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SCHEDULE OF TALKS

HFM 2024 Chennai Schedule						
	08.01.2024	09.01.2024	10.01.2024	11.01.2024	12.01.2024	13.01.2024
	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
	Probing Entanglement *Chair: R. Coldea*	**Kitaev Magnets** *Chair: J. Romhányi*	**Dipolar-Octupolar Spin Ice** *Chair: B. Gaulin*	**Dimerized Magnets** *Chair: N. Trivedi*	**Synthetic Platforms** *Chair: O. Benton*	**Spin Chains and vander Waals Magnets** *Chair: A. Mahajan*
9:00 AM 9:30 AM 9:50 AM 10:10 AM	Registration (8-9:30 AM) Welcome Remarks 9:40 a.m. S. Blundell T. Shimokawa	E. Andrade N. Perkins S. Bachhar P. Loosdrecht	E. Lhotel A. Nevidomskyy R. Sibille S. Sanyal	P. Corboz M. Nayak J. Rohmányi P. Sengupta	R. Samajdar P. Patil B. Kumar S. Saha	J. S. Lee P. C. Mahato H. Wu B. Koteswararao
10:30 AM	*Coffee Break (D6 hall)*	*Coffee Break (D6 hall)*	*Coffee Break (D7 area)*	*Coffee Break (D7 area)*	*Coffee Break (D7 area)*	*Coffee Break (D7 area)*
	Spins and Lattice *Chair: H. Kawamura*	**Kitaev Magnets** *Chair: Y. J. Kao*	**Spin Dynamics** *Chair: P. Holdsworth*	**Triangular Magnets** *Chair: B. Lake*	**Entropy Effects** *Chair: R. R. P. Singh*	**Kagome and Hyperkagome Magnets** *Chair: S. Blundell*
11:10 AM 11:40 AM 12:00 PM	J. Kishine L. Savary P. Mukharjee	N. Trivedi V. Tripathi M. Gohlke	C. Castelnovo 11:30 A. Szabó 11:50 F. Morineau 12:10 A. Roll	A. Wietek P. Khuntia R. Nath	L. Messio K. Shtengel P. Telang	F. Damay A. Ralko E. Kermarrec Concluding Remarks
12:20 PM	*Lunch (D6 hall)*	*Lunch (D6 hall)*	*Lunch (D7 area)*	*Lunch (D7 area)*	*Lunch (D7 area)*	*Lunch (D7 area)*
	New Materials *Chair: A. Tsirlin*	**Spin-Orbit Coupled Magnets** *Chair: H. O. Jeschke*	**2-6pm** Dakshin Chitra Tour	**Disorder in Magnets** *Chair: E. Andrade*	**Pyrochlore Magnets** *Chair: E. Lhotel*	
2:00 PM 2:30 PM 2:50 PM 3:10 PM	H. O. Jeschke I. Živković M. Gonzalez A. Maurya	A. Chernyshev R. Pohle L. Janssen L. Jaubert		A. A. Tsirlin R. R. P. Singh D. Joshi T. Vojta	P. Holdsworth S. Petit D. L. Gomez R. Schaefer	
3:30 PM	*Coffee Break (D6 hall)*	*Coffee Break (D6 hall)*		*Coffee Break (D7 area)*	*Coffee Break (D7 area)*	
	New Materials *Chair: F. Damay*	**Higher Rank Spin Liquids** *Chair: P. Corboz*		**Symmetry and Fractionalization** *Chair: N. Perkins*	**Metallic Magnets** *Chair: J. Reuther*	
4:00 PM 4:30 PM 4:50 PM 5:10 PM 5:30 PM	A. Mahajan O. Volkova A. Belik A. Vasiliev B. Lake	O. Benton H. Yan B. Placke J. Reuther		A. Keselman S. Pujari R. Ganesh Y. J. Kao	Harish I. Mazin I. Ishant H. Kawamura	
6:00 PM	***Welcome Reception***	**Poster Session (D6 hall)**	**6pm-10pm:** Conference Dinner	**Poster Session (D6 hall)**		

TUTORIALS

Microscopic models of Magnetic Mott insulators

Karlo Penc
Institute for Solid State Physics and Optics, HUN-REN Wigner Research Centre for Physics, H-1525 Budapest, Hungary

- The origin of the Heisenberg exchange and how does it compare to the dipolar interaction
- The origin of superexchange and 90-degree exchange
- Multiple spin exchanges
- Anisotropic interactions and spin-orbit coupling: on-site anisotropy, Dzyaloshinskii–Moriya and Kitaev interactions (first symmetry considerations, then some key ideas on how they arise microscopically)
- Spin dipoles, quadrupoles, and octupoles (at a very basic level)

Real Material Platforms for Highly Frustrated Magnetism

Bruce D. Gaulin
Department of Physics and Astronomy, McMaster University, Hamilton, Ontario, L8S 4M1, Canada

Exotic magnetic ground states have long been known to arise from both competing interactions and the constraints due to the local crystalline geometry. I will introduce a range of two dimensional and three dimensional architectures which tend to support exotic ground states, and which can be experimentally realized. In two dimensions these are mainly based on triangular motifs with edge-sharing triangles (forming a triangular net) and corner-sharing triangles (forming a kagome net) being prominent. In three dimensions these tend to be based on tetrahedra, and the corresponding analogues are face-centred cubic (for edge sharing tetrahedra) and pyrochlore lattices structures (for corner sharing tetrahedra). However, even not-obviously-frustrated crystalline lattices, such as the bipartite honeycomb lattice, can be interesting platforms for spin liquid states in the presence of bond-dependent competing interactions, as Kitaev and related magnets display. Real materials always exhibit disorder at some level and this can introduce complexity to exotic phenomena which is not necessarily easy to understand to begin with. I will also survey a variety of real material examples, where the materials' complexity, our ability to experimentally characterize and understand that complexity, and our theoretical picture of the beautiful underlying physics, all intersect.

Neutron Spectroscopy of Magnets

Radu Coldea
Clarendon Laboratory, University of Oxford Physics Department, Parks Road, Oxford OX1 3PU, UK

To be announced

A Practical Guide to Measuring Magnetic Structures using Resonant X-Ray Scattering (RXS)

Daniel G Porter

Diamond Light Source, Harwell Science and Innovation Campus, Didcot, Oxfordshire, OX11 0DE, UK

- Brief introduction to synchrotron x-rays & magnetic materials beamlines at Diamond
- Brief introduction to diffraction and polarisation and resonant x-ray scattering
- Planning an experiment - where to look and what to consider
- Identifying magnetic signals/ separating them from everything else
- Example measurements
- (if time) Demonstration of simulations

An overview of quantum spin liquids and their symmetry fractionalization

Inti Sodemann

Institute for Theoretical Physics, University of Leipzig, Leipzig, Germany

- What is a quantum spin liquid?
- Types of quantum spin liquids and their stability.
- Parton constructions of spin liquids and projective symmetry groups.
- Phase transitions and confinement.
- Outlook of the field and open problems

Quantum Monte Carlo for correlated spin systems

Arnab Sen

School of Physical Sciences,Indian Association for the Cultivation of Science Kolkata, INDIA.

- World line picture and necessity of nonlocal updates in quantum spin models
- Stochastic series expansion (SSE) as one possible versatile method for a wide variety of lattice spin models
- Typical estimators that can be calculated using SSE
- Quick recap of binning, autocorrelations etc
- Illustrative examples using specific lattice models in 1D, 2D , 3D
- Velocity of linearly dispersing modes, e.g., spin waves
- Understanding some conventional phase transitions in dimerized magnets
- Diagnostics of a Z_2 spin liquid in 2D and a U(1) spin liquid in 3D in designer Hamiltonians
- Brief discussion of the sign problem and how to get rid of it in exceptional cases (if time permits)

PROBING ENTANGLEMENT

Chair: R. Coldea

Probing singlet states in frustrated magnets with muons

Stephen J. Blundell[1,*]
[1]*University of Oxford, Department of Physics, Parks Road, Oxford OX1 3PU, UK*
**stephen.blundell@physics.ox.ac.uk*

The technique of muon-spin rotation (μSR) has emerged as one of the most important spectroscopic techniques in condensed matter physics, used to study everything from superconductors to skyrmions. It is now possible to understand the interaction between the muon and its neighbouring spins in quantitative detail to probe entanglement and decoherence [1] and to characterise the muon site in many different materials with high accuracy [2]. An outstanding problem is that many magnetically frustrated systems exhibit what is known as persistent spin dynamics (PSD) in μSR experiments, the origin of which has remained mysterious since their discovery in the 1990s. As the temperature is lowered, the muon-spin relaxation rate rises (as would be expected for the slowing-down of spin fluctuations) but this rate then saturates at low temperature. To explain this phenomenon, I will describe how muons can couple to singlet states [3] and how this can be extended to understand the way muons couple to a variety of systems exhibiting highly frustrated magnetism. μSR experiments are usually carried out without resonance, but I will describe a new project which aims to use insights from magnetic resonance and include them into μSR, thereby extending the reach of the technique.

(Work carried out in collaboration with B. M. Huddart, T. Lancaster, F. L. Pratt, J. M. Wilkinson, H. Wu.)

References

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[3] S. J. Blundell *J. Phys.: Conf. Ser.*, **2462**, 012001 (2023)

Entanglement-Based Identification of Quantum Spin Liquid and Quantum Frustrated Random Singlet States

Tokuro Shimokawa*, Snigdh Sabharwal and Nic Shannon
Theory of Quantum Matter Unit, Okinawa Institute of Science and Technology Graduate University, Onna-son, Okinawa, 904-0495, Japan
**tokuro-shimokawa@oist.jp*

The quantum frustrated random singlet (QFRS) state is an exotic state that arises when frustration, quantum fluctuation, and randomness are all strong [1]. This state was proposed as a possible explanation for the quantum spin liquid (QSL)-like features observed in several materials, including Kagome-lattice herbertsmithite and triangular- lattice organic salt κ-$(ET)_2Cu(CN)_3$. In fact, it has been reported that the QFRS state can exhibit gapless spin liquid-like behaviors, such as T -linear specific heat and broad continua in the dynamical spin structure factors. One obvious challenge is distinguishing between the QFRS state and other types of gapless QSL states that appear in the absence of randomness. While the entanglement entropy could be a useful metric for addressing this issue, particularly in 1D systems [2], its experimental measurement still remains challenging.

To tackle this problem, we propose using other entanglement measures developed in the field of quantum information to distinguish between these states. Specifically, we focus on several entanglement monotones, including one-tangle, two-tangle, concurrence and quantum Fisher information which can be witnessed through inelastic neutron scattering experiments [3]. We apply these entanglement measures to the S=1/2 random-bond triangular-lattice Heisenberg antiferromagnet [4] to investigate the entanglement properties of the QFRS state in the context of exact-diagonalization and calculation based on quantum-typicality. We find that the one- and two-tangles can detect the ground-state phase transition from the to the QFRS states. The most important remark is that the finite-temperature dependence of the two-tangle/quantum Fisher information has the ability to distinguish between the QFRS and some QSL states, such as those that emerge in the S=1/2 J_1-J_2 triangular-lattice and Kagome Heisenberg antiferromagnets [5].

Our results demonstrate that these entanglement measures are powerful tools for distinguishing between the QFRS state and other QSL states, thereby solving the long- standing identification problem in experiments.

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SPINS AND LATTICE

Chair: H. Kawamura

Generalized Dzyaloshinskii Moriya Interaction and Chirality-Induced Phenomena in Chiral Crystals

Jun-ichiro Kishine[1,2]*
[1]*The Open University of Japan,* [2]*Quantum Research Center for Chirality, IMS, Japan*
**kishine@ouj.ac.jp*

I will review recent advances on the studies on magnetic, electronic, spintronic, and phononic properties of chiral crystals, with a focus on the connection between Dzyaloshinskii Moriya interaction (DMI) and chirality in materials[1-6]. Importantly,a microscopic DMI is elevated to a macroscopic Lifshitz invariant (LI) in chiral crystals, where mirror-reflection and inversion symmetry are globally broken. As a consequence, chiral crystals exhibit nontrivial physical responses over a macroscopic scale. Indeed, in chiral magnetism, a chiral spin soliton lattice (CSL)[5,6], which is one of the prominent outcomes arising from the DMI and LI as envisioned by Dzyaloshinskii in 1960s, appears in monoaxial chiral magnetic crystals and exhibits a variety of nontrivial physical properties characterized by coherent and topological nature of the CSL. Furthermore, a giant spin polarization emerges over a macroscopic scale in a wide range of chiral materials from organic molecules to inorganic crystals. The first-order spatial dispersion like the LI also appears in elastic or phonon degrees of freedom in chiral crystals. These examples show how a time-even pseudo scalar term, which corresponds to a generalized concept of the DMI and LI, is realized in chiral media.

References

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Theory of the Thermal Hall Effect in Quantum Magnets Coupled to Phonons

Léo Mangeolle[1,2], Leon Balents[2], Lucile Savary[1,2]
[1]*CNRS, ENS de Lyon, France,* [2]*KITP, Santa Barbara*

We discuss general theories of the thermal Hall effect due to phonons coupled to other degrees of freedom, in particular collective fluctuations in quantum magnets. We describe the thermal Hall conductivity obtained both (i) from the skew scattering of [1,2,3] and (ii) from Berry phase effects acquired by [4,5] phonons interacting with magnetic fluctuations in both ordered [1,2] and disordered [3] magnets. We describe how time-reversal symmetry breaking is communicated to the phonons and that the mechanism leading to a Hall conductivity is fundamentally different from that of the longitudinal conductivity [1,2]. Applying these general results to a concrete case, we show that one obtains order of magnitudes for the Hall resistivity consistent with those reported in the experimental literature. Finally we *derive* a general hydrodynamic theory of phonons and the resulting energy current, including that due to the energy magnetization [4].

