coupled ground state quartet. Based on local-cluster quantum chemistry calculations, we have revealed that ReO6 octahedra are distorted along three principal axes with equal probability, implying a dynamic Jahn-Teller scenario. The splitting of the ground-state quartet into two doublets has been observed to persist at temperatures well above Tq, by both RIXS (resonant inelastic x-ray scattering) and thermodynamic experiments. Importantly, the amplitude of distortions caused by the Jahn-Teller effect is much larger than those observed to occur below Tq. This leads us to conclude that ReO6 octahedra remain dynamic to the lowest temperatures, while the emergence of the quadrupolar order serves as a correction to the local potential energy surface [4]. The full Hamiltonian, involving spin, orbit and vibronic degrees of freedom, predicts the appearance of additional weak modes at energies above the main d-d excitations. In addition to the evidence of such modes obtained by RIXS [3], we will present new data obtained using Raman spectroscopy, which indicates intrinsically broad features. Additionally, one Raman mode is seen to be strongly renormalized relative to a non-magnetic Ba2MgWO6 compound, pointing to hybridization with electronic degrees of freedom. We will also discuss the behavior in magnetic fields, where tetragonal domains, appearing below Tq, can be populated and depopulated depending on the direction of magnetic field. Using magnetization and REXS (resonant elastic x-ray scattering) results in magnetic field, we will demonstrate the hysteretic behavior originating from pinning of both magnetic and structural domain walls. The 'softness' of structural domains can be directly linked to the dynamic Jahn-Teller state of ReO6 ocathedra.

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232

Dielectric relaxation by critical magnons in frustrated spin chains

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Low dimensionality and geometric frustration boost quantum fluctuations, stabilizing highly correlated states at low temperatures. Conversely, conventional multiferroics research focuses on practical applications of the interplay between ferroelectricity and magnetism, exploring typically classical effects. As a result, little overlap exists between these fields.

Here, we demonstrate the potential of merging methods from both areas. Investigating the magnetoelectric coupling in a quantum magnetic material leads not only to a deeper understanding of its magnetism and quantum criticality but also to uncover qualitatively new phenomena. In particular, the latest results on the quantum spin systems Rb2Cu2Mo3O12 and Cs2Cu2Mo3O12 will be reviewed. These geometrically frustrated one-dimensional ferro-antiferromagnets show rich magnetic phase diagrams with a variety of field-induced magnetic phases. In addition, critical divergent electric susceptibility has been found in both systems at a magnetic quantum phase transition, providing a new way to explore criticality. Finally, we find novel quantum multiferroic behavior demonstrating the relaxation of electric dipoles mediated by magnons, which become soft at a quantum critical point.

233

Tunable Topologically Nontrivial Triplet Bands in XCuCl3

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We explore topologically nontrivial band structures formed by triplet excitations of disordered spingap quantum magnets. In particular, we consider the monoclinic dimer systems, KCuCl3 and TlCuCl3 that exhibit a singlet valence bond solid ground state below a critical magnetic field [1], [2]. Using symmetry arguments, we derive the possible anisotropic interactions and investigate the topology of the triplet excitations originating from those. Previous descriptions of the excitations in KCuCl3 were based on fully symmetric Heisenberg models [3], here we extend this picture and compare our results with existing experiments.

We demonstrate a rich set of possible configurations depending on the strength of the magnetic anisotropies and the direction of an external magnetic field. Depending on a mixture of experimentally tunable parameters and anisotropy values these triplets form analogs of Weyl semimetals, nodal line semimetals, and Chern insulators. We derive an effective Dirac Hamiltonian that describes the triplet hopping and include the discussion of the nontrivial surface modes and show how their topological properties interrelate. We demonstrate that for a wide range of probable anisotropy values, multiple behaviors may be selected by adjusting the lab magnetic field.

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234

Phonon-driven multipolar dynamics in a spin-orbit coupled Mott insulator

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Motivated by advances in pump-probe experiments and light-driven phenomena, we investigate the excitation of phonons in multipolar Mott insulators, and the effect thereof on multipolar orders. As a case study, we take the double perovskite osmates, a class of Mott insulators which play host to local octupolar and quadrupolar moments and have been proposed to have a ferro-octupolar ordered ground state. By exploiting a linear coupling of phonon modes to quadrupoles, we show how phonons resonantly excited by light can be used to detect and control octupolar order in the double perovskite osmates. Simulating the pump-probe dynamics of phonons excited by an initial light pulse, we demonstrate a coherent transfer of energy between degenerate phonon modes which is only possible in the presence of octupolar order, and we show how these dynamics of phonons could be used as an indirect probe for the hidden order. Further, we study the nonequilibrium dynamics of the octupolar order parameter under a resonant, chiral, phonon drive. Together with a phenomenological dissipation of energy in the phonon sector, the nonequilibrium steady state oscillations of the chiral phonon drive leads to an effective magnetic field, and thus drives the switching of octupolar order. We explain this using a Floquet-Magnus expansion, which indicates that the phonon-induced effective field is able to flip spins at domain walls. This work is an important first step in studying the nonequilibrium physics of multipolar materials through the excitation of phonons.

237

String, cluster and dynamic scaling theory following a field quench in spin ice

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Spin ice is a frustrated magnetic system [1] that at low temperature exhibits a Coulomb phase [2], a classical spin liquid with topological order and emergent magnetic monopoles [3]. The application of a strong magnetic field along the [100] direction brings the spin ice system in a highly saturated (magnetised) ordered state, where the ice rules prohibits the local fluctuations (magnetic monopoles) in the limit of low temperatures ($T \to 0$). This results in Kasteleyn transition (KT) [4] when the magnetic field is lowered, the formation of strings of flipped spins terminated by the monopoles being favourable.

In this work, we use Monte Carlo simulations to study the relaxation of the magnetization in a spin ice following a sudden quench across the KT. We show how the behaviour near the transition can be described by dynamical scaling theory and also identify a crossover [5] from dynamics driven by nucleation and growth of strings at short time to percolating clusters at long time.

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238

Angle Dependent Torque Magnetometry Studies of Monoclinic RuCl3

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α-$RuCl_3$ has been much explored as a candidate to display unconventional magnetism between spin-orbit entangled Ru3+ magnetic moments arranged on a honeycomb lattice. Most studies so far have focused on single crystal samples that undergo a structural phase transition from monoclinic to rhombohedral around 150 K and a magnetic transition to zigzag order around 7 K 1. Here we report highly-sensitive piezo-cantilever magnetic torque measurements on very small single crystals of ~100 microns diameter, which do not display any signatures of a structural phase transition upon cooling and instead display a single magnetic transition at 14 K.

We probe the angular dependence of the magnetic torque for fields up to 16 T rotated both in the plane normal to the honeycomb layers, as well as for fields rotated in the honeycomb planes, and also perform field sweeps at fixed orientation covering a wide range of angles. Our torque data collected upon varying almost continuously the applied field strength as well as the angular orientation allows clear detection of phase transitions via anomalies in the raw data and its derivatives with respect to both angle and field magnitude. The obtained magnetic phase diagrams and angular-dependence of torque show many differences compared to those reported for samples with a 7 K magnetic transition [2]. We discuss the results in the context of magnetic spin Hamiltonians proposed for α-$RuCl_3$.

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239

Development of High-Performance Tensor-Network Software

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Tensor networks have proven to be an incredibly valuable tool for studying frustrated quantum systems. I will present my work on the development of tensor network software for simulating quantum spin systems aimed at efficiently utilizing the next generation of high-performance multi-GPU clusters.

