# TT 33: Correlated Magnetism – Spin Liquids

Time: Wednesday 15:00–18:15 Location: H33

TT 33.1 Wed 15:00 H33

**An Atlas of Classical Pyrochlore Spin Liquids** — •Daniel Lozano-Gómez[1,2], Owen Benton[3], Michel Gingras[2], and Han Yan[4] — [1]Technische Universität Dresden, Dresden, Germany — [2]University of Waterloo, Waterloo, Canada — [3]Queen Mary University of London, London, United Kingdom — [4]The University of Tokyo, Kashiwa, Japan

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. Despite the rich variety of SLs realized in this lattice, a general framework for the classification and characterization of these is still lacking. In this work, we develop such a theoretical framework to allocate interaction parameters stabilizing different classical SLs and derive their corresponding effective generalized emerging Gauss's laws at low-temperatures. Combining this with Monte Carlo simulations, we systematically identify all classical SLs for the general nearest-neighbor anisotropic spin Hamiltonian on the pyrochlore lattice. We uncover new SL models with exotic forms of generalized Gauss's law and multipole conservation laws. 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.

TT 33.2 Wed 15:15 H33

**Higher-Rank Spin Liquids and Spin Nematics from Competing Orders in Pyrochlore Magnets** — •Niccolò Francini, Lukas Janssen, and Daniel Lozano-Gómez — Institut für Theoretische Physik and Würzburg-Dresden Cluster of Excellence ct.qmat, TU Dresden, 01062 Dresden, Germany

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.

TT 33.3 Wed 15:30 H33

**Raman Circular Dichroism of Chiral Quantum Spin Liquids** — •Eduard Koller[1,2,3], Valentin Leeb[1,3], Natalia Perkins[4], and Johannes Knolle[1,3,5] — [1]Technical University of Munich, Germany — [2]Institute for Advanced Study, TUM, Germany — [3]Munich Center for Quantum Science and Technology, Germany — [4]School of Physics and Astronomy, University of Minnesota, USA — [5]Blackett Laboratory, Imperial College London, United Kingdom

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.

TT 33.4 Wed 15:45 H33

**Low-Temperature Features of the Quantum Spin Liquid Candidate PCTO Crystal Structure** — •Alexander Mistonov[1], Abanoub Hanna[2], Elaheh Sadrollahi[1], Heidi Savey-Bennett[3], Martin von Zimmermann[4], Elizabeth Blackburn[5], Bella Lake[2], and Jochen Geck[1] — [1]Technische Universität Dresden — [2]Helmholtz-Zentrum Berlin — [3]The University of Manchester — [4]Deutsches Elektronen-Synchrotron DESY — [5]Lund University

$PbCuTe_2O_6$ (PCTO) is well known as a promising candidate for quantum spin liquid compounds. Magnetic ordering does not occur down to 0.02 K [1]. Additionally, diffuse continua are observed in magnetic spectra [2]. At the same time, heat capacity and dielectric response demonstrate signatures of an order-disorder ferroelectric (FE) transition at $\sim 1$ K [3]. According to thermal expansion measurements, this transition is believed to be accompanied by structural changes. We have performed a high-energy single-crystal X-ray diffraction experiment using a dilution refrigerator to investigate it for the first time. We have observed Bragg peaks that are forbidden for the reported high-temperature crystal structure (space group $P4_132$ [4]) and studied their evolution. In the current work, we share our findings from below and above the FE transition.

[1] P. Khuntia et al., Phys. Rev. Lett. 116, 107203 (2016).
[2] S. Chillal et al., Nat. Commun. 11, 2348 (2020).
[3] C. Thurn et. al., npj Quantum Mater. 6, 95 (2021).
[4] A. R. N. Hanna et al., Phys. Rev. Mat. 5, 113401 (2021).