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[3] Léo Mangeolle, Leon Balents, Lucile Savary *to appear* (2023)

[4] Léo Mangeolle, Lucile Savary, Leon Balents *to appear* (2023)

[5] Mengxing Ye, Lucile Savary, Leon Balents *arxiv:2103.04223* (2021)

Honeycomb $BaCo_2(AsO_4)_2$

Prashanta K. Mukharjee[1,*], S. Erdmann[1], B. Shen[1], J. Kaiser[1], A.Jesche[1], P. Gegenwart[1], A. A. Tsirlin[2]

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[2]*Felix Bloch Institute for Solid-State Physics, University of Leipzig, 04103 Leipzig, Germany*

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The exactly solvable Kitaev model by A. Kitaev in 2006 [1] marked a significant milestone in studying quantum spin liquids (QSLs) and topological phases in condensed matter physics. On the experimental side, the renowned α-$RuCl_3$ and iridates are extensively explored to look for signatures of the Kitaev QSL state. However, all the materials studied so far have certain irregularities, such as stacking faults, structural disorders, distortions of the octahedra, etc., which give rather substantial non-Kitaev terms restricting access to true Kitaev physics. In this regard, discovering a material that can minimize the above non-Kitaev terms is of paramount importance. Recently, it was pointed out that materials with d^7 ions, like Co, also possess pseudospin-1/2 moment and have necessary structural arrangements, which may lead to a dominant Kitaev interaction in such systems [2,3]. In this context a number of interesting compounds possessing two-dimensional honeycomb geometry e.g. $Na_3Co_2SbO_6$, $Na_2Co_2TeO_6$, $BaCo_2(PO_4)_2$, $BaCo_2(AsO_4)_2$ (BCAO) have been proposed which may show features of Kitaev QSL. In comparison to other cobaltates, BCAO has the following two distinctive features (a) a low critical field to suppress the magnetic order (b) it is free from stacking faults and structural disorders, which motivates us to explore it further as a prospective QSL candidate. Though the realization of Kitaev physics in these Co-based materials is under active debate, their underlying magnetism continues to show exotic properties stimulating further theoretical and experimental studies.

In this work, we elucidate the thermodynamic properties of the candidate material BCAO using high-resolution thermal expansion and magnetostriction measurements [4]. At $T = 2$ K, with an increase in field, the linear magnetostriction coefficient shows two well-separated anomalies around critical field $H_{c1} \simeq 0.2$ T and $H_{c2} \simeq 0.5$ T, corresponding to two field-induced transitions. The transition around H_{c1} is hysteric, pointing towards a first order type transition, whereas the transition at H_{c2} lacks hysteresis, reflecting a second order nature. Notably, we have observed an intermediate state between H_{c2} and the saturated state inline with recent experimental reports. We draw the in-plane phase diagram from the above experiments and other complementary techniques and discuss the admixture of first and second-order types of magnetic transitions in $BaCo_2(AsO_4)_2$.

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NEW MATERIALS

Chair: A. Tsirlin

Search for and validation of 3D spin liquid candidates

Harald Jeschke

Okayama University, Japan

While many promising spin liquid candidates are two-dimensional, it is an exciting challenge to find highly frustrated three-dimensional materials with spin-liquid signatures. In this talk, I will show that density functional theory based energy mapping can play an important role in connecting materials with many-body theories; the method has evolved from giving a rough idea of possible exchange interactions to pinning down Heisenberg Hamiltonian parameters very precisely. In the hyperkagome material $PbCuTe_2O_6$, energy mapping shows that the material is much more frustrated than estimated from perturbation theory. In the material $K_2Ni_2(SO_4)_3$ with two interconnected trillium lattices, energy mapping identifies a Hamiltonian that is more frustrated than an individual trillium lattice and allows detailed explanation of the exotic behavior of the material. Chromium spinels are a fascinating class of materials where DFT energy mapping substantially enhances our understanding of frustration and ordering tendencies.

Work done in collaboration with Bella Lake, Yasir Iqbal, Johannes Reuther, Ivica Zivkovic, Henrik Ronnow, Pratyay Ghosh, Ronny Thomale and many others.

Two-trillium magnetic lattice in $K_2Ni_2(SO_4)_3$ and its highly dynamic and correlated state seen by inelastic neutron scattering

<u>Ivica Zivkovic</u>[1] *, Virgile Favre[1], Aman Sharma[1], Henrik Ronnow[1], Matias Gonzales[2,3], Vincent Noculak[2,3], Johannes Reuther[2,3], Yasir Iqbal[4]

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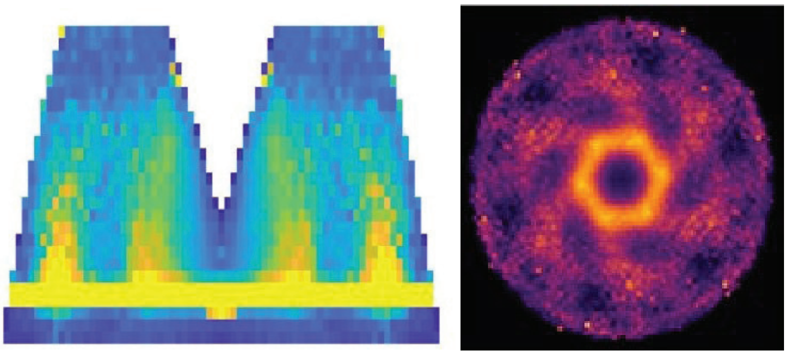
Quantum spin liquids (QSLs) emerged as promising systems for observations of entanglement and fractional excitations in magnetic materials. As quantum fluctuations are enhanced in low-dimensional systems, the main focus was predominantly given to 1Dand 2D systems. Nevertheless, highly frustrated 3D systems have been shown to support QSL, as in pyrochlore and hyper-kagome lattices. Recent report [1] indicated a novel type of a frustrated, 3D magnetic lattice, consisting of two interconnected trillium lattices in $K_2Ni_2(SO_4)_3$, a member of a langbeinite family. Due to its high chemical variety, this family offers many opportunities to investigate the influence of connectivity, spin values and disorder on properties of QSLs.

The first step in understanding the properties of any particular QSL is the investigation of correlations that develop below a characteristic temperature given by exchange interactions between magnetic moments. We performed inelastic neutron scattering experiments on single crystals of $K_2Ni_2(SO_4)_3$, which unambiguously demonstrate its highly dynamic and correlated state. We have observed clear streaks of intensity in its dynamical structure factor $S(Q,\omega)$ without any obvious q-dependence. The extent of correlations is seen to diminish above approximately 2 meV, in agreement with thermodynamic properties reported previously [1]. The qq-maps show particular patterns of correlations, a fingerprint of its underlaying magnetic network, of which the most revealing one resembles a six-wheeled galaxy of stars. The chirality of this wheel is a consequence of the non-centrosymmetric space group $P2_13$ found in langbeinites. Most importantly, these patterns of correlations were successfully described using classical Monte Carlo and quantum Pseudo-Fermion Functional Renormalization Group calculations incorporating the set of exchange interactions calculated by density functional theory [1]. We will discuss the source of this dynamics and how it might relate to investigation of other members of the langbeinite family.



References

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Dynamics of $K_2Ni_2(SO_4)_3$ governed by proximity to a 3D spin liquid model

Matías G. Gonzalez[1,2,*], **V. Noculak**[1,2], **A. Sharma**[3], **V. Favre**[3], **J-R. Soh**[3], **A. Magrez**[4], **R. Bewley**[5], **H. O. Jeschke**[6], **H. M. Rønnow**[3], **I. Živković**[3], **Y. Iqbal**[7], **and J. Reuther**[1,2]

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I will discuss the pseudo-fermion functional renormalization group (PFFRG) and classical Monte Carlo (cMC) calculations on the magnetic properties of $K_2Ni_2(SO_4)_3$, a $S = 1$ compound consisting on two interconnected trillium lattices [1,2]. As shown in Fig. 1, we obtain a good agreement between theory and experiments. Furthermore, we also obtain an excellent agreement between cMC at finite temperature and PFFRG at finite cutoff Λ, showing a quantum-to-classical correspondence phenomenon.

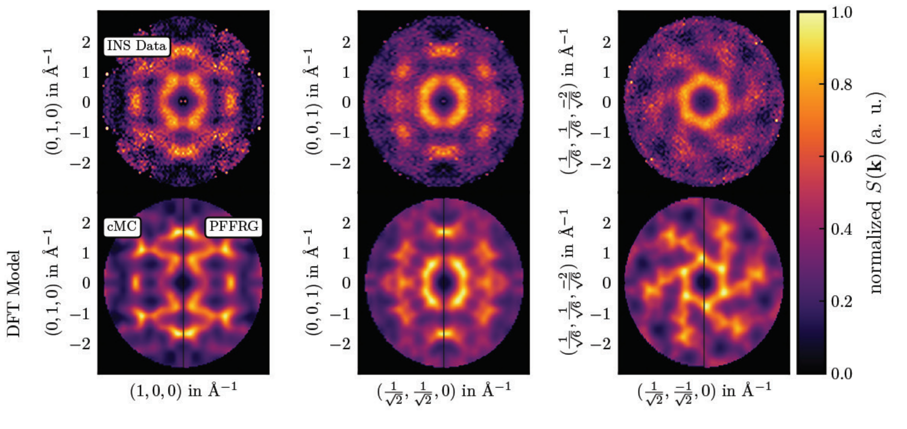

Figure 1: Inelastic neutron scattering measurements compared with cMC and PFFRG calculations corresponding to the DFT model of the $K_2Ni_2(SO_4)_3$ compound.

The highly dynamical properties of $K_2Ni_2(SO_4)_3$ can be explained by its proximity to a tetra-trillium lattice. This lattice of corner-sharing tetrahedra consists on a trillium lattice where every triangle is replaced by a tetrahedron. We show that this new lattice holds a spin liquid both in the quantum and classical cases, and explore the similarities in the spin structure factor to the $K_2Ni_2(SO_4)_3$ compound.

Results correspond to those presented in Ref. [3]

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Magnetization plateaus in EuTAl$_4$Si$_2$ (T = Rh, Ir)

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Magnetization plateaus at fractions of saturation magnetization has been one of the indication for magnetic frustration present in a material system [1,2]. Experimental observation of 'quantum plateaux', for example in $SrCu_2(BO_3)_2$, are also associated with unconventional spin superstructure owing to competing interactions present in the system [2]. We hereby report an unusual magnetic response of the title compounds, i.e., $EuRhAl_4Si_2$ (T_N =11.7 K) and $EuIrAl_4Si_2$ (T_N = 14.7 K), composed of a one-third magnetization plateau at temperature 2 K stretched over a magnetic field of 2 T and 4 T, respectively. Both of these sibling materials crystallized in a simple tetragonal structure with space group *P*4/*mmm*, in a manner such that the magnetic europium atoms form a square lattice in the *ab*-plane [3]. We discuss a scenario of magnetic frustration owing to competing ferromagnetic and antiferromagnetic interactions, corroborated by magnetocaloric effect and anisotropic magnetic phase diagram in addition to the anisotropic magnetization in the Rh-analog [5].

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NEW MATERIALS

Chair: F. Damay

Novel magnetism in the honeycomb system $Cu_3LiRu_2O_6$ with Ru^{4+} ($4d^4$)

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Honeycomb systems containing ions with a large spin-orbit coupling and a nominally non-magnetic single-ion state have been proposed to host novel magnetic ground states [Phys. Rev. Lett. **111**, 197201 (2013)]. Our susceptibility data on $Cu_3LiRu_2O_6$ (CLRO; containing Ru^{4+} ($4d^4$)) exhibit a broad maximum around 300 K and a Curie-Weiss fit of the data above 300 K yields an effective moment of 2.42 μ_B and a Curie-Weiss temperature θ_{CW} = -222 K. The system contains Cu^{1+} which is non-magnetic and the magnetism arises from the Ru^{4+} ions which we suggest have J_{eff} = 1. There is no evidence of magnetic order down to 300 mK in heat capacity which varies as T^2 at low-T. The temperature variation of the shift K of the ^{7}Li nuclear magnetic resonance (NMR) signal shows a broad maximum at about 300 K below which it decreases and then below about 100 K it acquires a finite T-independent value which continues down to 2 K (our lowest temperature), indicating a finite spin susceptibility and hence a magnetic state. The variation with temperature of the ^{7}Li K in $Cu_3LiRu_2O_6$ mimics that of $H_3LiIr_2O_6$ (HLIO; a Kitaev Quantum Spin Liquid) other than the fact that the broad maximum in K vs T appears at 300 K in CLRO compared to about 140 K in HLIO. The ^{7}Li NMR spin-lattice relaxation rate $1/T_1$ shows no evidence of magnetic order and varies linearly with temperature at low-T which is reminiscent of gapless fermionic excitations. Our results point towards the observation of excitonic magnetism in a d^4 system together with the stabilisation of a spin liquid state at low-T.