240

Anisotropic Skyrmion and Multi-q Spin Dynamics in Frustrated Centrosymmetric Gd2PdSi3

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Skyrmions are highly-studied vortices of magnetization with non-trivial topology that behave as extended quasiparticles [1]. They are usually stabilized by Dzyaloshinskii–Moriya interactions (DMI) in noncentrosymmetric bulk materials, where they form skyrmion lattices (SkLs) [2]. However, exceptions to this stabilization mechanism have recently been discovered in frustrated centrosymmetric Gd- and Eu-based bulk SkL hosts with net zero DMI [2,3], where both the dominant skyrmion stabilization mechanisms at finite applied magnetic fields, and the nature of their zero-field magnetic ground states, remain controversial.

To address these questions, we have investigated static and dynamic spin properties of the most-studied centrosymmetric SkL host, Gd_2PdSi_3 [2–4], via local-probe muon spectroscopy (μSR) [5]. We find that spin fluctuations in its non-coplanar skyrmion phase are highly anisotropic with qualitatively different behaviour of the dominant out-of-plane and the subdominant in-plane spin fluctuations. Our results suggest that the enigmatic stabilization mechanism behind SkL phases in frustrated centrosymmetric rare-earth magnets is likely to be intimately related to this strong anisotropy. Moreover, we also observe surprisingly strong anisotropy of spin fluctuations in the ground-state (IC-1) incommensurate magnetic phase of the material, indicating that it takes the form of a complex multi-q (meron-like) magnetic structure, confirming the hypothesis of Ref. [4], and refuting some of the theoretical predictions. Intriguingly, in this phase, in-plane spin fluctuations dominate. Finally, the higher-field coplanar incommensurate phase IC-2 is found to be a single-q structure with nearly isotropic spin dynamics.

Our study Ref. [5] of skyrmion dynamics in Gd_2PdSi_3 highlights the importance of spin anisotropy even in centrosymmetric SkL hosts and puts strong constraints on possible skyrmion stabilization mechanisms in these highly-frustrated materials. Furthermore, we propose that our methods could also be used to study low-T spin dynamics and anisotropy of the metastable skyrmions found in some DMI-based SkL hosts.

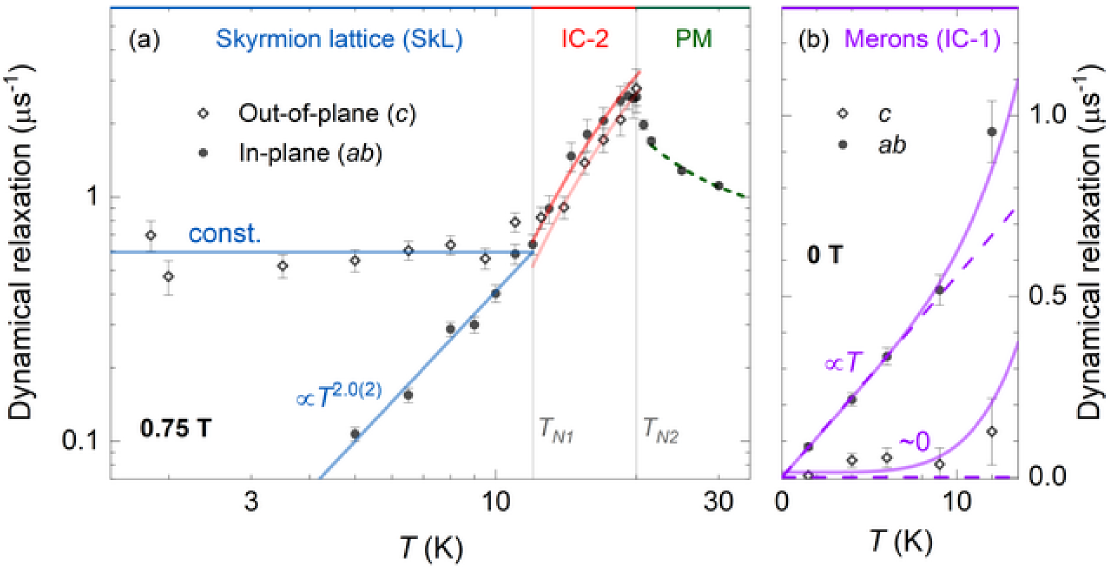

Figure 4: **Figure 1.** (a) Contributions to dynamical muon-spin relaxation due to out-of-plane (c-axis) and in-plane (*ab*-plane) spin fluctuations in the anisotropic skyrmion-lattice (SkL) phase, isotropic incommensurate (IC-2) phase, and the paramagnetic (PM) phase of Gd_2PdSi_3 under an applied magnetic field of 0.75 T. (b) Anisotropic spin fluctuations in the meron–antimeron (IC-1) zero-field ground state of Gd_2PdSi_3.

Figure 1. (a) Contributions to dynamical muon-spin relaxation due to out-of-plane (c-axis) and in-plane (*ab*-plane) spin fluctuations in the anisotropic skyrmion-lattice (SkL) phase, isotropic incommensurate (IC-2) phase, and the paramagnetic (PM) phase of Gd_2PdSi_3 under an applied magnetic field of 0.75 T. (b) Anisotropic spin fluctuations in the meron–antimeron (IC-1) zero-field ground state of Gd_2PdSi_3.

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242

Six-fold clock anisotropy in honeycomb CoTiO3 probed by single-crystal torque magnetometry

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We report magnetic torque measurements to probe the angular dependence of the magnetic anisotropy in the easy-plane honeycomb magnet CoTiO3, proposed to display order-by-disorder physics, where the ground state magnetic structure is selected via quantum fluctuations out of a manifold of many classically-degenerate states. Previous experiments observed a finite energy gap, which implies a finite energy cost to rotate spins in-plane away from a set of six symmetry-equivalent energy-preferred directions. The origin of the in-plane anisotropy is non-trivial as it cannot come from single-ion physics, or from two-spin interactions treated in a mean-field approximation, and has been attributed to a quantum zero-point energy contribution to the ground state energy and/or contribution from higher-order spin-orbital exchange [1]. To characterize the magnetic anisotropy directly we have performed single-crystal piezo-cantilever torque measurements as a function of field orientation. Below the magnetic ordering temperature, we have observed a clear six-fold angular dependence of the torque upon rotating the field orientation in the ab plane. We have characterized the dependence of the six-fold signal upon increasing the applied field magnitude from low-field, when adjacent honeycomb layers are spontaneously antiferromagnetically aligned, all the way to high field, when spins in adjacent layers are polarized by the applied field. We discuss the observed behaviour in the context of models for the six-fold in-plane clock anisotropy.

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243

Non-trivial spin dynamics in a hyperhoneycomb Kitaev material under pressure

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Kitaev's discovery of an exactly solvable quantum spin liquid model on the honeycomb lattice [1] and a subsequent proposal for how this anisotropic bond-dependent model could arise in realistic materials [2] have led to a surge of research into effective spin-1/2 honeycomb magnets with strong spin-orbit coupling. Furthermore, it has been realized that the Kitaev interaction could also give rise to quantum spin liquids in 3-dimensional analogs of the honeycomb lattice, including the hyper-honeycomb lattice which is realized in the material β-Li_2IrO_3. While β-Li_2IrO_3 orders at ambient pressure, adopting a complicated incommensurate magnetic structure with counter-rotating moments [3], there are indications that the magnetic order is suppressed under pressure [4]. We present high-pressure (2 GPa) ^{7}Li nuclear magnetic resonance (NMR) measurements on single crystals of this material. The spectra show evidence for a structural phase transition around 200 K and a coexistence of phases, consistent with the results of other measurement techniques. The spectra and shift measurements demonstrate a strong suppression of the local magnetic susceptibility at high pressure. However, the spin-lattice relaxation $(1/T_1)$ shows a clear $T^{1.7}$ power-law temperature dependence. Our measurements [5] rule out the presence of a sizeable spin gap despite indications of structural dimerization. The results are inconsistent with a gapped singlet ground state of dimers and trimers that was previously proposed, and are instead evocative of a more exotic quantum spin liquid-like ground state.