TT 33.5 Wed 16:00 H33

**What is carrying the heat in the thermal Hall effect of honeycomb magnets?** — •Ralf Claus, Jan Bruin, Yosuke Matsumoto, Pascal Reiss, Akmal Hossain, Lichen Wang, Pascal Puphal, Bernhard Keimer, and Hidenori Takagi — Max-Planck-Institut für Festkörperforschung, D-70569 Stuttgart

The observation of a half-integer quantized thermal Hall effect in the honeycomb magnet $\alpha$-$RuCl_3$ was interpreted as an experimental hallmark for Kitaev majorana fermions. However, follow-up studies only partly reproduced this result and have offered alternative explanations such as phonons or topological magnons. To narrow down the nature of the heat carrying quasiparticles, we conducted a comparative study of the longitudinal ($\kappa_{xx}$) and transversal ($\kappa_{xy}$) heat transport on $\alpha$-$RuCl_3$ and $Na_3Co_2SbO_6$ (NCSO). Both share the same crystal symmetries and have comparable magnetic phase diagrams. However, one key difference is that for applied in-plane magnetic fields $B > 3$ T NCSO is in a fully spin-polarized phase convincingly excluding the presence of any majorana fermions. Remarkably, we observed a finite $\kappa_{xy}$ in NCSO up to $B \approx 10$ T, which displays striking similarities in shape, angle-dependence, and magnitude to that of $\alpha$-$RuCl_3$. Furthermore, the field dependences of $\kappa_{xx}$ and of the thermal Hall angle ($\kappa_{xy}/\kappa_{xx}$) across all $\alpha$-$RuCl_3$ and NCSO samples suggest a substantial phononic contribution to $\kappa_{xy}$. Ultimately, we propose that topological magnons are responsible for generating the Hall temperature gradient which in turn is significantly enhanced by phonon-magnon interaction.

TT 33.6 Wed 16:15 H33

**Variational Monte Carlo Simulations of Two-dimensional Quantum Spin Liquids** — •Florian Michael and Benedikt Fauseweh — TU Dortmund University, Dortmund, Germany

In this project we use state-of-the-art variational algorithms to train neural quantum states for the quantum spin liquid phase of the J1-J2 Heisenberg model on a square lattice. Specifically, this approach makes use of a hybrid architecture of a restricted Boltzmann machine and pair-product states, capturing both global and local correlations efficiently. To further increase the precision of the wave function representation as well as mitigate finite-size effects, we apply quantum number projections and impose twisted boundary conditions.

The project is implemented within the NetKet framework, leveraging the automatic differentiation and just-in-time compilation of JAX as well as GPU accelerated high-performance clusters. The goal is to further advance the application of neural quantum states in quantum many-body physics and gain new insights on properties of quantum spin liquids that are currently difficult to simulate due to their long-range entanglement and absence of magnetic order.

TT 33.7 Wed 16:30 H33

**Quantum simulation of fermionic, non-Abelian lattice gauge theories in (2+1)D** — •Gaia De Paciani[1,2], Lukas Homeier[1,2,3], and Fabian Grusdt[1,2] — [1]Department of Physics and Arnold Sommerfeld Center for Theoretical Physics (ASC), Ludwig-Maximilians-Universität, München, Germany — [2]Münich Center for Quantum Science and Technology (MCQST), München, Germany — [3]University of Colorado, Boulder, Colorado

Understanding and simulating non-Abelian quantum spin-liquids and dimer models is an open challenge in the condensed matter and high energy physics landscape. Recent advancements in the field of quantum simulations have significantly expanded its potential for applications, particularly in the context of lattice gauge theories (LGTs). Nevertheless, maintaining gauge invariance throughout a simulation remains a critical challenge, especially for large-scale non-Abelian LGTs. We propose a novel approach to simulate non-Abelian U(N) LGTs with dynamical fermionic matter in (2+1) dimensions, enhancing the reliability of the simulation through the suppression of the occupation of gauge invariant sectors. We present a comprehensive framework to simulate gauge-invariant dynamics and we propose two experimental platforms – utilizing ultracold alkaline-earth-like atoms and Rydberg-dressing – to implement these models, enabling the quantum simulation of large-scale non-Abelian gauge theories in near-term experiments.

**15 min. break**

**Invited Talk** TT 33.8 Wed 17:00 H33

**Emergent Dynamical Gauge Fields in Generic Kitaev Spin Liquids: From Monolayer to Multilayers** — •Aprem Joy and Achim Rosch — Institute for Theoretical Physics, University of Cologne

Emergent gauge fields and fractional excitations are long sought-after in modern condensed matter physics. The Kitaev spin liquid and its potential realization in the so called “Kitaev materials" have been at the frontier of this search. The Kitaev spin liquid realizes an emergent static Z2 gauge field with vison excitations strongly interacting with Majorana fermions, by virtue of its gauge flux. While static in the idealized Kitaev model, single visons and vison pairs become dynamical degrees of freedom in the presence of perturbations. We develop a concise theory of the universal properties of single visons in weakly perturbed Kitaev models. We focus both on single-layer and multilayer systems, motivated by the layered structure of materials. When Kitaev models are stacked on top of each other, weakly coupled by Heisenberg interaction, a rich zoo of mobile gauge excitations emerge whose dynamics is strongly constrained by topology and residual conservation laws, resulting in sub-dimensional mobilities, reminiscent of fractons. Furthermore, we show how vison dynamics in Kitaev materials can lead to novel signatures in relaxation experiments.