Antiferromagnetic Order of Ferromagnetic Spin-1/2 Ladders In $MoOBr_3$

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Molybdenum compounds are often non-magnetic. Its 4d orbitals are more extended in space and better overlapped with ligands than in 3d metals due to a larger principal quantum number. Hereby we present a rare case of magnetism of localized magnetic moments on Mo^{5+}($4d^1$) ions. The magnetic subsystem of molybdenum oxybromide, $MoOBr_3$, is constituted by orthogonal spin S = 1/2 two-leg ladders running along the c – axis shown in left panel of Fig. 1. The ladder itself is organized by edge-sharing $MoBr_4O_2$ octahedra on the rung and corner-sharing on the leg. In any given ladder, the Mo atoms are shifted either above (+z) or below (−z) the basal plane of the Br atoms. In measurements of ac - magnetic susceptibility χ, shown in right panel of Fig. 1, and specific heat C_p the formation of an antiferromagnetic order at T_N = 33 K has been established, while both GGA+U calculations and Curie-Weiss fitting of the experimental data at elevated temperatures point to the predominance of ferromagnetic exchange interaction. The latter can be attributed to the spin exchange between Mo^{5+} ions on the rungs through orthogonal p-orbitals of the ligand. Reduced effective magnetic moment evidences the unquenched orbital moments anti-aligned with the spins. The work is supported by the megagrant project 075-15-2021-604.

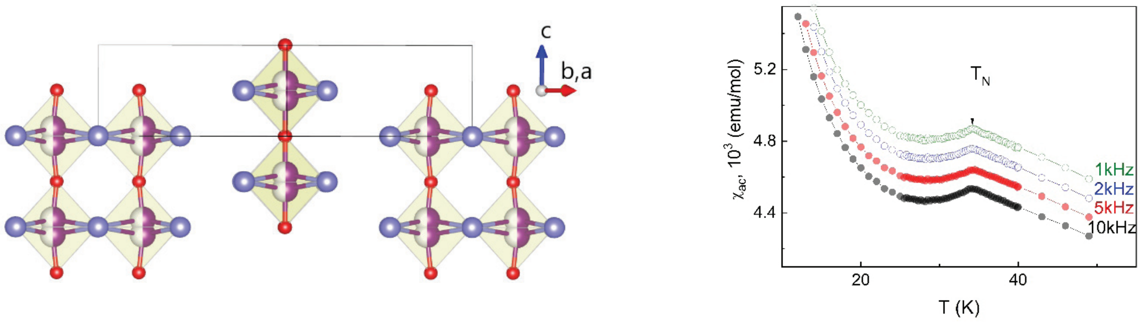

Figure 1. Left panel: the fragment of crystal structure of $MoOBr_3$. Large half – filled spheres are Mo^{5+} ions coordinated by middle size spheres of Br^- in the ab plane and small spheres of O^{2-} along c – axis. Right panel: Temperature dependence of ac- magnetic susceptibility of $MoOBr_3$ taken at various frequencies. The arrow indicates the temperature of the formation of antiferromagnetic state at T_N.

Frustration-driven different magnetic ground states in $Y_2A'A''Mn_4O_{12}$

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A-site ordered quadruple perovskites, $AA'_3B_4O_{12}$, show many interesting physical and chemical properties, for example, inter-site charge transfer and disproportionation, giant dielectric constant, multiferroic properties, and an electric dipole helical texture. These discoveries have led to a considerable research effort to synthesise and characterise such quadruple perovskites. $AA'_3B_4O_{12}$ has a 12-fold-coordinated A site and a square-planar-coordinated A' site (Figure 1a), while B sites have a usual octahedral coordination for perovskites. The $AA'_3B_4O_{12}$ subfamily of the perovskite family has numerous representatives.

In the last years, we explored another special class of perovskite materials with the general composition of $A_2A'A''B_4O_{12}$ (Figure 1b). They are called A-site columnar-ordered quadruple perovskites, where A' is a site with a square-planar coordination and A'' is a site with a tetrahedral coordination. The presence of 3d-5d transition metals at three sites – A', A'', and B – with original columnar-type arrangements of A cations can lead to newfunctionalizes because of unusual exchange pathways not seen in other perovskites.

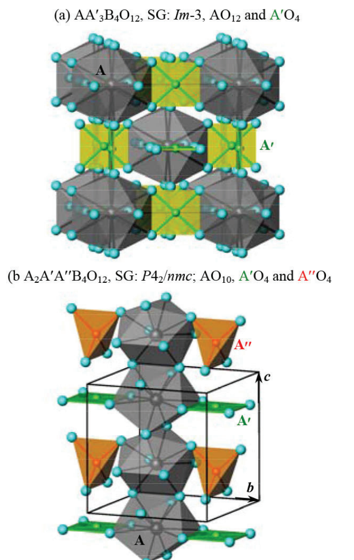

Fig. 1. A-site cation arrangements in (a) $AA'_3B_4O_{12}$ and (b) $A_2A'A''B_4O_{12}$ quadruple perovskites

In this work, we will present results on $Y_2A'A''Mn_4O_{12}$. Depending on the composition at the A' and A'' sites different magnetic ground states and a different number of magnetic transitions are realized: $Y_2MnMnMn_4O_{12}$ (with reduced ordered moments and competitions between antiferromagnetic and ferrimagnetic ground states), $Y_2MnGaMn_4O_{12}$ (with spin-glass magnetic properties), $Y_2CuMnMn_4O_{12}$ (with three ferrimagnetic transitions at 175, 115, and17 K and two spin-reorientation transitions at 115 and 17 K), $Y_2CuGaMn_4O_{12}$ (with one ferrimagnetic transition at 115 K), and $Y_2CuZnMn_4O_{12}$ (with a ferrimagnetic transition at115 K and a spin-reorientation transition at 30 K).

Square kagome systems

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In 2001, Siddharthan and Georges introduced a two-dimensional network of corner-sharing triangles with square lattice symmetry [1]. In variance with kagomé lattice, which is a two-dimensional network of corner-sharing triangles with hexagonal voids, square kagome lattice (SKL) is a two-dimensional network of corner-sharing triangles with alternative square and octagonal voids. There are two non-equivalent positions for the magnetic ions, α and β, being in ratio one to two. It has been shown numerically that the properties of a square kagomé antiferromagnet should be similar to those on a kagomé lattice. A finite temperature phase transition into a phase with ordered resonance loops and broken translational symmetry has been predicted for SKL. This transition is not forbidden by Mermin-Wagner theorem since it stems from the breaking of a translational symmetry. Recently, it has been shown that the model of geometrically frustrated SKL possesses just single thermodynamically stable solution for arbitrary values of model parameters. The very existence of this solution means that the model cannot exhibit either first or second order phase transitions at non-zero temperatures [2]. The temperature dependence of the specific heat of spin-1/2 Heisenberg SKL antiferromagnet has been analyzed by Tomczak and Richter who predicted the broad peak located at $T \sim 0.85J$ which is a correlation one typical for any low-dimensional magnetic systems, and the second one, at $T \sim 0.10J$, which indicates an additional energy scale relevant to SKL being ascribed to the energy of the lowest spin triplet excitation [3]. For a long time, the studies of the thermodynamic properties of compounds with SKL or its derivatives were carried out exclusively by theoretical methods, albeit the nature provided such patterns in some rare minerals. Among these minerals are nabokoite $KCu_7(SO_4)_5(TeO_3)OCl$, atlasovite $KCu_6FeBiO_4(SO_4)_5Cl$, elasmochloite $Na_3Cu_6BiO_4(SO_4)_5$ and favreauite $PbCu_6BiO_4(SeO_3)_4(OH)H_2O$. The intrinsic properties of SKL in nabokoite and atlasovite are masked by the presence of magnetic ions extraneous to this network. Recently, the iron-free sibling of atlasovite, $KCu_6AlBiO_4(SO_4)_5Cl$, has been synthesized. It has been established that down to 58 mK this compound persists in a gapless quantum spin liquid state. Additionally, a novel sodium bismuth oxo-cuprate phosphate chloride, $Na_6Cu_7BiO_4(PO_4)_4Cl_3$, containing both square kagomé layers and interlayer Cu2+ ions has been synthesized. This material shows no magnetic ordering down to 50 mK forming quantum spin liquid state similar to $KCu_6AlBiO_4(SO_4)_5Cl$.

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Exotic excitations of the antiferromagnetic XXZ spin-1/2 spin chain compounds $ACo_2V_2O_8$ in longitudinal and transverse magnetic field

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The antiferromagnetic spin-1/2 spin chain with Heisenberg-Ising (XXZ) anisotropy is a rich source of novel phenomena. Good physical realizations are the compounds $SrCo_2V_2O_8$ and $BaCo_2V_2O_8$ where the Co^{2+} ions have effective spin-1/2 and are coupled by antiferromagnetic interactions into chains while collinear long-range magnetic order occurs below $T_N \sim 5$ K due to weak interchain coupling. In a longitudinal magnetic field applied along the easy axis, the magnetic order is suppressed and using inelastic neutron scattering and optical spectroscopy we find the evidence for complex bound states of magnetic excitations, known as Bethe strings. Furthermore, the characteristic energy, scattering intensity and linewidth of the observed string states exhibit excellent agreement with precise Bethe ansatz calculations. Our results confirm the existence of the long-sought Bethe string excitations predicted almost a century ago. Application of transverse magnetic field along the direction perpendicular to the easy axis induces a quantum phase transition where the antiferromagnetic order is destroyed at a three-dimensional quantum critical point. The evolution of the excitations is investigated as a function of field revealing a complex series of modes and continuua. At a particular field still within the antiferromagnetically ordered phase we find a sequence of excitations whose energies match the lightest three E8 particles corresponding to the maximal exceptional Lie E8 algebra.

KITAEV MAGNETS

Chair: J. Romhanyi

Disorder, low-energy excitations, and topology in theKitaev spin-liquid

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The Kitaev model is a fascinating example of an exactly solvable model displayinga spin-liquid ground state in two dimensions. However, deviations from the original Kitaev model are expected to appear in real materials. In this work, we investigate the fate of Kitaev's spin-liquid in the presence of disorder – bond defects or vacan- cies – for an extended version of the model. Considering static flux backgrounds, we observe a power-law divergence in the low-energy limit of the density of states with anon-universal exponent. We link this power-law distribution of energy scales to weaklycoupled droplets inside the bulk, in an uncanny similarity to the Griffiths phase often present in the vicinity of disordered quantum phase transitions. If time-reversal symmetry is broken, we find that power-law singularities are tied to the destruction of thetopological phase of the Kitaev model in the presence of bond disorder alone. However, there is a transition from this topologically trivial phase with power-law singularities to a topologically non-trivial one for weak to moderate site dilution. Therefore, dilutedKitaev materials are potential candidates to host Kitaev's chiral spin-liquid phase.

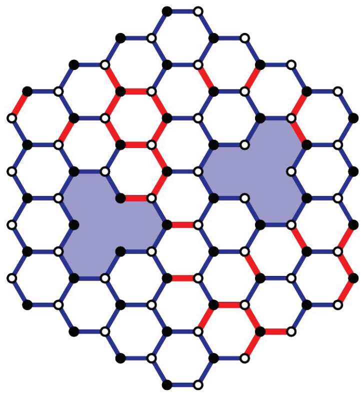

Figure 1: Bound-state flux configuration. The shaded *l* = 12 plaquette shows the binding of a flux by each vacancy.

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Dynamics of vacancy-induced modes in the non-Abelian Kitaev spin liquid

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University of Minnesota

We study the dynamical response of vacancy-induced quasiparticle excitations in the site- diluted Kitaev spin liquid with a magnetic field. Due to the flux-binding effect and the emergence of dangling Majorana fermions around each spin vacancy, the low-energy physics is governed by a set of vacancy-induced quasi-zero-energy modes. These localized modes result in unique characteristics of the dynamical spin correlation functions,which intriguingly mimic the single-quasiparticle density of states and further exhibit a quasi-zero-frequency peak. By recognizing the potential observability of these local correlation functions via scanning tunneling microscopy (STM), we show how the STM response is sensitive to the local flux configuration, the magnetic field strength, and the vacancy concentration. Constructing a simple model of the localized modes, we also elucidate how the local correlation functions can be interpreted in terms of the hybridization between these modes.

$H_{5.9}Li_{0.1}Ru_2O_6$ (Ru^{3+}, J_{eff}=1/2): a Kitaev Quantum Spin Liquid alternative to α −$RuCl_3$

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Kitaev Quantum Spin Liquids (KQSL) host novel ground state and excited state properties. A prominent example is $\alpha - RuCl_3$ having Ru^{3+} (J_{eff} = 1/2) on a honeycomb lattice[Ref.1]. In a zero applied field this compound is magnetically ordered and a field of 80 kOe is required to suppress the order and reveal the KQSL state. Herein we report the synthesis of $H_{5.9}Li_{0.1}Ru_2O_6$, with Ru^{3+} (J_{eff} = ½) on a honeycomb lattice. Our heat capacity measurements suggest no ordering down to 400 mK in spite of a large Curie-Weiss temperature of − 44 K as extracted from our susceptibility data. Our ^{7}Li NMR measurements find a power-law variation of the ^{7}Li spin-lattice relaxation rate below 40 K. From zero-field muon spin relaxation, we find neither oscillations in the muon asymmetry nor any 1/3 tail in the muon asymmetry suggestive of the absence of long-range order and of the presence of dynamic moments. These results are similar to those of $H_3LiIr_2O_6$ (suggested to be a KQSL) except that the saturation of the muon depolarisation rate λ in $H_{5.9}Li_{0.1}Ru_2O_6$ sets in at 10 times the temperature in $H_3LiIr_2O_6$ [Ref.2]. Based on our data, we propose that $H_{5.9}Li_{0.1}Ru_2O_6$ is a KQSL even in a zero field.