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244

Magnon vs Spinons in RuCl3 in Intermediate Field Phase

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We discuss the high-resolution results of neutron scattering in the high-quality single crystals of the leading Kitaev candidate, α-RuCl3, at magnetic fields above Bc = 7.3 T, where the zero-field antiferromagnetic zigzag ordered ground state is suppressed. The characteristics of this state remain a topic of significant debate. This data helps clarify the shape of the excitation modes and the spin gaps. We find that the excitation spectrum above 8 T maintains a low-energy gap for both directions of the applied magnetic field at the two-dimensional Γ-point. Above this gap, we observe that the dispersions remain broad, with even the "sharper" features being consistently broader than the elastic resolution at all measured fields. Even at 10 T, where there seem to be sharper features appearing close to the Gamma point giving a notion of magnon-like modes, these sharp features disappear away from the Gamma point. These results challenge the traditional understanding of magnons and complicate the multimagnon picture. Instead, they support the idea of a field-induced spin liquid regime, characterized by a mix of a continuum of excitations and bound states of fractionalized excitations that are elevated by the magnetic field.

247

Spin Fluctuations in Intermetallic Rare Earth Systems on a Frustrated Anisotropic Triangular Lattice

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Historically, spin 1/2 Ising and Heisenberg systems on a triangular lattice with nearest-neighbour antiferromagnetic exchange interactions are the archetypal examples of geometric magnetic frustration. The triangular lattice systems were the first to be proposed as candidates for a quantum spin liquid ground state, where there is an unusually high degree of entanglement of the spins and consequently the system is capable of supporting nonlocal excitations without ordering. The present theoretical consensus is that the ground state of a two-dimensional triangular lattice has an ordered noncollinear $120°$ spin structure with a significantly reduced sublattice magnetization for both classical (large spin S) and quantum (S = 1/2) systems.

More generally, the role of in-plane anisotropy and interplanar coupling must be included. Such anisotropy is particularly relevant to materials based on $4f$ ions, where spin orbit effects become increasingly important and the coupling between spins depends on bond orientation. Among rare-earth systems, there have been extensive investigations of Ce^{3+} (4f1) and Yb^{3+} (4f13) based intermetallic compounds, where rich phenomenology has been observed, including heavy Fermion behaviour and non-Fermi liquid behavior in the proximity of a quantum critical point. The ground states of these systems are considered to be mainly governed by the competition between the Kondo and the Ruderman-Kittel-Kasuya-Yosida (RKKY) exchange interaction, both mediated by the conduction electrons.

Combining these two arenas, whereas earlier investigations concentrated on insulating systems, there are an increasing number of studies of frustrated magnetism in metallic systems. Because the RKKY interaction is of a longer range than the superexchange interaction, the frustration effect in metallic compounds may be most evident in low carrier density systems. When quantum fluctuations become enhanced due to magnetic frustration, exotic phases such as complex spin density wave ordering or quantum spin liquids have been proposed. It is therefore clearly important to search for experimental realizations of such spin liquid behaviour—rare-earth-based triangular lattice compounds are promising candidates. Examples include the low carrier density system $YbAl_3C_3$, which is thought to dimerize without ordering, opening up a spin gap in the magnetic excitation spectrum. Recently, RM_3X_3 (R = rare earth, M = Al, Cd, and Zn, X =C, P, and As) compounds, which crystallize in the hexagonal $ScAl_3C_3$ -type structure (space group P63 /mmc) have been synthesised and their physical properties reported. In this crystal structure the magnetic rare-earth ions form two-dimensional triangular lattice layers, well isolated by the interleaved M- and X -atoms. As such, they are good experimental realizations of anisotropic spin-orbit-coupled triangular lattice models.

Measurements of the spin lattice relaxation using muon spin relaxation (μSR) have been particularly valuable in the search for spin liquid behaviour. We report a muon spin relaxation investigation of the low temperature partially ordered phase and associated spin fluctuations in $CeCd_3X_3$ (X=As,P). The growth of an anomalous and sizable magnetic contribution to the specific heat below 10 K has been found to correspond to enhancement in the spin lattice relaxation rate, which onsets on a temperature scale 20x the ordering transition. Tuning the conductivity through chemical substitution and lattice constant, we discuss the roles of geometric magnetic frustration, Kondo and RKKY interactions in these Ce based intermetallic compounds. We also set the response of these compounds in the wider context of triangular lattice systems.

248

Terahertz spectroscopy of candidate quantum spin liquid materials

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Terahertz spectroscopy has played an instrumental role in elucidating the charge dynamics of superconductors and other strongly correlated systems in condensed matter physics. With its pulsed form of magnetic field, the technique can also be broadly applied to magnetic systems where various spin excitations can be directly studied. We show that not only magnons in conventional magnets are effectively probed but novel spin excitations can be detected in disordered spin systems such as quantum spin liquids. As an example, anomalous power-law features in the optical conductivity in $TbInO_3$ and related compounds will be presented along with their temperature and magnetic field dependences. Their origin will be analyzed in terms of the coupling between incipient spinons, emergent internal gauge fields, and external electromagnetic field.

249

Phonon thermal transport in α-$RuCl_3$

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Given its status as perhaps the most promising candidate material for observing Kitaev quantum spin liquid physics, α-$RuCl_3$ continues to attract much attention from the community. As a technique well-suited to probe the charge-neutral excitations in this material, thermal transport measurements of α-$RuCl_3$ have featured prominently in that discussion - in particular, regarding the oscillatory field dependence observed in thermal conductivity, as well as the reported (but debated) half-integer-quantized 2D thermal Hall conductance ascribed to protected chiral Majorana edge currents.

Despite some variability attributed to sample dependence, many common features are shared between the published results of various groups, even if a consensus has yet to be reached on their interpretation. While the presence of more exotic excitations should not be discounted, we will discuss the compelling evidence for a dominant contribution from phonons to the field-dependent thermal transport in α-$RuCl_3$. In addition, we will discuss other studies showing the important role that phonons play in the thermal transport more generally in other frustrated magnets and strongly correlated materials.

250

Exploring the magnetism of the honeycomb antiferromagnet Na2Co2TeO6 with ultrasound measurements

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The honeycomb lattice antiferromagnet Na2Co2TeO6 (NCTO) has recently been proposed to exhibit a strong Kitaev interaction [1,2]. While it orders at low magnetic fields, its magnetic phase diagram is complex. The origin and magnetic structure of several low-field phases remains unclear and, furthermore, it has been suggested that a field-induced quantum spin liquid phase can be found between ~ 7.5 to 9.5 T. Additionally, NCTO is found to exhibit a large thermal Hall effect, in both conventional [3] and "planar" geometries [4], results that have been attributed to phonons, but so far have no well-established mechanism.