[1] A. Joy and A. Rosch, Phys. Rev. X 12, 041004 (2022);
[2] A. Joy and A. Rosch, npj Quantum Mater. 9, 62 (2024).

TT 33.9 Wed 17:30 H33

**Pressure-dependent magnetism of the Kitaev candidate $Li_2RhO_3$** — •Efrain Insuasti Pazmino[1], Bin Shen[2], Ramesh Dhakal[3], Friedrich Freund[2], Philipp Gegenwart[2], Steve M. Winter[3], and Alexander A. Tsirlin[1] — [1]Leipzig University, Germany — [2]University of Augsburg, Germany — [3]Wake Forest University, USA

In the search for a Quantum Spin Liquid (QSL) state in real materials, hydrostatic pressure is employed to move honeycomb Kitaev compounds closer to or farther from a QSL state. The candidates studied so far have exhibited long-range magnetic ordering at lower temperatures. However, the candidate $Li_2RhO_3$ does not show a magnetic transition at low temperatures but instead exhibits spin freezing. Magnetic couplings obtained through theoretical super-exchange and Exact Diagonalization calculations evolve away from the Kitaev limit as pressure increases. Interestingly, the freezing temperature determined in our magnetization measurements remains constant under increasing pressure and does not correlate with the changes in magnetic couplings. An analysis of simulations and experiments suggests that spin freezing could arise from extrinsic factors such as stacking faults and crystal defects. Furthermore, the $J_3$ coupling was found to be unusually small in comparison with other Kitaev materials. Our work shows commonalities in the pressure evolution of the Kitaev iridates and rhodates where the decrease in the bond angle suppresses the Kitaev coupling while enhancing the off-diagonal anisotropy.

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TT 33.10 Wed 17:45 H33

**Frustrated multipolar degrees of freedom: The quadrupolar Kitaev model** — •Partha Sarker and Urban Friedrich Peter Seifert — Institute for Theoretical Physics, University of Cologne, Zülpicher Straße 77, D-50937 Köln

Frustrated multipolar exchange interactions between spin-S local moments ($S > 1/2$) have been suggested to possibly give rise to quantum spin liquid-like ground states featuring an emergent gauge structure and fractionalized excitations. However, only little is known about characteristic features and experimental signatures of such "multipolar spin liquids". To this end, in this work we turn to the "Quadrupolar Kitaev model" of $S = 1$ moments on a honeycomb lattice as a drosophila, for which recent numerical studies have found a deconfined ground state with topological order. As the model, similar to the spin-S generalization of the Kitaev honeycomb model, is not exactly solvable, we use a combination of mean-field theory and exact symmetry analysis to investigate competing ground states, including multipolar liquids, and their (fractionalized) excitations.

TT 33.11 Wed 18:00 H33

**Phases of the Anyonic Hubbard Ladder for Fibonacci Anyons** — •Nico Kirchner[1], Adam Gammon-Smith[2], and Frank Pollmann[1] — [1]Technical University of Munich, TUM School of Natural Sciences — [2]School of Physics and Astronomy, University of Nottingham

Two-dimensional systems such as quantum spin liquids may exhibit anyonic excitations that feature exchange statistics beyond the bosonic and fermionic cases. A fundamental question regarding such quasiparticles is how the richer exchange statistics influence their mutual interactions and which phases may arise in systems of anyons as a consequence. To study this topic, we consider the particular case of Fibonacci anyons subject to an anyonic Hubbard model with nearest-neighbor repulsion on a two-leg ladder. Focusing on half-filling, for low interaction strengths a metallic phase is found, whereas for strong repulsion, the anyons form a charge-density wave in real space. Within this regime, the effective interactions arising from the exchange statistics give rise to multiple distinct phases that can be distinguished using the scaling of the entanglement entropy and the spectra of matrix product state transfer matrices.