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Optically induced quantum spin-disordered state in the Kitaev material α-RuCl3.

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One way to characterize quantum spin-liquids is through the fractionalization of spin excitations. A prime example of this is found in the exactly solvable Kitaev model of spin-1/2 moments with anisotropic exchange interactions on a tri-coordinated lattice. To find examples of this kind of physics in nature turns out to be challenging. The currently best-known examples of materials in which Kitaev-like physics plays a central role are the layered spin-orbit entangled J=1/2 systems Na2IrO3, α-Li2IrO3, and α- RuCl3. However, these materials all possess additional interactions, which, among other, lead to a magnetically ordered state at low temperature preventing the formation of a pure Kitaev spin-liquid (KSL) state. Apart from the ongoing quest for materials showing a true KSL ground state, one can also destabilize the magnetic order in the existing materials, which potentially can induce the sought-after KSL state. In this contribution I will discuss two methods to destabilize magnetic order in α-RuCl3. The first one is through the application of an in-plane magnetic field. Though it has been shown by various authors that this indeed leads to suppression of the ordered state in α-RuCl3, the nature of the field-induced state is not fully clear. The second approach is a pump-probe method which creates holon and doublon excitations. These excitations are found to couple efficiently to magnetic excitations which in turn disorder the magnetically ordered state. For sufficiently high excitation densities the magnetic order is fully suppressed, leading to a quantum disordered magnetic state. This contribution is based on [1-5].

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KITAEV MAGNETS

Chair: Y.J. Kao

Proposal to detect fractionalized excitations in quantum spin liquids

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Quantum spin liquids have been difficult to observe in experiments because of their lack of magnetic order and broad signatures in inelastic neutron scattering. We show that while the response to single-spin excitations is broad, the spectral function corresponding to two-spin excitations has sharp signatures. The electric and magnetic anyons that are created by two spin flips, display fracton-like behavior with restricted mobility along specific one-dimensional directions and provide a fingerprint of fractionalization that should be observable by inelastic light scattering and pump-probe experiments.

Search for fractionalized excitations and topological orderin perturbed Kitaev systems

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The honeycomb Kitaev model is interesting for the long-range topological order ofits ground state, and its fractionalized excitations consisting of free Majorana fermionsand gapped half-vortices. Competing interactions and external perturbations such as a Zeeman field result in fundamental changes in the nature of the excitations, as well as asloss of topological order. It is also important to understand whether topological order that is initially lost due to some competing interaction may be revived through another independent perturbation. The ongoing debate triggered by thermal Hall measurements - on whether Ising topological order may be revived through field suppression of magnetic order in the Kitaev material α-$RuCl_3$ - illustrates the significance of resolving this question. In this context, we have developed some numerical tools for studying quasiparticle stability [1] and thermal Hall transport [2] in gapped spin systems, and applied it to a Kitaev-Heisenberg model subjected to a Zeeman field. We formulate the problem of quasiparticle decay as a delocalization transition in the many-bodyHilbert space. Using this approach, we find to our surprise that low-energy fractionalized quasiparticles can be stable even in the magnetically ordered phase. For the thermal Hall response we use a purification-based tensor network strategy making no prior assumptions about the nature of the quasiparticles. Contrary to some of the recent experimental claims, we find no evidence for a re-emergent Kitaev spin liquid phase inthe vicinity of field suppressed magnetic order characterized by half-quantized thermal Hall conductivity. Instead, in this regime, we find that the peak thermal Hall responseis large, even exceeding the half-quantized value, and decreasing to zero at low temperatures on account of gapping of the edge states. This suggests a bosonic mechanismfor the thermal Hall effect, and absence of Ising topological order.

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Quantum spin-liquid phase with spinon-like excitations inan anisotropic Kitaev- Γ model on a honeycomb lattice

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The characterization of quantum spin liquid phases in Kitaev materials has been asubject of intensive studies over the recent years, both theoretically and experimentally. Most notably, the honeycomb-lattice magnet α-$RuCl_3$ has been considered as a candidate material for hosting the Kitaev spin liquid. Most theoretical studies, however, have focused on an isotropically interacting model with its coupling strength being equivalent on each bond in an attempt to simplify the problem.

Here, we present our results on an extended spin-1/2 Kitaev-Γ model on a homeycomb lattice with an additional tuning parameter, d, that controls the coupling strengthon one of the bonds: we connect the limit of isolated Kitaev-Γ chains, which is knownto exhibit an emergent $SU(2)_1$ Tomonaga-Luttinger liquid phase [1], to the 2D model.We report on an instance [2], in which the Tomonaga-Luttinger liquid persists for finite inter-chain coupling. A quantum spin liquid phase develops for ferromagneticKitaev and antiferromagnetic Γ exchange in analogy to *sliding Luttinger liquids*. This quantum spin liquid phase differs from the Kitaev spin liquid and features spinon-like excitations similar to those of the antiferromagnetic Heisenberg chain.

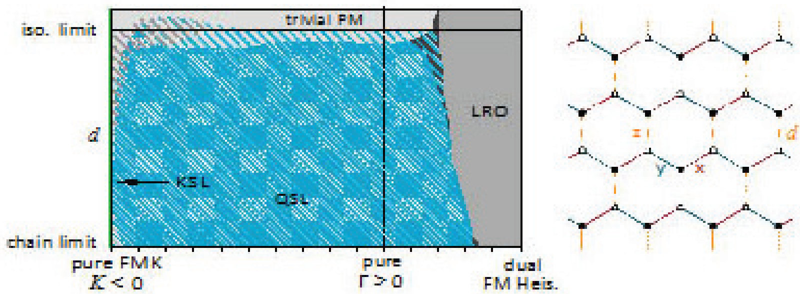

Figure 1: Schematic phase diagram (left) of the anisotropic Kitaev-Γ model on theHoneycomb lattice (right) with varying coupling strength along the z-bond.

In addition, we find a variety of phases ranging from incommensurate, Néel, to non-coplanar magnetic order with up to 12-site unit cells. We use numerical ED and DMRG on various cluster geometries in a complementary way to overcome finite-sizelimitations in the ground state, and investigate both thermal and dynamical propertiessupporting the existence of the QSL.

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SPIN-ORBIT COUPLED MAGNETS

Chair: H.O. Jeschke

Quantum phases in ferro-antiferromagnets

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Quantum spin nematics and unconventional magnetically ordered phases are among the exotic states that can be stabilized in quantum magnets with competing interactions. I will report on our recent results concerning paradigmatic $S = 1/2$ J_1–J_2 square-lattice [1] and J_1–J_3 honeycomb-lattice [2] ferro-antiferromagnetic models, with the former focusing on the search for the quantum spin nematics and the latter on the emergence ofthe classically unstable quantum phases, potentially relevant to a large group of Kitaevmaterials. The minimally-augmented spin-wave theory is advertised as an effective tool to explore quantum phases beyond their classically stable ranges. Our works provides vital guidance to the intense experimental searches of the quantum spin nematicsand other unconventional quantum phases, arming them with realistic expectations.

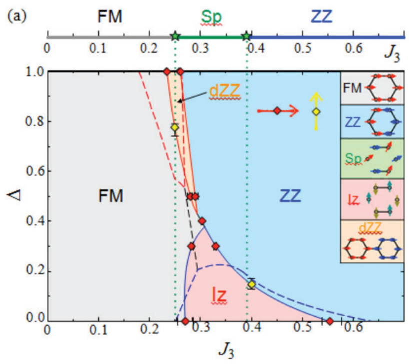

Figure 1: From [2]. The classical (a) and quantum (b) phase diagrams of the J_1–J_3 honeycomb-lattice ferro-antiferromagnetic model.

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Spin Nematics Meet Spin Liquids: Exotic Phases in the Spin-1 Bilinear-Biquadratic Model with Kitaev Interactions

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New discoveries are often made on the border between different disciplines. One major discipline in solid state physics is dedicated to quantum spin liquids, an unconventional state of matter accompanied by emergent gauge fields, topological order and fractionalized excitations [1]. Another concept is that of spin nematics, a magnetically ordered state dominated by quadrupole moments, which breaks spin-rotation symmetry by selecting an axis, while not choosing a particular direction [2]. Usually seen as two separate areas of study, we are interested in connecting those two disciplines, by asking the question: “What happens, when a spin nematic and a spin liquid meet?”

To answer this question, we adopt the newly developed U(3) formalism [3] and investigate the S=1 Kitaev model under the influence of bilinear-biquadratic interactions. We obtain a comprehensive phase diagram including triple-q chiral-ordered and quadrupolar-ordered phases, in addition to already known ferro, antiferro, zigzag and stripy phases [4] (see Fig.1). Intriguingly, next to quadrupolar-ordered and semi-ordered phases, the competition between Kitaev and positive biquadratic interactions also promotes a noncoplanar finite-temperature chiral spin liquid (CSL) state with macroscopic degeneracy and finite spin scalar chirality, which can be transparently understood, on an effective eight-color model.

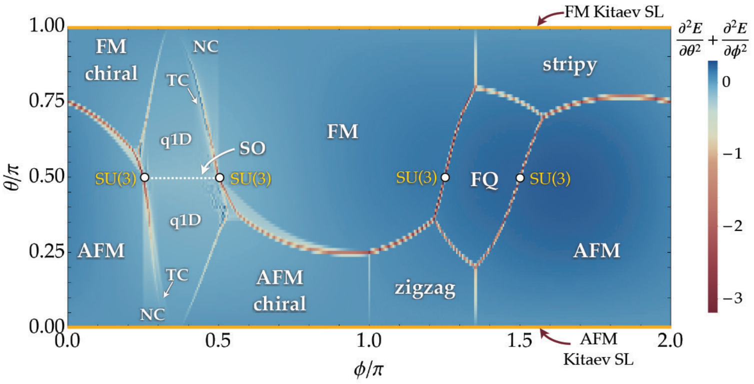

Fig.1: Semiclassical ground state phase diagram of the S=1 bilinear-biquadratic model with Kitaev interactions on the honeycomb lattice. The model stabilizes ferromagnetic (FM), antiferromagnetic (AFM), zigzag, stripy, and spin-nematic ferroquadrupolar (FQ) phases. The competition between chiral order, the Kitaev spin liquid (SL), and quadrupolar semi- order (SO) gives rise to unconventional twisted conical (TC), quasi-one-dimensional (q1D) Coplanar, and noncoplanar (NC) ordered phases.

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Triple-q order and spin vestigial states in $Na_2Co_2TeO_6$

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$Na_2Co_2TeO_6$ is a Kitaev magnet that has recently been shown to realize a triple-q ground state—a noncollinear magnetic long-range ordering characterized by a finite scalar spin chirality [1]. Such an unusual magnetic ground state is expected to lead to a peculiar behavior at finite temperatures, with potential fluctuation-induced new phases and novel types of critical behaviors. We present a study of the finite-temperature properties of extended Kitaev-Heisenberg models, in particular in the regimes where non- collinear chiral ground states are realized [2]. We have performed large-scale Monte Carlo simulations that allow us to not only map out in detail the finite-temperature phase diagram, but also lead to a thorough understanding of the natures of the intermediate vestigial phases and the various finite-temperature transitions involved. The theoretical results are compared with experiments on $Na_2Co_2TeO_6$.

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Manipulating geometric frustration with impuritiesin $Er_2Ti_{2-x}Sn_xO_7$ and spin liquids

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In highly frustrated magnetism, it is usually believed that pristine crystals are necessary, and impurities are unwanted perturbations. Our motivation here is to take the opposing view, and use impurities as a tool to design the properties of frustrated magnets. Motivated by experiments on the rare-earth pyrochlore oxide $Er_2Ti_{2-x}Sn_xO_7$ [1] [Fig. 1.(a)], the idea is to tune the Hamiltonian of our system via non-magnetic dilution x. In other words, we will use impurities as a knob to explore parts of the phase diagram that would remain unaccessible otherwise.

We report the phase diagram of $Er_2Ti_{2-x}Sn_xO_7$ for $0 \leq x \leq 2$, using classical Monte-Carlo simulations [2,3]. To build a detailed theory, we extract from simulations the specific heat, susceptibility, neutron-scattering structure factor, microscopic fluctuations and spin dynamics. Our results are able to reproduce the experimental phase diagram semi-quantitatively [1], with a competition between Γ_5 and Palmer-Chalker antiferromagnetic orders [Fig. 1(b)]. In particular the pronounced asymmetry in favour of Γ_5 observed in experiments is recovered numerically, that we explain in connectionto the underlying disorder-free phase diagram. Our results strongly support the fact thatthe properties of frustrated magnets can be tuned in a controlled way by non-magneticdilution.

In a second part, we will extend this analysis to spin liquids on the pyrochlore lattice, and show how to manipulate their properties with structural disorder [3].