We have applied sound velocity and attenuation measurements to further characterize the temperature-field phase diagram of NCTO. The ultrasound technique is highly sensitive to phase transitions, revealing anomalies caused by the coupling between phonons and magnetic order parameters. Our results show the presence of additional transitions at fields below 9.5 T, showing that the phase diagram of the material is significantly more complicated than what was seen in previous studies. We will also show how this phase diagram varies as a function of field angle and present the temperature dependence of sound velocity in the ostensible spin liquid phase. Furthermore, we demonstrate (in a particular range of parameters) an absence of acoustic magnetochiral and Faraday effects that might otherwise be expected to be related to the observed phonon thermal Hall effects.

251

Quantum spin torque driven transmutation of quantum spin liquid

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The standard model of spin-transfer torque (STT) in quantum spintronics has recently been extended to incorporate entangled quantum localized spin states, enabling the exploration of nonequilibrium phenomena in strongly correlated systems. We present preliminary results on quantum STT in the Kitaev quantum spin liquid (QSL) model and/or an antiferromagnetic (AFI) model within bilayer systems where spin-polarized current flows parallel to the interface, closely mimicking experimental setups. Using time-dependent matrix product state (TDMPS) methods, we observe strikingly different dynamics of local quantum spins (LQSs) in QSLs compared to AFI or ferromagnetic insulator (FI) top layers. Unlike ultrafast light-driven methods that often disrupt local magnetism and induce transitions into far-from-equilibrium phases, quantum STT enables controlled excitation of different quantum states simply by modulating current pulse properties. Notably, precise control of injected electron pulses, such as single-electron or Ne-electron levitons, facilitates targeted manipulation of spin states. Building upon these results, we propose to compute quantum Fisher information (QFI) for potential time-resolved resonant inelastic X-ray scattering (trRIXS) measurements and explore the addition of a third layer to study frequency and noise properties of currents pumped into it by nonequilibrium QSLs or AFIs. These findings advance the understanding of quantum STT-driven dynamics and open pathways to experimental detection and device integration of these phenomena.

252

Structural frustration: the curious case of lithium

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Lithium and sodium are the only known solids that become disordered upon cooling. The nature of their low temperature structures has remained unsolved for six decades. Remarkably, this problem is intimately connected to frustration and order-by-disorder. At low temperatures, these two metals form close-packed structures. Their structural ordering can be mapped to a one-dimensional Ising model. Under ideal conditions, a hidden gauge symmetry connects all close-packed structures. In term of the Ising model, the energy only depends on the net magnetization and is insensitive to the precise spin structure. This leads to a liquid-like low-temperature state where an infinite number of structures compete with one another. Small effects such as phonon zero-point energy can break this degeneracy and 'select' an ordered structure. This is consistent with several experimental facts, such as the onset of fcc order under pressure. We argue that ideas from frustrated magnetism can play a role in seemingly unrelated areas such as crystal structure.

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253

Loops and Networks in 1T Transition Metal Dichalcogenides

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Quantum dimer models are well known in the context of frustrated magnets, where they describe configurations of singlets. A natural extension is the concept of a quantum loop model, which describes systems with two dimers touching at every site of a lattice. Inspired by these ideas, we present minimal models for structural phases in transition metal dichalcogenides (TMDs). They are materials of the form MX_2 (for example, MoS_2 and ReS_2), where M is a transition metal atom and X is a chalcogen atom. Each of the M and X layers forms a triangular lattice. We focus on the 1T structure, with ABC stacking of layers. Distortions of the 1T structure are known in many materials – we seek to explain them using loops and networks of dimers. We construct Rokhsar-Kivelson-like models and map out phase diagrams. We find phases that closely resemble experimentally observed distortions. We propose testable signatures in the form impurity-induced long-ranged textures.

254

Tunable spin liquid phase in the spin vorticity model on the octochlore lattice

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The nearest-neighbor spin ice (NNSI) model has been central to the study of frustrated magnetism for nearly three decades, offering a framework to explore emergent gauge fields and monopole excitations from geometrically frustrated spins. From a coarse-grained vector field perspective, these spins obey a zero-divergence condition at localized regions of the lattice, effectively defining an emerging Gauss law. By reversing this constraint and imposing a zero-curl condition on the spins within plaquettes of the lattice – akin to an effective Ampere's law – the recently introduced spin vorticity model (SVM) [1] is obtained.

At zero temperature, the ground state is defect-free and consists of closed *membranes*, in constrast to the closed *loops* of NNSI [2]. At nonzero temperature, in contrast to the point-like monopole excitations in NNSI, the SVM features *string-like* excitations, analogous to closed current loops. Previously, this model was studied on the pyrochlore lattice with highly constrained up-to-third-nearest-neighbour couplings [1]. Drawing inspiration from the NNSI analog on the octochlore lattice [3], we extend the SVM to the octochlore lattice of corner-sharing octahedra which incorporates up-to-second-nearest-neighbour interactions (J_1, J_2 and J'_2).

Through Monte Carlo simulations and self-consistent Gaussian approximation calculations, we identify an extended region of parameter space exhibiting classical spin liquid features with two tunable dimensionless spin-spin couplings. Interestingly, as found for the pyrochlore lattice [1], we here too find strong evidence for a sharp phase transition at nonzero temperature. However, in contrast to the pyrochlore SVM, this octochlore model offers potential material realizations in anti- or inverse-perovskite materials due to the tunability of its parameters. We further investigate the mechanisms underlying the formation of this exotic classical spin liquid phase, providing deeper insights into the novel physics of the SVM.

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255

Repulsively bound magnon excitations of a spin-1/2 XXZ chain in a staggered transverse field

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Motivated by the chain antiferromagnet $BaCo_2V_2O_8$, we study the excitation spectrum of the one-dimensional spin-1/2 XXZ chain across a magnetic quantum phase transition induced by the application of a site-dependent transverse magnetic field. Considering a situation where the transverse magnetic field has a strong uniform component and a weaker staggered part, we determine the nature of the excitations giving rise to the spin dynamical structure factor using a combination of analytical approaches and the numerically exact time-dependent matrix product state method. Below the quantum phase transition, we identify high-energy many-body two-magnon and three-magnon repulsively bound states which are clearly visible due to the staggered component of the magnetic field. At high magnetic fields and low temperature, single magnons dominate the dynamics. These results are in very good agreement with terahertz spectroscopy measurements.

256

Charge and spin current pumping by ultrafast demagnetization dynamics

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The surprising discovery of ultrafast demagnetization – where electric field of femtosecond laser pulse couples to electrons of a ferromagnetic (FM) layer causing its magnetization vector {\em to shrink while not rotating}, is also assumed to be accompanied by generation of spin current in the direction orthogonal to electric field. However, understanding of the microscopic origin of such spin current and how efficiently it can be converted into charge current, as the putative source of THz radiation, is lacking despite nearly three decades of intense studies. Here we connect the standard pumping phenomena driven by microwave precession of magnetization vector replacing periodic time-dependence of magnetization precession with nonperiodic time-dependence of demagnetization, as obtained from experiments on ultrafast-light-driven Ni layer. Applying time-dependent nonequilibrium Green's functions, able to evolve such setup with arbitrary time dependence, reveals how demagnetization dynamics pumps both charge and spin currents in directions both parallel and orthogonal to electric field of laser pulse, even in the absence of spin-orbit coupling and thereby induced spin-to-charge conversion mechanisms. Although pumped currents follow dMz/dt in some setups, this becomes obscured when NM layers are disconnected and pumped currents start to reflect from FM boundaries (as is the case of experimental setups). Finally, we use the Jefimenko equations to compute electromagnetic radiation by charge current pumped in disconnected setup during demagnetization, or later during its slow recovery, unraveling that radiated electric field only in the former time interval exhibits features in 0.1–30 THz frequency range probed experimentally or explored for applications of spintronic THz emitters.

257

Phase diagram of the J1-J2 spin chain: insights from the matrix-product-state path integral

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The antiferromagnetic J1-J2 spin chain (i.e. the Heisenberg chain with additional next-nearest-neighbour interactions) is a long-studied model of strong correlations and magnetic frustration. It is known to exhibit a phase transition, as J2/J1 is increased, from a Luttinger liquid (the 1D cousin of the Néel state) to a spin-Peierls (valence bond solid) phase. In this talk I present two new insights into the physics of this spin chain, both derived using the matrix-product-state path integral [1]. First, I show that the correct critical theory for the phase transition, including the Wess-Zumino (topological) term, can be derived straightforwardly by taking the continuum limit of the matrix-product-state path integral [2]. Second, I show that there is in fact a second transition, of a rather subtle kind, that takes place at negative J2/J1: a sort of 'freezing out' of entanglement fluctuations [3].

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259

Magnetic simulations using Sunny

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Sunny is an open-source software package for modeling atomic-scale magnetism. This tutorial will demonstrate Sunny in a hands-on format. Topics to be covered include symmetry analysis to determine allowed interactions, graphical visualization tools, and various capabilities for simulating spin dynamics.

This tutorial will also touch on advanced Sunny features such as (1) the generalization of classical Landau-Lifshitz spin dynamics via the theory of SU(N) coherent states and (2) efficient spin wave theory calculations on very large magnetic cells with chemical disorder.

Interested participants may wish to pre-install Sunny following instructions here:
https://github.com/SunnySuite/Sunny.jl

262

Kagome spin ice HoAgGe

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Spin ice denotes a novel state of matter, arising in certain geometrically frustrated magnets that do not have a single minimal-energy state but rather fulfill an ice constraint, leading to highly degenerate local spin configurations. While three-dimensional pyrochlore spin ice is well established, its two-dimensional counterpart "Kagome spin ice", with 2 in-1 out or 1 in-2-out ice rule, leading to a honeycomb lattice of positive/negative magnetic monopoles, was only studied on artificial nanorods of ferromagnet films. The rare-earth intermetallic HoAgGe has non-Kramers 4f10 moments on a distorted kagome lattice with the four lowest CEF modes contributing to magnetism at low temperatures. Remarkably the in-plane magnetization at low temperatures reveals a series of metamagnetic transitions separating fractional magnetization plateaus. Refinement of single crystal neutron diffraction reveals that all these states fulfill the kagome ice rule, establishing HoAgGe as first crystalline kagome spin ice [1]. Magnetotransport and anomalous Hall effect (AHE) show pronounced signatures related to the transitions between the fractional magnetization plateaus. They allow to distinguish domains with opposite toroidal orders and differing AHE yet similar magnetization, implying a hidden time-reversal-like degeneracy, related to the non-trivial distortion of the kagome lattice in HoAgGe [2]. We also investigate critical behavior and the universality classes of the different spin ice transitions in HoAgGe by polarized neutron diffuse scattering analysis. Work in collaboration with Kan Zhao and Hua Chen.

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263

Magnetic order mediated by fluctuating valence bonds in a quasi-2D quantum magnet Cu3B2O6

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$Cu_3B_2O_6$ (CBO) is an unusual magnetic material. The magnetic Cu^{2+} ions reside in a complex 2D network with a mixture of ferro and antiferromagnetic interactions, stacked with weak inter-layer bonding. The resultant crystal structure is a triclinic structure with 30 Cu^{2+} ions in a unit cell [1-2]. Ever since its first discovery, the magnetic ground state in this material has been controversial. Although early bulk measurements revealed a phase transition at T_N ~10 K [3], failure to detect any magnetic Bragg peaks in powder neutron diffraction below TN led to the initial proposal of the observed transition as a collective singlet formation [4]. However, NMR and muSR measurements have provided strong evidence of a highly unconventional magnetic order [5-6]. To resolve this controversy, we carried out elastic and inelastic neutron scattering experiments on an ^{11}B-enriched large single-crystal sample. We found magnetic Bragg peaks with an ordering wavevector of q=(0.5, 0, 0) below 10 K and a magnon mode emanating from the magnetic wavevector. Surprisingly, additional high-energy excitations are observed that show a distinct ring-like momentum dependence and a very weak energy dependence, which can be modelled using fluctuating valence bonds. What is unusual is the observation of two distinct types of spin excitations, one corresponding to Neel ordering and the other from a spin-singlet ground state. One exciting possibility is that these two types of ground states, one with long-range order and the other with spin-liquid-like correlation, co-exist in this material. CBO may be a rare example of two different magnetic quasi-particle species interacting.

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264

Mixed Anion Rare Earth Magnets as a New Frontier in Frustrated Magnetism

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Breakthroughs in the field of frustrated magnetism are often linked with the discovery (or re-discovery) of new materials platforms. Among rare earth magnets, systems with mixtures of anions present a unique opportunity to tailor the lattice type, dimensionality, and superexchange pathways, all of which can manifest in new magnetic phenomena. In this talk, I will describe my group's exploration of mixed anion rare earth magnets, many of which crystallize in structures with quasi-two-dimensional triangular bilayers. We attempt to expose general trends governing structural stability and magnetic order moving through families that include oxysulfides, oxyselenides, and sulfotellurides. Through selected case studies, I will illustrate the interesting opportunity that these new materials platforms present.

266

Pulling order from the brink of disorder: Observation of a nodal line spin liquid and fluctuation stabilized order in the FCC lattice K2IrCl6

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Competing interactions in frustrated magnets can give rise to highly degenerate ground states from which correlated liquid-like states of matter often emerge. The face centered cubic antiferromagnet is one of the oldest and most important models of frustrated magnetism. However, there a few materials that maintain cubic symmetry at low temperatures and permit the study of the spin-dynamics of this model. In this talk, I will discuss the specific example of K_2IrCl_6 that realizes a $j = 1/2$ Heisenberg-Kitaev model on the FCC lattice. I will present inelastic neutron scattering measurements on this compound that show the emergence of a "nodal-line" classical spin-liquid, where the magnetism is characterized by a three-dimensional Hamiltonian but with correlations that are long range along two dimensions and short range along the third. T he nodal line spin liquid is highly susceptible to small perturbations that cause K_2IrCl_6 to magnetically order at low temperatures. However, a proximity to the nodal line spin liquid dramatically enhances quantum fluctuations that dictate the thermodynamics of this material and, contrary to the usual expectation, stabilize magnetic order by self-consistently generating an excitation gap.

268

Spin Noise Spectroscopy of Witness-Spin Dynamics and Ground State in Herbertsmithite ZnCu3(OH)6Cl2

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A Kagome lattice of spin-1/2 Cu in Herbertsmithite $ZnCu_3(OH)_6Cl_2$ [1,2] is conjectured to be in a quantum spin liquid state with spinon excitations. Each kagome plane is separated from its homologues by a layer of spinless Zn atoms. However, some spin-1/2 Cu atoms substitute randomly on these intra-planar Zn sites and these "witness-spins" can provide an exceptional interrogative of the conjectured QSL state. To explore such dynamics of witness-spins, we measured the magnetization noise $M(t,T)$ in $ZnCu_3(OH)_6Cl_2$ [3] using a mK SQUID-based spin noise spectrometer [4-6] with fT/√Hz-sensitivity and μs-time resolution.