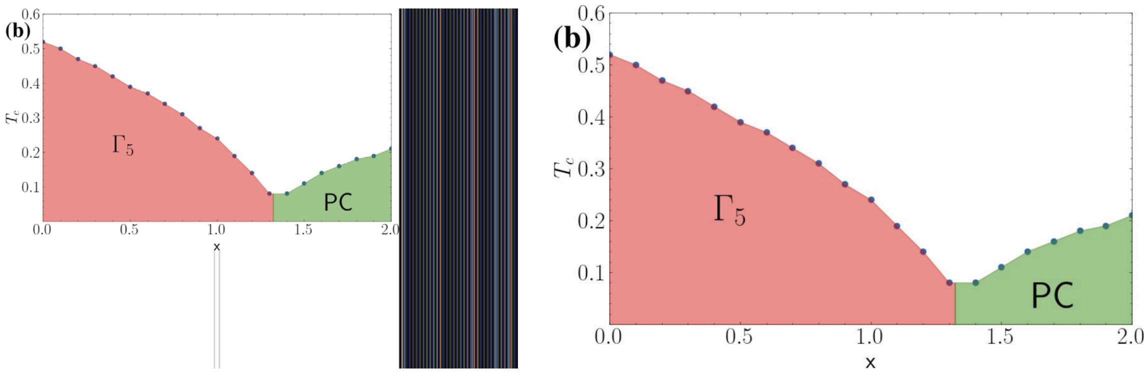

Figure 1: Phase diagram of $Er_2Ti_{2-x}Sn_xO_7$ obtained in experiments [1] and from classical Monte-Carlo simulations [2,3] with Γ_5 (red) and Palmer-Chalker (green) antiferromagnetic phases.

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HIGHER RANK SPIN LIQUIDS

Chair: P. Corboz

Classical spin liquids, irrational orphans and higher-rankgauge fields

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Classical spin liquids (CSL) are the quintessential frustrated systems, defined by the combination of large ground state degeneracies and strong local constraints. Fromtheir low temperature physics emerge effective gauge fields and charges and imbuingthem with quantum fluctuations may lead to quantum spin liquids. In recent years, there has been an increasing appreciation of the diversity of classical spin liquids. They mayhave algebraic or short-ranged correlations, and may exhibit various forms of emergentgauge theory, including those with intrinsically immobile fractonic charges. In this talk,I will discuss recent work exploring the CSL landscape.

Firstly, I will introduce some new, simple models which exhibit exotic forms of CSL. This includes spin liquids with fractonic Gauss' laws and those with line-like singularities in their correlation functions [1-3].

Secondly, we explore the controlled introduction of vacancy sites as a means to probe the emergent gauge fields within CSLs. Previous research has established that when a cluster of vacancies in a CSL leaves only one "orphan" spin on a single constrained cluster, this orphan behaves like a free spin with a fractional moment in response to an external field [4]. I will illustrate scenarios in which this fractional moment size becomes both irrational and tunable. The interactions between these orphan spins are mediated by the underlying CSL and provide insights into the nature of the corresponding gauge theory. Applying this to a spin liquid with rank-2 tensor gauge fields, orphan spin interactions exhibit infinite range and unusual temperature scaling [5].

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Classification of Classical Spin Liquids

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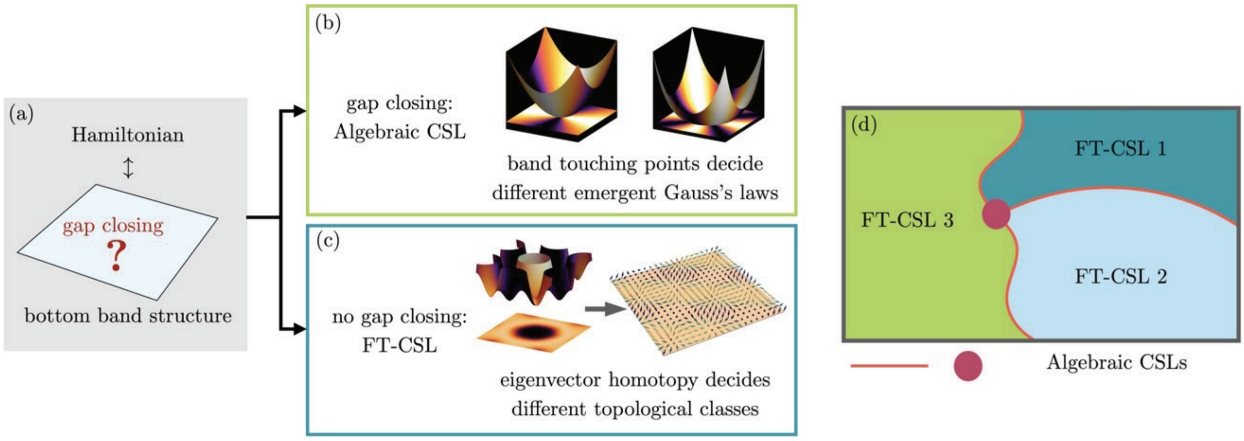
The hallmark of highly frustrated systems is the presence of many states close in energy to the ground state. Fluctuations between these states can preclude the emergence of any form of order and lead to the appearance of spin liquids. Even on the classical level, spin liquids are not all alike: they may have algebraic or exponential correlation decay, and various forms of long wavelength description, including vector or tensor gauge theories. Here, we introduce a classification scheme, allowing us to fit the diversity of classical spin liquids (CSLs) into a general framework as well as predict and construct new kinds. CSLs with either algebraic or exponential correlation-decay can be classified via the properties of the bottom flat band(s) in their soft-spin Hamiltonians. The classification of the former is based on the algebraic structures of gapless points in the spectra, which relate directly to the emergent generalized Gauss's laws that control the low temperature physics. The second category of CSLs, meanwhile, is classified by the fragile topology of the gapped bottom band(s). Utilizing the classification scheme we construct new models realizing exotic CSLs, including one with anisotropic generalized Gauss's laws and charges with subdimensional mobility, one with a network of pinch-line singularities in its correlation functions, and a series of fragile topological CSLs connected by zero-temperature transitions. The work is based on [1,2,3].



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Dimension-Dependent Critical Scaling Analysis and Emergent Competing Ising Fracton Spin Liquid on the Honeycomb Lattice

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Fractons are quasiparticles which are incapable of independent motion. They are known to arise naturally as a consequence of dipole conservation in higher-rank gauge theories. One route towards experimental realization of fractonic physics is therefore to construct models that realize such exotic gauge theories, ideally built only from short- ranged two-body interactions. The construction of such models has been successful in the context of classical spin systems. Thus far these models have been constructed from continuous degrees of freedom, but this has the drawback that one cannot isolate and study discrete fractons. Here, we present an Ising model exhibiting a fractonic spin liquid regime. In this case, fractons are naturally present as discrete excitations, and there exists a clear route to studying quantum effects by introducing off-diagonal terms, e.g. via a transverse field.

Ground states of the model fulfill a constraint, $M_h = 0 \ \forall h$, illustrated in Fig. 1 (a). We show that defects, i.e. hexagons with $M_h = \pm 1$, are (type-I) fractons, appearing at the corners of membranes of spin flips as illustrated in Fig. 1 (b). Because of the three- fold rotational symmetry of the honeycomb lattice, these membranes can be *locally* combined such that no excitations are created, giving rise to a set of ground states described as a liquid of membranes.

In order to simulate the model's properties, we devise – to our knowledge, the first – purpose-built cluster algorithm for Monte Carlo simulations of fractons. Simulating the model, we find that it exhibits a first order phase transition at low temperatures, but that the low temperature state nevertheless lacks signs of conventional order. Instead, the structure factor [Fig. 1 (c)] shows no sharp features pointing towards conventional magnetic order but instead has sharp, four-fold pinch points at the corners of the Brillouin zone.

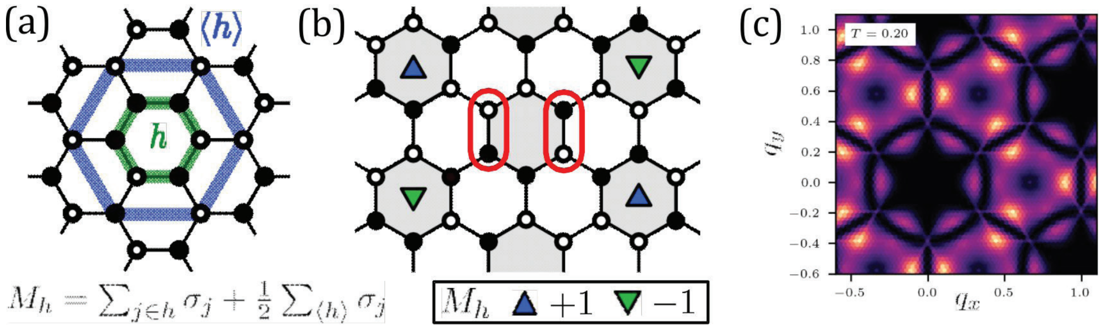

Figure 1: Ground states of the model fulfill the constraint, M_h = 0, illustrated in (a). Flipping a membrane of spins, as indicated in red in (b) creates fractons at the four corners of the membrane. Panel (c) shows the structure factor at low temperature, which matches predictions for a higher-rank Coulomb phase.

Reference: Benedikt Placke, Owen Benton and Roderich Moessner; *arXiv:2306.13151*

Tensor gauge theory and fractons in a classical spin liquid on the square lattice

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Classical spin liquids are non-trivially correlated magnetically disordered spin phasesthat arise in systems with extensive classical ground state degeneracies. A prime example is the pyrochlore Ising model with its characteristic dipolar spin correlations and pinch point singularities in the spin structure factor both resulting from an emergent gauge structure reminiscent of electrodynamics. Recently, classical spin liquids have attracted renewed attention as higher-rank generalizations of the pyrochlore Ising model have been constructed where the gauge structure is of tensor type. As a remarkable consequence, excitations in these systems can be fractonic, i.e., with a restricted mobility in real space. Here, we discuss a simple spin model on a two-dimensional square lattice that realizes a classical spin liquid with such an emergent tensor gauge structure as manifested by higher-fold pinch points in the spin structure factor. In the Ising version of this model the non-trivial spin correlations and fracton excitations can be easily visualized using a string state construction. The emergent gauge structure of the Ising model is further confirmed by numerical sampling of ground state spin configurations. Finally, the simple construction of our model also allows us to investigate the fate of the classical gauge structure when quantum fluctuations are added perturbatively, which induces tunneling between the classical ground states.

DIPOLAR-OCTUPOLAR SPIN ICE

Chair: B. Gaulin

Impact of disorder on the magnetic properties of Nd-based pyrochlore magnets

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Nd-based pyrochlore oxide compounds are of peculiar interest due to the dipole- octupole character of the magnetic moment of the Nd^{3+} ion. In particular, $Nd_2Zr_2O_7$ was shown to stabilize exotic phases in which the magnetic moment has both dipolar and octupolar characters, and which result from the competition between ferromagnetic and antiferromagnetic interactions. When decreasing temperature, $Nd_2Zr_2O_7$ enters into an unconventional Coulomb phase below about 1 K, and eventually stabilizes a so-called "all in - all out" ordering below about 300 mK, which encompasses fragmented excitations [1,2,3,4,5]. A rich field induced phase diagram has also been highlighted [6,7,8].

In this talk I will focus on the impact of introducing disorder on these physics. Two types of disorder have been considered: i) non-magnetic substitution on the magnetic site, which results in a dilution on the Nd pyrochlore lattice, ii) substitution on the non-magnetic site, which is expected to affect the superexchange paths and the crystal electric field of the Nd^{3+} ion [8]. We show that, even in the presence of strong substitution rates (up to 20 %), the magnetic state, and the associated excitations are pretty robust. Nevertheless, the octupolar character of the correlated state is weakened as disorder increases, which results in larger ordering temperature and ordered dipolar moment. These results will be discussed in relation to the magnetic properties of other Nd-based pyrochlore compounds.

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Strong light-matter interaction and hidden octupolarmoments in cerium-based quantum spin ices

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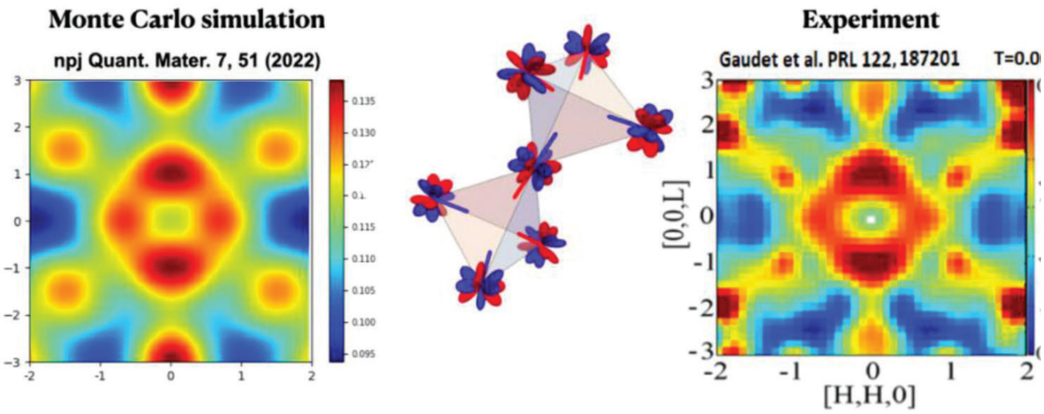
The search for quantum spin liquids (QSL) – topological magnets with fractionalized excitations – has been a central theme in condensed matter and materials physics. While theories are no longer in short supply, tracking down materials realizing a QSL has turned out to be remarkably tricky. Pyrochlore systems have proven particularly promising, with quantum spin ice a theoretically well-established example described by an emergent quantum electrodynamics, with excitations behaving like photon and matter quasiparticles. In this talk, I shall first review our theoretical efforts [1-3] in determining the model parameters in the three recently discovered cerium-based sister compounds: $Ce_2Zr_2O_7$, $Ce_2Sn_2O_7$ and $Ce_2Hf_2O_7$, through a combination of finite temperature Lanczos, Monte Carlo and analytical spin dynamics calculations. Intriguingly, the octupolar nature of the cerium magnetic moments hides some otherwise characteristic signatures from neutrons and resolves the puzzles in the response to the external magnetic field [3,4].