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271

Field dependent Phases of Quantum Compass Models

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The well-known Kitaev model on the honeycomb lattice can be viewed as part of a larger class of models with bond-directional Ising interactions, often referred to as quantum Compass models. It is therefore of considerable interest to understand the field dependent phase diagram of this more general class of models. Here we focus mainly on one- and two-dimensional models and study in particular the square lattice compass model and Kitaev's honeycomb model. General arguments show that the bond-directional Ising interactions will give rise to multiple phases in a magnetic field, before the fully polarized phase is reached. In several cases, exact ground-states can be found at specific field values. These ground-states display magnetic ordering but have exact degeneracies. Furthermore, they exist below a well formed gap and are therefore part of an extended phase that occupy a significant part of the field dependent phase diagram. Using, high precision numerical techniques, iDMRG, iPEPS combined with large scale exact diagonalizations, we develop a more detailed picture of the complete phase diagram. For Kitaev's honeycomb model this indicates the possibility of a new, previously undocumented phase appearing in a [111] field.

273

Competition between two antiferromagnetic phases studied through Coherent Resonant Scattering

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The Fe-intercalated transition metal dichalcogenide Fe_xNbS_2 exhibits a highly tunable antiferromagnetic (AFM) ground state as a function of Fe intercalation ratio (x) near $x = \frac{1}{3}$. The ground state transitions between two distinct phases: a stripe-AFM phase for $x < \frac{1}{3}$ and a zigzag-AFM phase for $x > \frac{1}{3}$. Remarkably, at the nominal doping of $x = \frac{1}{3}$, these two phases coexist and compete as a function of temperature, as evidenced by neutron scattering experiments. We asked: how do these two electronic order compete within the same material? Specifically, we seek to answer how these phases evolve in real space.

During phase competition, the two phases adjust their real-space distributions based on their interaction and relative stability. We focus on whether the competing phase emerges from regions of weak order parameters, such as disordered areas and boundaries in the phase texture, or from regions with strong order parameters, like a topological defect seeded within ordered domain core. These scenarios suggest distinct real-space phase texture evolution (Fig B), which we probe using coherent resonant scattering. This technique encodes real-space electronic domain patterns into speckle patterns observed on the Bragg peaks in Fourier space.

We analyze the evolution of these speckle patterns in the context of competing electronic phases. Our findings establish a connection between the two AFM phases in Fe_xNbS_2 and highlight the unique capability of coherent resonant scattering to study competing and coexisting electronic ground states for the first time.

274

Spinon spin current

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We present the theory of the longitudinal spin Seebeck effect between a Heisenberg spin-1/2 chain and a conductor. The effect consists of the generation of a spin current across the spin chain-conductor interface in response to the temperature difference between the two systems. In this setup, the current is given by the convolution of the local spin susceptibilities of the spin chain and the conductor. We find the spin current to be fully controlled, both in the magnitude and the sign, by the backscattering interaction between spinons, fractionalized spin excitations of the Heisenberg chain. In particular, it vanishes when the spinons form a non-interacting spinon gas. Our analytical results for the local spin susceptibility at the open end of the spin chain are in excellent agreement with numerical DMRG simulations.

275

Intrinsic Thermal Hall Effect in Mott Insulators

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In light of recent experimental data indicating a substantial thermal Hall effect in square lattice antiferromagnetic Mott insulators, we investigate whether a simple Mott insulator can sustain a finite thermal Hall effect. We verify that the answer is "no" if one performs calculations within a spin-only low-energy effective spin model with non-interacting magnons. However, by performing determinant quantum Monte Carlo simulations, we show the single-band t-t′-U Hubbard model coupled to an orbital magnetic field does support a finite thermal Hall effect when $t' \neq 0$ and $B \neq 0$ in the Mott insulating phase. We argue that the (carrier agnostic) necessary conditions for observing a finite thermal Hall effect are time-reversal and particle-hole symmetry breaking. By considering magnon-magnon scattering using a semi-classical Boltzmann analysis, we illustrate a physical mechanism by which finite transverse thermal conductivity may arise, consistent with our symmetry argument and numerical results. Our results contradict the conventional wisdom that square and triangular lattices with SU(2) symmetry do not support a finite thermal Hall effect and call for a critical re-examination of thermal Hall effect data in insulating magnets, as the magnon contribution should not be excluded a priori.

276

The role of quantum fluctuations in rare-earth pyrochlore oxides

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Rare-earth pyrochlore oxides provide a rich platform for exploring exotic magnetic phenomena, ranging from the highly degenerate spin-ice states governed by emergent gauge theories in $Dy_2Ti_2O_7$ and $Ho_2Ti_2O_7$, to order-by-disorder effects in $Er_2Ti_2O_7$, multi-phase magnetism in $Yb_2Ti_2O_7$, and the ongoing quest to realize a quantum spin liquid state in experiment. Many of these materials are well described by localized spin-$\frac{1}{2}$ moments on a pyrochlore lattice coupled via anisotropic interactions. While the classical limit of this model has been extensively studied, a full quantum mechanical treatment remains challenging. In this work we study the Kramers nearest-neighbour anisotropic spin-1/2 Hamiltonian in the vicinity of a classical pinch-line spin liquid using a pseudo-fermion functional renormalization group approach, which incorporates quantum fluctuations beyond mean-field theory. Our results reveal a dramatic modification to the classical phase diagram not captured within spin-wave treatments. Indeed, the phase boundaries undergo significant shifts, alongside the emergence of regions without conventional magnetic order. We also discover a quantum analog of the classical pinch-line spin liquid at the intersection of the two conventional magnetically ordered phases and the non-conventional magnetic phase. This highlights the importance of accurately capturing quantum fluctuations when interpreting experimental observations in pyrochlore magnets as well as in assessing the fate of higher-rank classical Coulomb spin liquids.

277

Field-induced magnon formation, shadow modes and magnon decay in the spin-1/2 Heisenberg honeycomb antiferromagnet YbBr3

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Much of the research on quantum spin liquid (QSL) candidate systems consists on the qualitative and quantitative caracterization of their complex spin excitation spectra against model predictions for various QSL phases. Typically, these spectra contain non-trivial excitation continua associated with a short-range correlated yet massively entangled ground state. Our recent investigation of the spin-1/2 Heisenberg antiferromagnet on the honeycomb lattice YbBr3 revealed however, that such a complex spin excitation spectrum can also appear in unfrustrated albeit maximally fluctuating and entangled magnetic systems. Using a combination of high-resolution inelastic neutron scattering (INS) spectroscopy and cylinder matrix-product-states (MPS) simulations, we find quantitative agreement between the measured spectra and the model predictions under the application of an external magnetic field up to saturation. The field-evolution of the spectrum at the K and M' points located at the boundary of the Brillouin zone (BZ) showcase three remarkable effects: (i) the total (at K) and partial (at M') absence of magnon-like weight in zero-field preceded by the formation in-field of a sharp peak in the spectrum consistent with magnon formation, (ii) an unusually sharp high-energy signal with an energy which depends linearly with the field identified as a "shadow" of the uniform spin-precession mode, and (iii), the complete decay of magnon-like intensity immediately below the saturation field. Our results establish clear benchmarks for a theoretical description of strongly interacting magnons. We conclude that strong quantum fluctuations even in the absence of magnetic frustration, can give rise to an extremely rich excitation spectrum.

278

Altermagnetism and superconductivity in a multiorbital t-J model

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Motivated by exploring correlated multi-orbital altermagnets ($A\ell M$s) we study minimal t-J models on the square-octagon lattice which favors such a collinear magnetic order. While antiferromagnetic order breaks translational and time-reversal symmetries, the $A\ell M$ state (equivalently, a d-wave ferromagnet) features multipolar order which separately breaks time-reversal and crystal rotation symmetries but preserves their product leading to spin-split bands with zero net magnetization. We study the mean field phase diagram of these multiorbital models as we vary doping and interactions, discovering two types of $A\ell M$ order: (i) itinerant weak-coupling $A\ell M$ metals driven by quasi-1D van Hove singularities, as well as (ii) strong $A\ell M$ order at half-filling. We also find regimes of superconductivity including uniform s-wave and d_{xy}-wave pairing states, incipient d_{xy}-wave pair density wave order, and uniform phases with coexisting singlet-triplet pairing and $A\ell M$ order. Our inhomogeneous mean field theory approach reveals that the coexistence phases are unstable to phase separation, but longer-range interactions could lead to stripe order. Our results may be relevant to studies of doping and pressure on $A\ell M$ materials.

280

Search for multi-magnon bound states in Li2CuO2 single crystals: inelastic neutron scattering, specific heat-, thermal expansion , and Raman measurements

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We report diffraction and inelastic neutron scattering (INS) (in addition to Ref. [1]), specific heat cp-data for high quality single crystals of the edge-sharing chain cuprate Li2CuO2 collected in a wide temperature region from 20 to 70 K well above the Neel transition TN ≈ 9.2 to 9.4 K at ambient magnetic field. The heat capacity cp is analyzed within a sensitive cp/T3-plot adopting and generalizing an analytical expression [2] by adding precursor multi-magnon bound state (PMMBS) of any order. This way, the problem of missing intensity around 40 K [2] can be removed. The obtained excitation energies of PMMBS are in accord with recent and new INS data for Li2CuO2 [1] regarding single magnon, two-magnon and three-magnon bound states. The results are discussed within the context of a recently proposed Bose condensation scenario of MMBS [3] at very low temperature. The anomalously small value of the critical exponent β as derived from neutron diffraction measurements (β describes the sublattice magnetization) points to a violation of the scaling law α+2β+γ=2 in the critical region below TN. caused by the vicinity of a multicritical point and sizable spiral fluctuations as well as to a nontrivial order parameter involving also lattice degrees of freedom.in accord with a strong shrinking of the unit cell near TN. reflected by a huge thermal expansion anomaly along the c-axis. From these findings suggest strong anharmonicities and quantum effects for some Li- and possibly also O vibrations can be expected. In contrast Raman measurements reveal both hardening and softening of O and Li related phonon modes in the critical region above 6 K connected with usual weak anharmonicity.

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283

Probing Quantum Magnets via Non-Linear Spectroscopy

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The response of quantum many-body systems to weak perturbations can be cast within the general framework of linear response, forming the foundation for many of the most important and widespread tools in use today in condensed matter physics. However, it still provides only a limited set of information, forcing an expansive landscape of physics out of our reach. Pushing beyond these conventional boundaries and into the realm of non-linear responses promises to provide new insights into our understanding of quantum many-body systems. In the field of quantum magnetism, this new dawn is already fast approaching, spurred by the recent application of multi-dimensional coherent spectroscopy to the THz range of magnetic excitations.

We provide a brief overview of the theoretical questions at play and how non-linear (higher-order) susceptibilities arise, both in current experiments and in numerical calculations. One of the key questions concerns what new (useful) information can be extracted from such non-linear susceptibilities. We explore a number of examples, including fractionalization in one-dimensional magnets and revealing multipolar excitations in higher-spin magnets.

284

Hysteretic magnetic torque by chirality-driven magnetization in $Co_{1/3}TaS_2$

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$Co_{1/3}TaS_2$ is a triangular lattice antiferromagnet that exhibits 3Q ordering below the Néel temperature, T_{N2}, of 26.5 K. The all-in and all-out 3Q states in $Co_{1/3}TaS_2$ generate local net magnetizations in opposite directions, with the global net magnetization determined by the relative proportions of these states. Angle-dependent magnetic torque measurements at low temperatures revealed clockwise and counterclockwise hysteresis over a wide angular range. This behavior cannot be explained by conventional magnetization responses, as it originates from a local net magnetization that remains unaffected by the external field. Torque calculations based on magnetization data measured along the c-axis show excellent agreement with experimental results. During cooling, even a slight c-axis magnetic field component disrupts the neutral balance of the 3Q states. Topological Hall effect measurement, including initialization curves from various initial states, confirms that the observed hysteresis arises entirely from changes in the relative proportions of four states with different chiralities.

286

Probing Fractionalized Excitations in Kitaev Spin Liquids via Phonon Dynamics

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In this talk, we present a theoretical study of phonon dynamics in quantum spin liquids, with a focus on sound attenuation and Raman scattering as experimental probes. We investigate the coupling between phonons and fractionalized excitations in extended Kitaev spin liquids in both two and three dimensions. Through Raman scattering, we analyze the temperature-dependent asymmetric Fano lineshape, demonstrating that interactions between optical phonons and a continuum of fractionalized spin excitations provide signatures of Majorana fermions and Z_2 fluxes. We compare our theoretical findings with experimental results from α-$RuCl_3$ and β-Li_2IrO_3. Additionally, we calculate sound attenuation in α-$RuCl_3$, where magnetoelastic interactions reveal phonon scattering by Majorana fermions. Our results show how temperature, magnetic field, and disorder influence phonon dynamics, providing key insights into fractionalized excitations in Kitaev materials.

287

Spin-1 liquid on pyrochlore and checkerboard lattices

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We propose a local, SU(2) and time-inversion symmetric spin-1 Hamiltonian on the 3D pyrochlore and 2D checkerboard lattices. The ground states of this Hamiltonian are known exactly and form an exponentially large degenerate manifold. They are reminiscent of the spin-1 AKLT chains in 1D and similarly to those are characterised by the absence of magnetic order and exponentially decaying spin-spin correlations, which, in turn, strongly indicate a spin gap. Furthermore, these spin-1 systems may also support surface/edge spin 1/2 excitations. We also consider additional Neel interactions between spins within the same tetrahedron and in two neighbouring tetrahedra and derive the effective Hamiltonian which splits the degeneracy of the ground state manifold.

288

Manipulation of Large Responses due to Multipoles on Geometric Frustrated Lattices

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Metallic frustrated magnets provide exciting platforms for finding nontrivial dynamics in highly degenerate states due to magnetic interaction and charge transfer. The most studied are kagome and pyrochlore based materials and the most convenient and popular probe for searching for nontrivial phases is the anomalous Hall effect. For example, metallic spin liquid states due to quadrupolar fluctuations may host a chiral spin liquid on a pyrochlore lattice [1,2]. On the other hand, the octupolar degree of freedom may lead to a large anomalous Hall effect in antiferromagnets [3]. By taking the frustrated antiferromagnet Mn3Sn as an example, we show that the octupolar degree of freedom leads to the time reversal symmetry-broken state and exhibits anisotropic spin spitting band in momentum space with topological electronic structure [3,4,5]. I will review its strikingly large responses to various perturbations (field, current, strain etc.) due to its spin frustration and highlight the fascinating spintronic functionalities including tunneling magnetoresistance [5,6,7]. On the other hand, geometrical frustration in charge transfer may form a flat band. If time permits, I will talk about a novel flat band system that may harbor a topological character and thus large anomalous transverse responses.