The second part of the talk will focus on the combined experimental and theoretical evidence of strong interaction between the fractionalized excitations (spinons) and the emergent gauge field in $Ce_2Sn_2O_7$. Recent neutron backscattering measurements, with extremely high energy resolution, offer an unprecedented glimpse into the spectrum of the spinons [5]. The theoretical analysis corroborates the evidence of strong interaction between these particles and the emergent "photons" in the theory that mimics the quantum electrodynamics, but with the energy scales that are 11 orders of magnitude lower [5].



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Dipolar-octupolar correlations and hierarchy of exchange interactions in $Ce_2Hf_2O_7$

Victor Porée[1], Anish Bhardwaj[2,3,4], Elsa Lhotel[5], Sylvain Petit[6], Nicolas Gauthier[7], Han Yan[8,9], Jeffrey A. Quilliam[7], Andriy H. Nevidomskyy[8], Hitesh J. Changlani[2,3], Romain Sibille[1,*]

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Pyrochlore materials stabilizing a 'dipole-octupole' doublet are of interest as candidates for quantum spin ice (QSI) phases [1]. Among cerium pyrochlores, $Ce_2Sn_2O_7$ was first reported as hosting a mysterious low-temperature correlated phase using bulk properties [2], based on which it was also identified as supporting a 'dipole-octupole' doublet [3]. A rise of magnetic entropy and a decrease of effective magnetic dipole moment were observed below about 1 K, while muon spin relaxation data excluded long-range magnetic order down to 0.02 K [2]. Later results evidenced the progressive growth of a signal below 1 K in thermal neutron scattering using powder samples, indicating the strengthening of the octupolar moment in the correlated phase [4], explained by a dominant octupolar coupling leading to an octupolar QSI. The associated continuum of spinon excitations was measured in detail [4-5]. Investigations of $Ce_2Zr_2O_7$ also concluded to an octupolar QSI [6-8].

In this work, we investigate the correlated state of the cerium pyrochlore $Ce_2Hf_2O_7$ [9]. Using neutron scattering we find signatures of both dipolar and octupolar correlations, showing that the manifold of ice states has a hybrid character [10]. A distinct dipolar inelastic signal is also observed, as expected for spinons in an octupolar QSI. Fits of thermodynamic data using exact diagonalization methods indicate that the largest interaction is an octupolar exchange, with a strength roughly twice as large as other terms. This hierarchy of exchange interactions – far from a perturbative regime but still in the octupolar QSI phase – rationalises our observations in neutron scattering.

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Parton construction for Dipolar-Octupolar spin liquids in pyrochlore

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We study the uniform U(1) quantum spin liquid (QSL) with low-energy fermionic quasiparticles for pyrochlore magnets with dipolar-octupolar symmetry, employing a fermionic parton mean field theory approach. Self-consistent calculations stabilize an uniform U(1) QSL with both gapped and gapless parton excitations. We analyse parton mean field solutions both with and without time-reversal symmetry. In the stable U(1) QSL ground state we charecterise low-temperature specific heat behaviour that could be unique signature of these fermionic U(1) QSL phases. Thus, this provides a possible way to understand the metallic specific heat response in Nd_2ScNbO_7.

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SPIN DYNAMICS

Chair: P. Holdsworth

Moving on fractals: transport properties in spin ice

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The dynamical properties of spin ice have long puzzled the frustrated magnetism community. Spin ice hosts emergent magnetic monopole excitations, and in a previous publication [1] we demonstrated that these monopoles are constrained to move on emergent dynamical fractals. This discovery explained the anomalous magnetic noise and rapidly diverging relaxation time scales observed experimentally in the spin ice material $Dy_2Ti_2O_7$ in thermodynamic equilibrium.

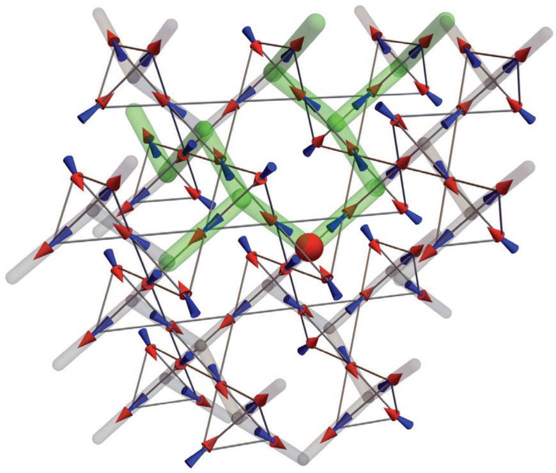

Figure 1: Illustration of a monopole in spin ice. Under the new model of monopole dynamics [1], the monopole can only move along the bonds marked in green, which form a fractal structure.

In this work we analyse the effects of the emergent dynamical fractal on the motion of magnetic monopoles driven out of thermodynamic equilibrium. Importantly, we identify several signatures that should be observable under achievable experimental conditions. It is our hope that this work will inspire experimental studies on $Dy_2Ti_2O_7$ and related compounds, to unearth further exotic behaviour and to consolidate our understanding of the dynamics of these exciting topological materials.

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Dynamics of antiferromagnetic spin ice in spinels

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In the breathing pyrochlore spinel $LiGa_{0.95}In_{0.05}Cr_4O_8$, chemical disorder stabilises a spin-nematic state with spin-ice correlations, albeit with up/down rather than in/out spins. In this talk, I will theoretically explore the dynamics of this antiferromagnetic spin-ice phase [1]. Semiclassical dynamical simulations successfully recover the key features of inelastic neutron-scattering measurements [2]: a broad finite-energy peak alongside a continuum of scattering near the (200) wave vector that extends from the elastic line to high energies. To interpret this result, we develop a small-fluctuation theory for the spin-ice-like nematic ground states, analogous to linear spin-wave theory for conventionally ordered magnets, which reproduces the numerical simulation results quantitatively. In particular, the inelastic peak is well explained by collective modes confined to *ferromagnetic* loops of the underlying nematic order. In addition, we find a sharp, linearly dispersing mode in the dynamical structure factor, which originates in long-wavelength fluctuations of the nematic director: Identifying this mode will be an interesting target for future experiments on these materials. I will also comment on the long-time relaxation dynamics of the nematic order, which is driven by activated fluctuations of the spin-ice degrees of freedom over a very broad distribution of time scales.

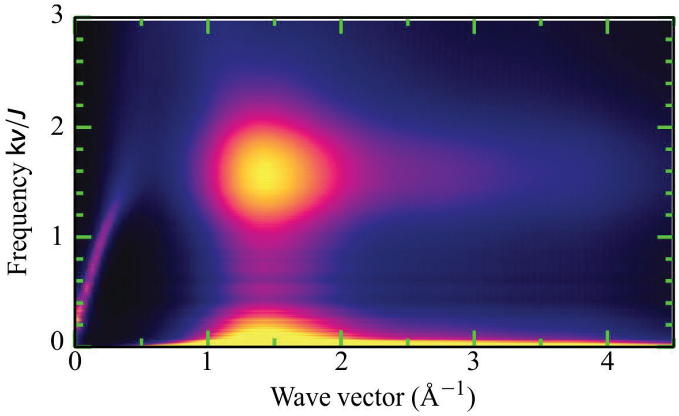

Figure 1: Simulated inelastic neutron-scattering pattern for the nematic spin-ice phase.

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Investigation of monopole dynamics in classical spin iceusing the fluctuation-dissipation relation

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Understanding monopole dynamics in spin ice is a central challenge of frustrated magnetism. While the equilibrium regime was recently proposed to be described by fractal dynamics [1], the low temperature out-of-equilibrium regime properties remain poorly understood due to the difficulty of experimental and theoretical investigations.

Here we address these physics experimentally in both the equilibrium and out-of- equilibrium regimes (typically below 0.6 K) of spin ice. To this end, we have developed a unique experimental set-up, which measures in the same environment magnetization fluctuations (as low as 10^{-15} T) and AC susceptibility in small applied magnetic fields (typically 50 μOe). With those two physical quantities we can directly probe the nature of the out-of-equilibrium regime through the fluctuation-dissipation relation:

$$\bar{M}^2(\omega) = \frac{2k_B T}{\pi V}\frac{\chi''(\omega)}{\omega}$$

It also allows us to experimentally determine the absolute value of the magnetic noise in spin ice, which was not done up to date.

We present measurements performed in the two classical spin ice compounds, $Dy_2Ti_2O_7$ and $Ho_2Ti_2O_7$, in the 5 mHz-10^5 Hz frequency range and from 200 mK to 4.2 K. We show that in both systems the fluctuation-dissipation relation is obeyed down to about 400 mK, in spite of the out-of-equilibrium regime reported from magnetization measurements below about 600 mK. Below 300 mK, dynamics can be described by the fluctuation-dissipation relation by considering an effective temperature instead of the sample temperature, in the same way as in spin glass compounds [2]. This renormalization confirms that the system is indeed in an out-of-equilibrium state and provides a new parameter to quantitatively understand the monopole dynamics in this highly diverging relaxation time range.

In addition, these measurements give access to the relaxation times and their distribution in the two compounds in the whole measured temperature range. Specifically, in the equilibrium temperature range in which the fluctuation-dissipation relation is obeyed, we observe the double relaxation time behavior reported in Ref. [3] both in the AC susceptibility and the noise spectra of $Ho_2Ti_2O_7$.

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Multipolar interactions and spin dynamics in $Tb_2Ti_2O_7$

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Despite the large number of studies carried out over the last 2 decades on rare earth pyrochlore materials [1-8], the physics of terbium-based compounds, notably $Tb_2Ti_2O_7$, remains puzzling. This particular material shows no long-range order down to sub-kelvin temperature, yet exhibits static and dynamic magnetic correlations that still defy our understanding. We present here an in-depth study that sheds new light on this issue. In the first step, we have studied the low energy sector by inelastic neutron scattering, revealing the dispersion of a magnetic mode (0.1-0.3 meV) and completing the results reported in [9]. Our study is supported by RPA calculations of the S(Q,E) scattering function, taking into account quadrupole-quadrupole interactions among the elements of the ground CEF doublet [9,10,11]. We could reproduce the dispersion of this mode and concluded that $Tb_2Ti_2O_7$ is close to the boundary between a quantum spin ice and a quadrupolar ordered phase. In a second step, we also considered the dispersion of the first excited crystal field doublet, located at about $\Delta = 1.5$ meV above the ground doublet. RPA simulations, based on an anisotropic bilinear exchange Hamiltonian [11] yield spectra directly comparable with the data [9], enabling us to determine a set of magnetic exchange parameters. These results demonstrate the key role of both quadrupolar and dipolar interactions, which are undoubtedly at the heart of the unexplained properties of $Tb_2Ti_2O_7$.

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DIMERIZED MAGNETS

Chair: N. Trivedi

Tensor network studies of the Shastry-Sutherland and anisotropic triangular-lattice Heisenberg models

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The frustrated quantum antiferromagnet $SrCu_2(BO_3)_2$ constitutes a realization of the paradigmatic Shastry-Sutherland model. It exhibits a very rich phase diagram as a function of pressure and magnetic field, including an intriguing sequence of magnetization plateaus, several supersolid phases, a finite-temperature critical point, and more. In this talk I will discuss recent progress in the numerical study of this model using infinite projected entangled-pair states (iPEPS), a tensor network ansatz to represent states in the 2D thermodynamic limit, and show how it helped to shed new light on the fascinating properties of $SrCu_2(BO_3)_2$. In the second part I will discuss how iPEPS can be used to efficiently study the incommensurate phase at arbitrary wave vector in the anisotropic triangular lattice Heisenberg model. A systematic scaling analysis provides evidence of a quantum spin liquid phase situated between the antiferromagnetic and incommensurate phases, in agreement with previous variational Monte Carlo results.

Field-induced bound-state condensation and spin-nematic phase in $SrCu_2(BO_3)_2$

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Using inelastic neutron scattering (INS) up to 26 T and Matrix Product States (MPS) simulations on cylinders, we show that the magnetic-field-induced gap clos- ing in the Shastry-Sutherland compound $SrCu_2(BO_3)_2$ is due to the condensation of a spin-2 bound state [1], and not to that of a triplet, as in standard dimer-based anti- ferromagnets. The most direct indication of this anomalous behaviour can be seen in the field dependence of the main triplet band. The lowest branch does not cross the ground state but has a kink beyond which it acquires a slope equal to the Zeeman energy $g\mu_B H$, while the other two branches have slopes equal to $2g\mu_B H$ and $3g\mu_B H$ respectively (see Fig. 1). This should be contrasted to the case of triplet condensation, where the lowest branch becomes flat at zero energy while the other two have slopes $g\mu_B H$ and $2g\mu_B H$ respectively. The bound state that condenses can be thought of as a Cooper pair of triplets, and the persistence of a gap in the triplet spectrum is the equivalent of the quasiparticle gap in superconductors. Further consequences, including the presence of two- and three-triplon bound states in the spectrum, are discussed.