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New Materials / 290

Spin-liquid candidate based on S=1/2 Ti3+ ions with a langbeinite structure

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A quantum spin-liquid (QSL) phase represents an ultimate goal for the strongly-correlated research in magnetism. The purported entangled ground state could lead to emergent excitations beyond those predicted by a semi-classical approach. Aside from a 1D S=1/2 antiferromagnetic chain, QSL candidates in D>1 rely on some sort of geometric frustration to prevent long-range order in the presence of magnetic interaction between magnetic moments. Known examples of geometrically-frustrated lattices are triangular and kagome in 2D and hyper-kagome and pyrochlore in 3D [1]. Recent investigation [2] has shown that a 3D network of spins forming two interconnected trillium lattices represents a new, so far unexplored avenue of research in geometrically-frustrated magnetism. Recently, we have managed to synthesize and characterize K2Ti2(PO4)3, which is comprised of a fully quantum S=1/2 spins residing on Ti3+ ions. Half of the metallic sites of the langbeinite structure are occupied by non-magnetic S=0 ions (Ti4+), with the distribution of charges and its influence on magnetic properties unknown at the moment. In an ideal case, this would represent an S=1/2 network on a trillium lattice, which is indicated to be insufficiently frustrated to prevent long-range order to set in [3]. The high-temperature regime exhibits a Curie-Weiss behavior, with a characteristic Weiss temperature of -25K. On the other hand, thermodynamic measurements down to 2K do not indicate any features characteristic of long-range order. Furthermore, muSR results performed down to 30mK show a highly dynamic ground-state, without wiggles associated with long-range magnetic order. We conclude that K2Ti2(PO4)3 represents a highly interesting compound, confirming that the langbeinite structure provides a rich environment for the discovery of new geometrically-frustrated systems.

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292

The Surprisingly Rich Spin Dynamics of Ordered Quantum Magnets

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In this talk I will report on a selection of recent exeriment theory collaborations which were investigating dynamical spin spectral functions in a range of ordered quantum magnets. Using a combination of state of the art inelastic neutron scattering experiments, numerical cylinder matrix product state simulations and theoretical considerations we demonstrate that the excitation spectra of ordered quantum magnets are much more diverse in phenomena than the standard spin-wave theory based picture conveys. We will discuss phenomena such as bound states in magnetization plateaux, interplay between continua and spin wave branches, roton-like dispersion minima in unfrustrated magnets and the excitation spectra of spin nematic phases.

Metallic magnets / 293

Quantum critical spin-liquid-like behavior in the S = 1/2 quasikagome-lattice compound CeRh1−xPdxSn investigated using muon spin relaxation and neutron scattering

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We present the results of muon spin relaxation (μSR) and neutron scattering on the Ce-based quasikagome lattice CeRh1−xPdxSn (x = 0.1 to 0.75). Our zero-field (ZF) μSR results reveal the absence of both static long-range magnetic order and spin freezing down to 0.05 K in the single-crystal sample of x = 0.1 [1]. The weak temperature-dependent plateaus of the dynamic spin fluctuations below 0.2 K in ZF-μSR together with its longitudinal-field (LF) dependence between 0 and 3 kG indicate the presence of dynamic spin fluctuations persisting even at T = 0.05 K without static magnetic order. On the other hand, the magnetic specific heat divided by temperature C4f/T increases as −logT on cooling below 0.9 K, passes through a broad maximum at 0.13 K, and slightly decreases on further cooling. The ac-susceptibility also exhibits a frequency-independent broad peak at 0.16 K, which is prominent with an applied field H along the c direction. We, therefore, argue that such a behavior for x = 0.1 can be attributed to a metallic spin-liquid-like ground state near the quantum critical point in the frustrated Kondo lattice. The LF-μSR study suggests that the out of kagome plane spin fluctuations are responsible for the spin-liquid (SL) behavior. Low-energy inelastic neutron scattering (INS) of x = 0.1 reveals gapless magnetic excitations, which are also supported by the behavior of C4f proportional to T1.1 down to 0.06 K. The ZF-μSR results for the x = 0.2 polycrystalline sample exhibit similar behavior to that of x = 0.1. A saturation of λ below 0.2 K suggests a spin-fluctuating SL ground state down to 0.05 K. The ZF-μSR results for the x = 0.5 sample are interpreted as a possible long-range antiferromagnetic (AFM) ground state below TN = 0.8 K, in which the AFM interaction of the enlarged moments probably overcomes the frustration effect.

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294

Field-induced bound-state condensation and spin-nematic phase in SrCu2(BO3)2 in very high magnetic field

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In quantum magnets studied to date, closing the energy gap by applying a magnetic field could be understood as Bose-Einstein condensation of triplet magnons resulting in a long-ranged magnetic order. However, in theory this is not the only possibility: if the first magnetic excitation to touch the singlet has a larger spin, then the resulting phase cannot host magnetic order, but will instead have a more complex order parameter more closely analogous to a liquid crystal. We demonstrate with experiments and numerics that such a possibility can arise in SrCu2(BO3)2 which realizes the Shastry-Sutherland model, a paradigmatic frustrated magnet. Our high-field inelastic neutron scattering experiments have been conducted on the compound with magnetic fields up to 25.9T and we find a rich set of excitations whose energies and spectral intensities have been measured as a function of magnetic field. Using cylinder matrix-product states calculations on the model with Dzyaloshinskii-Moriya interactions, we reproduce and interpret the experimental spectra. Multiple unconventional spectral features such as the gradients of the one-triplet branches and the persistence of the single-triplet gap point to a condensation of spin-2 bound states, thus realizing a spin-nematic phase. The single-triplet gap reflects a direct analogy with superconductivity, suggesting that the spin-nematic phase in SrCu2(BO3)2 is best understood as a condensate of Cooper pairs of hardcore bosons.

[1] Field-induced bound-state condensation and spin-nematic phase in SrCu2(BO3)2 revealed by neutron scattering up to 25.9 T. Nature Communications, 15(1) 442, January 2024.

295

Spin-charge separation and resonant valence bond spin liquid in a kinetically-frustrated lightly-doped Mott insulator

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Ideas about resonant valence bond liquid and spin-charge separation have led to key concepts in physics such as quantum spin liquids, emergent gauge symmetries, topological order, and fractionalisation. Despite extensive efforts to demonstrate the existence of a resonant valence bond phase in the Hubbard model that originally motivated the concept, a definitive realisation has yet to be achieved. Here, we present a solution to this long-standing problem by uncovering a resonant valence bond phase exhibiting spin-charge separation in realistic Hamiltonians. We show analytically that this ground state emerges in the dilute-doping and infinite-onsite-repulsion limit of a half-filled Mott insulator on corner-sharing tetrahedral lattices with frustrated hopping. We confirm numerically that the results extend to finite exchange interactions, finite-sized systems and finite dopant density. We further conducted a preliminary study on the nature of the excitations and spin-liquid correlations, suggestive of bosonic holon behaviour. Although much attention has been devoted to the emergence of unconventional states from geometrically frustrated interactions, our work demonstrates that kinetic energy frustration in doped Mott insulators may be essential for stabilising robust, topologically ordered states in real materials.

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