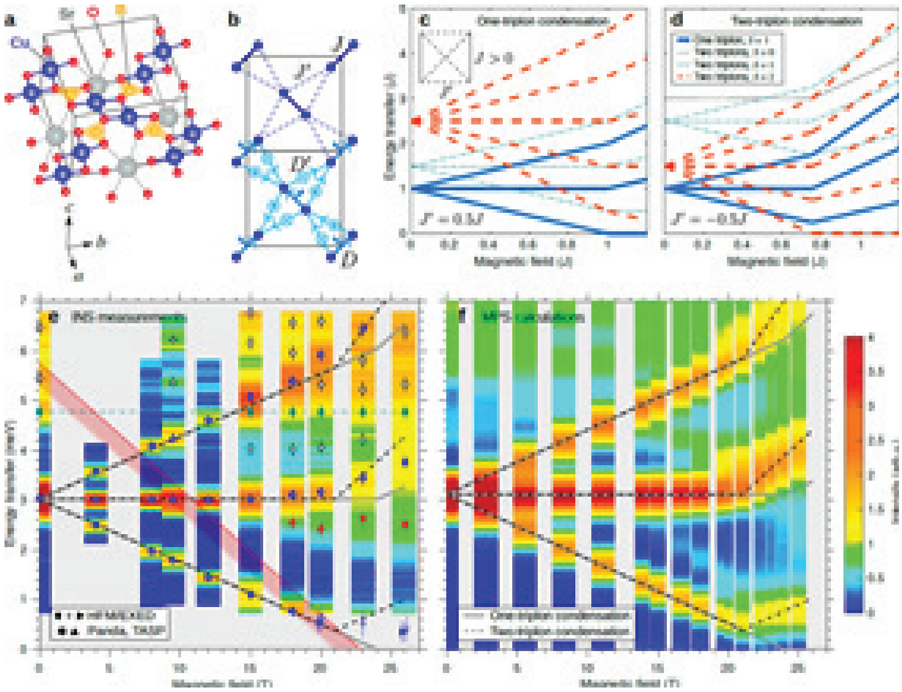

Figure 1: Structure and INS in a field (sketch, experiments and MPS) of $SrCu_2(BO_3)_2$.

References: Ellen Fogh et al, arXiv:2306.07389.

Topologically nontrivial triplet bands

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We explore topologically nontrivial band structures formed by triplet excitations of disordered spin-gap quantum magnets. In particular, we consider the monoclinic dimer systems, $KCuCl_3$ and $TlCuCl_3$ 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 $KCuCl_3$ were based on fully symmetric Heisenberg models [3], here we extend this picture and compare our results with existing experiments.

We propose that depending on the strength of the magnetic anisotropies and the direction of an external magnetic field, the 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.

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Tuning quantum geometry of topological triplon bands inthe generalized Shastry-Sutherland model

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A persistent challenge in experimentally realizing topological magnonic states is the mismatch between the positions of the Berry curvature maxima and the magnon density distribution in the magnetic Brillouin zone (MBZ). Being bosonic, low energy magnons are concentrated near the bottom of the magnon bands. On the other hand, the Berry curvature is typically concentrated near the MBZ edges, far from the band minimum. As a result the topological character of the low energy magnonic states are suppressed, making experimental signatures of topological magnons, such as the magnon Hall effect, elusive. Overcoming this bottleneck is an active area of research in contemporary quantum magnetism. In a recent work, we have shown that the quantum geometry of the topological triplon bands in the generalized Shastry-Sutherland model can be tuned by applying a transverse magnetic field. The Rashba pseudospin-orbit coupling induced by the tilted external magnetic field leads to elementary excitations having nontrivial topological properties with π-Berry flux. The interplay between the in-plane and out-of-plane magnetic field thus allows us to effectively engineer the band structure in this bosonic system. In particular, the in-plane magnetic field gives rise to a Berry curvature hotspot near the bottom of the triplon band and at the same time significantly increases the critical magnetic field for the topological triplon band. We calculate explicitly the experimental signature of the thermal Hall effect (THE) of triplonsin $SrCu_2(BO_3)_2$ and show pronounced and tunable transport signals within the accessible parameter range, particularly with a change of sign of the thermal Hall conductance. Thetilted magnetic field is also useful in reducing the bandwidth of the lowest triplon band. We show it can thus be a flexible theoretical and experimental platform for the correlatedbosonic topological system.

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TRIANGULAR MAGNETS

Chair: B. Lake

Quantum Electrodynamics as the Organizing Principle of Triangular Antiferromagnets

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Quantum electrodynamics in 2+1 dimensions (QED3) has been proposed as a criti- cal field theory describing the low-energy effective theory of a putative algebraic Diracspin liquid or of quantum phase transitions in two-dimensional frustrated magnets. Weprovide compelling evidence that the intricate spectrum of excitations of the elementary but strongly frustrated J1-J2 Heisenberg model on the triangular lattice is in one-to-onecorrespondence to a zoo of excitations from QED3, in the quantum spin liquid regime.This includes a large manifold of explicitly constructed monopole and bilinear excitations of QED3. Moreover, we observe signatures of an emergent valence bond solid (VBS), which suggests a scenario where only the critical point of a transition from the120-degree Néel order to a VBS is described by QED3.

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Rare-earth heptatantalates: A novel platform for quantum spin liquids

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Quantum spin liquid (QSL) states that are highly quantum entangled, yet they pre- serve lattice symmetries, have been experimentally observed in a variety of geometri- cally frustrated materials, including realizations of the two-dimensional triangular lat- tice. On this lattice, the simplest isotropic Heisenberg exchange leads to magnetic or- dering, therefore, deviations away from this model are needed to stabilize a QSL state. The majority of triangular-lattice QSL candidate materials are hampered by structural disorder, which can also induce QSL-like properties.

We have recently discovered a QSL ground state in a novel triangular-lattice antiferromagnet neodymium heptatantalate, $NdTa_7O_{19}$, with perfect triangular symmetry and no detectable structural disorder [1]. In-depth experimental studies including neutron scattering and muon spin relaxation detected no magnetic ordering even at temperatures of only a few tens of millikelvins, much below the exchange-interaction scale of this compound. Furthermore, sizable Ising-like spin correlations between the nearest neighbors on the triangular lattice and persistent spin dynamics were detected in the effective spin-1/2 ground-state Kramers doublet. This behavior was attributed to large magnetic anisotropy, typical for rare earths (RE).

Recently, progress has been made also in theoretical understanding of this intrigu- ing magnetic ground state of neodymium heptatantalate, which critically depends on strong anisotropy of the exchange interaction on the triangular lattice [2]. Moreover, as the magnetic anisotropy is RE specific, the large family of rare-earth heptatantalates, $RETa_7O_{19}$ [3], provides a new generic framework for QSLs and other quantum disor- dered phases. Indeed, our investigations show that, in this context, the erbium based compound $ErTa_7O_{19}$ is a new promising member of this family.

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Double magnetic transitions and exotic field-induced quantum phase in the triangular lattice antiferromagnets $Sr_3Co(Nb,Ta)_2O_9$

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Geometrically frustrated magnets are a special class of compounds where mag- netic frustration impedes magnetic long-range-order, leading to an abundance of novel states of matter, including quantum spin-liquid [1,2]. Herein, we report the magnetic properties of two frustrated triangular lattice antiferromagnets $Sr_3Co(Nb,Ta)_2O_9$ with an effective $j_{\rm eff} = 1/2$ of Co^{2+} [3]. Both the compounds feature two-step magnetic transitions at low temperatures [($T_{\rm N1} \simeq 1.47$ K and $T_{\rm N2} \simeq 1.22$ K) and ($T_{\rm N1} \simeq 0.88$ K and $T_{\rm N2} \simeq 0.67$ K), respectively], driven by a weak easy-axis anisotropy. Under mag- netic field $Sr_3CoNb_2O_9$ evinces a plateau at 1/3 magnetization. Interestingly, the high field magnetization of $Sr_3CoTa_2O_9$ reveals an exotic regime (between $H_{\rm S1}$ and $H_{\rm S2}$), below the fully polarized state in which the heat capacity at low temperatures is governed by a power law ($C_{\rm p} \propto T^{\alpha}$) but with a reduced exponent $\alpha \simeq 2$. These results demonstrate an unusual field induced quantum state with gapless excitation in the strongly frustrated magnet $Sr_3CoTa_2O_9$. The leading in-plane antiferromagnetic exchange coupling is estimated to be $J/k_{\rm B} \simeq 4.7$ K and 5.8 K for the Nb and Ta compounds, respectively. The complete $T-H$ phase diagram is discussed for both the compounds.

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DISORDER IN MAGNETS

Chair: E. Andrade

Randomness vs. frustration in spin-1/2 triangular antiferromagnets

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Triangular antiferromagnets are one of the best playgrounds for an experimental realization of the quantum spin-liquid state. In this talk, I will summarize our work on the triangular spin-1/2 materials and highlight an intricate interplay between the effects of randomness and frustration. I will argue that structural randomness occurs in many of the recently studied candidates, from $YbMgGaO_4$ [1] to $Na_2BaCo(PO_4)_2$. I will further introduce the family of $AYbX_2$ compounds (A = Na, K; X = O, S) as the best disorder-free triangular candidates [2,3]. Current experimental evidence for their spin-liquid behavior will be summarized, and effects of the interlayer frustration will be considered.

This work is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – TRR 360 – 492547816.

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Thermal expansion and magnetostriction as the probe ofexotic magnetism in Griffths-McCoy singularities in Quantum Spin Glasses

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In the paramagnetic ground-state phase of a random quantum spin system, the presence of quenched disorder leads to Griffiths-McCoy singularities, which progressively become stronger as the ordered phase is approached. At zero temperature, the local spin susceptibility distribution develops long tails arising from rare regions in the disorder configuration and ultimately causes the spin-glass susceptibility to diverge while the equal time spin-spin correlation length is still finite. We discuss the interplay of Griffiths-McCoy singularities and quantum critical phenomena in transverse-field Isingspin glasses based on series expansions around the high transverse-field limit in arbitrary spatial dimensions [1,2] and the exact diagonalization study of small clusters [3].Implications for experiments will be discussed.

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Quantum spin-glass criticality in disordered frustrated dimer magnets

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We study the effect of quenched disorder on non-collinear magnetism in frustrated quantum magnets near quantum criticality. Specifically, we consider a triangular-lattice bilayer Heisenberg model with bond disorder. The clean system has two phases: a dimer quantum paramagnet and a 120° Neel phase, separated by a quantum critical point. Intralayer bond disorder destroys the 120° Neel phase via dipolar textures and results in spin-glass order, such that the system features a quantum phase transition between spin-glass and dimer paramagnetic phases. We study the vicinity of this transition using variant of bond-operator theory and calculate static observables as well as excitation spectra. Bond disorder leads to strong inhomogeneities near the transition and induces real-space localization of excitation modes. In particular, the spin-glass order parameter displays strong quantum fluctuations, indicating the proximity to a spin-liquid-like phase.

Stripe order, impurities, and symmetry breaking in a dilutedfrustrated magnet

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We investigate the behavior of the frustrated J_1-J_2 Ising model on a square lattice under the influence of random dilution and spatial anisotropies. Spinless impurities generate a random-field type disorder for the spin-density wave (stripe) order parameter. These random fields destroy the long-range stripe order in the case of spatially isotropic interactions. Combining symmetry arguments, percolation theory and large-scale Monte Carlo simulations, we demonstrate that arbitrarily weak spatial interactionanisotropies restore the stripe phase. More specifically, the transition temperature T_c into the stripe phase depends on the interaction anisotropy ΔJ via $T_c \sim 1/|\text{In}(\Delta J)|$ for small ΔJ. This logarithmic dependence implies that very weak anisotropies are sufficient to restore the transition temperature to values comparable to that of the undi- luted system. We analyze the critical behavior of the emerging transition and find it to belong to the disordered two-dimensional Ising universality class, which features the clean Ising critical exponents and universal logarithmic corrections. We also discuss the generality of our results and their consequences for experiments.

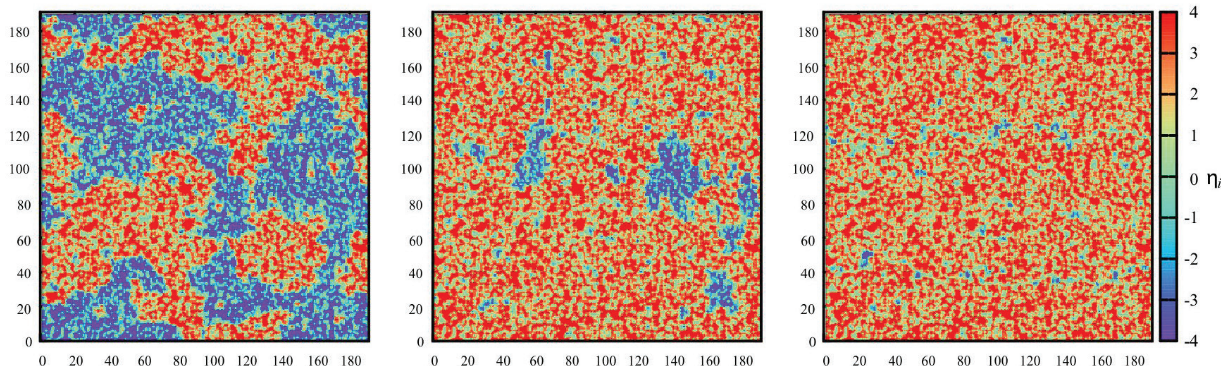

Figure 1: Snapshots of the local nematic order parameter for several anisotropies.

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SYMMETRY & FRACTIONALIZATION

Chair: N. Perkins

Ground states of triangular lattice SU(4) antiferromagnets

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We study SU(4) quantum antiferromagnets on the triangular lattice, that arise from Mott-insulating phases of fermions with four flavors. We consider different fillings ofthe SU(4) fermions, which lead to different representations of SU(4) on each site.

The case of a single fermion per site, corresponding to the fundamental represen- tation of SU(4), has been examined in a number of previous works, however no clear consensus as to the nature of the ground state in the thermodynamic limit has been reached. We report a complementary analysis of the model using variational Monte Carlo (VMC) [1]. Our findings are consistent with previous numerical studies on nar-row circumference cylinders [2] but uncover a novel candidate for the ground state ofthe system in the 2D limit. This state combines breaking of SU(4) flavor symmetry down to SU(3)×U(1) along with bond trimerization (see Fig. 1).

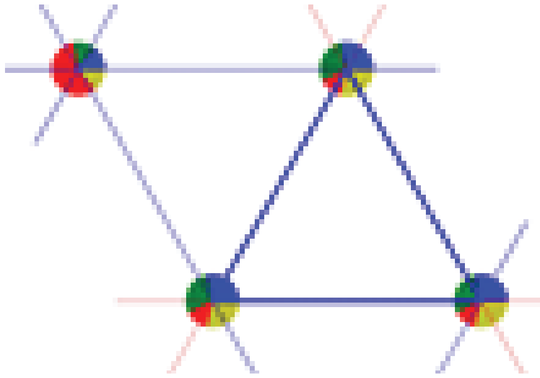

Figure 1: Spontaneous SU(4) symmetry breaking and trimerization in the Heisenbergmodel for spins in the fundamental representation on each site.

We illuminate our findings by considering a mapping to an effective model of SU(4) spins on the honeycomb lattice with a fundamental - anti-fundamental representation on the two sublattices. We show that a phase transition between the SU(4)-symmetricand SU(4)-broken states on the triangular lattice maps to a phase transition between dimerization and flavor-anti flavor Néel ordering on the honeycomb lattice.

In the case of two fermions per site, which corresponds to the self-conjugate representation of SU(4), we study the bilinear-biquadratic antiferromagnetic model [3]. Considering an effective dimer model following [4], we argue that by tuning the strength of the biquadratic coupling the system can be brought to close vicinity of the RVB spin liquid phase.

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Deconfined pseudo criticality in a spin-1 quantum antiferromagnetic model on the square lattice

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Berry phase interference arguments that underlie the theory of deconfined criticality for $S = 1/2$ antiferromagnets have also been invoked to allow for possible deconfined transitions in $S = 1$ magnets, e.g. the proposal of a spin-nematic to a valence bond solid by Grover and Senthil [1]. Similar arguments have been put forth to describea Néel to Haldane-nematic as well as a Néel to columnar-VBS transition by Wang, Kivelson and Lee [2]. We searched for this latter transition in a designer model setting by exploiting the SU (3)-symmetry of the biquadratic interactions between $S = 1$ degrees of freedom. In a square lattice $S = 1$ model consisting of Heisenberg (J_H) and biquadratic exchanges(J_B) that favour a Néel phase and a designer Q-term (J_Q) interaction which favours a columnar-VBS, we study this transition using large-scale quantum Monte Carlo simulations. For $J_H = 0$, this model has an enhanced SU (3) symmetry and is equivalent to the SU (3) J-Q model in the fundamental representation with a Néel-VBS transition that has been argued to be deconfined critical through QMC simulations [3,4]. Upon turning on J_H which brings the symmetry down to SU (2), we find multiple signatures – a single critical point between Neel and VBS phase,high quality collapse of correlation ratios and order parameters, lack of double-peakedhistograms near the critical point for largest sizes studied – that are very suggestive ofa continuous transition scenario. However, Binder analysis shows that these otherwise continuous looking transitions are rather weakly first-order or pseudocritical. We findthe same to be the case for the SU(3)-transition itself when $J_H = 0$.

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Berry phase in the rigid rotor: the topology of odd-polygon antiferromagnets

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The rigid rotor is a classic problem in quantum mechanics, describing the dynamics of a rigid body with centre-of-mass held fixed. Solved by Casimir in 1931, it describes the rotational spectra of molecules. We show that this problem admits a new class of solutions when a Berry phase is introduced. These solutions are realized in the low- energy spectra of Heisenberg antiferromagnets defined on odd-polygons.

The configuration space of the rigid rotor is $SO(3)$, the space of all rotations in three dimensions. This is a topological space that allows for two types of closed loops: trivial loops that can be adiabatically shrunk to a point and non-trivial loops that cannot. With time-reversal-symmetry, the *only* way to introduce a Berry phase is to attach a π- phase to all non-trivial loops. We find the corresponding stationary states and spectra. This problem appears in the effective low-energy theory for odd-polygon antiferromagnets. The set of classical ground states has a precise mapping to $SO(3)$. Consequently, the path-integral action is the same as that of a rigid rotor. Crucially, a π-Berry phase accrues over any 2π rotation of the spins. We demonstrate the equivalence between the magnet and the π-rotor by exact diagonalization.

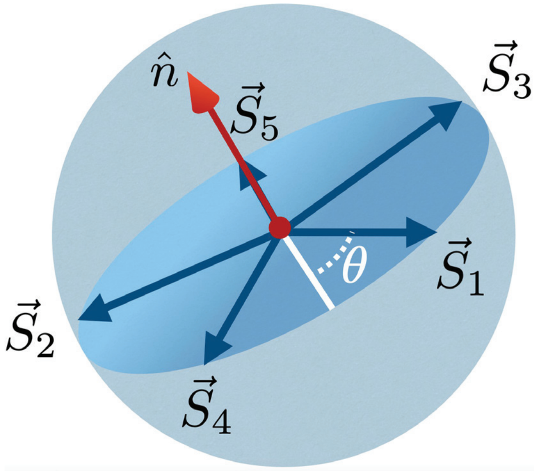

Figure 1: Classical ground states of a pentagon antiferromagnet are related by *SO*(3) rotations.

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Study of spin-1/2 antiferromagnetic kagome Heisenbergmodel by symmetric projected entangled simplex states

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We utilize symmetric projected entangled simplex states (PESS) to classify possible Z_2 spin liquid phases based on the short-range physics associated with the fractional- ization of both the on-site and space-group symmetries. We numerically obtain the optimal Z_2 ground state of the nearest-neighbor spin-1/2 antiferromagnetic Heisenberg model on the kagome lattice. Using variational simple update and the corner trans- fer matrix renormalization group, we show the four RVB states converge to different energy levels and the 0-flux(I) state has the lowest energy. The excitation spectrum, however, indicates softening of the fermionic excitation, which suggests a possible transition to a closeby Dirac spin liquid.

SYNTHETIC PLATFORMS

Chair: O. Benton

Frustrated quantum magnetism in Rydberg atom arrays

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Frustrated quantum magnets have long been happy hunting grounds for strongly correlated many-body physics. Today, interacting arrays of Rydberg atoms have emerged as versatile platforms for exploring exotic many-body phases and their dynamics and provide a new route to realize models of Ising quantum magnets. Motivated by recent experimental advances, we show that the combination of Rydberg interactions and appropriate lattice geometries naturally leads to emergent Z_2 gauge theories endowed with matter fields. Based on this mapping, we demonstrate how Rydberg platforms can be used to realize elusive topological spin liquid states with anyonic excitations that have been proposed as ground states of various frustrated spin-1/2 magnets. We characterize this state in terms of its fractionalized spinon and vison excitations and discuss their relevance to experimental verifications of topological properties. Furthermore, we also highlight the emergence of new spin liquid states with more complex gauge groups, such as U(1)xU(1), as well as higher spin models, and discuss their realization in present-day neutral atom platforms.

Quantum Monte Carlo simulations in the restricted Hilbert space of Rydberg atom arrays

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Rydberg atom arrays have emerged as a powerful platform to simulate frustrated systems, and realize potential spin liquid states. To verify the same numerically, we develop a versatile quantum Monte Carlo sampling technique which operates in the reduced Hilbert space generated by enforcing the constraint of a Rydberg blockade. We use the framework of stochastic series expansion and show that in the restricted space, the configuration space of operator strings can be understood as a hard rod gas in $d + 1$ dimensions. We use this mapping to develop cluster algorithms which can be visualized as various non-local movements of rods. Finally, we show that the algorithm can efficiently generate the phase diagram of a Rydberg atom array, to temperatures much smaller than all energy scales involved, on a Kagome link lattice. This is of broad interest as the presence of a $Z2$ spin liquid has been hypothesized recently [1].

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Emergent Qubits, Toric Code Model and Quantum Circuits

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We reduce a class of spin-1/2 models, including the toric code model, exactly into independent emergent qubits by constructing appropriate unitary transformations, and further reduce these transformations exactly into quantum circuits that can produce the toric code and other eigenstates on quantum processors [1]. We introduce the basic idea through a model on a trestle realizing exact quantum paramagnetic eigenstates with free multipolar moments, and then work it out for the toric code model on toroidal, cylindrical and planar geometries. Current experimental realizations of the toric code model are reported to be on planar geometries (except a recent one on torus), and in the ground state of a specific form. The quantum circuit we have devised can generate any toric code eigenstate with a freedom of superposition in every degenerate eigensubspace.

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Spin-Wave Dynamics in a Trident Artificial Spin Ice

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Artificial spin ices [1] are periodic arrangements of interacting nanomagnets which allow investigating emergent phenomena in the presence of geometric frustration. Recently, it has been shown that artificial spin ices can be used as building blocks for creating functional materials, such as magnonic crystals. A number of promising geometries have been proposed, beyond the square and kagome lattices. One of the interesting structures is a trident artificial spin ice [2] in which the unit cell is composed of interacting horizontal and vertical nanomagnets, which leads to tunable frustration and anisotropic magnetostatic interactions. While artificial spin ices built upon geometries display anisotropic interactions.

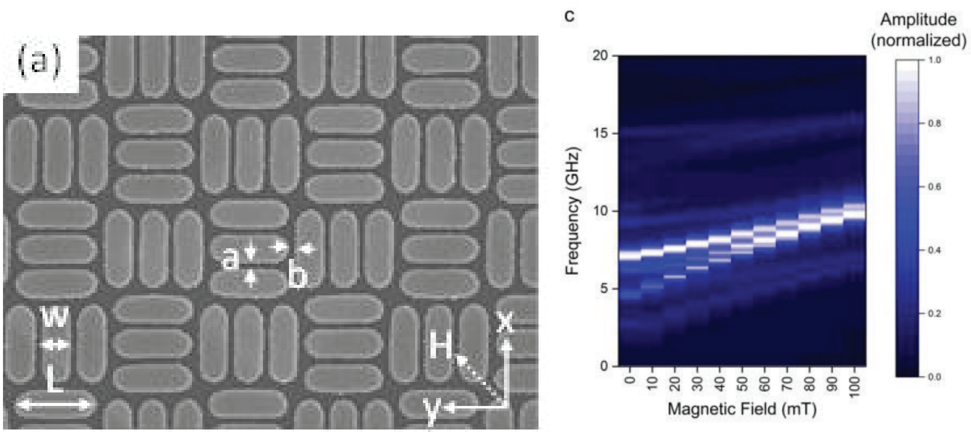

Fig. 1 (a) SEM images of the trident spin ice (b) The spin wave dispersion of the system

In this work, we investigate the magnetization dynamics in a system exhibiting anisotropic magnetostatic interactions owing to locally broken structural inversion symmetry as shown in Fig. 1(a) [3]. We find a rich spin-wave spectrum and investigate its evolution in an external magnetic field [See Fig. 1(b)]. We determine the evolution of individual modes, from building blocks up to larger arrays, highlighting the role of symmetry breaking in defining the mode profiles. Moreover, we demonstrate that the mode spectra exhibit signatures of long-range interactions in the system. These results contribute to the understanding of magnetization dynamics in spin ices beyond the kagome and square ice geometries and are relevant for the realization of reconfigurable magnonic crystals based on spin ices.

Acknowledgments

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ENTROPY EFFECTS

Chair: R.R.P. Singh

Order by disorder and phase transitions

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Although classical models may seem trivial compared to the quantum models with which we are familiar, they still hold many mysteries, as for example the well known spin ice models. We are interested in this talk to less degenerate models, where the order by disorder phenomena lifts the degeneracy at infinitesimal temperatures and leads to exotic symmetry breaking and emergent order parameters. Motivated by the physical properties of Vesignieite BaCu3V2O8(OH)2, we study the example of the J1-J3 Heisenberg model on the kagome lattice, with J3>>|J1|. The nature of the ground state and the possible phase transitions are investigated through analytical calculations and parallel tempering Monte Carlo simulations. Entropic effects favor collinear configurations and lead to an emergent q=4 Potts parameter and to a finite temperature phase transition. Effect of magnetic vacancies on the order and on the transition are discussed.

Order by disorder in classical kagomé antiferromagnets with chiral interactions

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The Heisenberg antiferromagnet on the kagomé lattice is an archetypal example ofhow large ground state degeneracies arise, and how they may get resolved by thermal and quantum fluctuations. Augmenting the Heisenberg model by chiral spin interactions has proved to be of particular interest in the discovery of chiral quantum spin liquids. I will focus on the classical variant of this chiral kagomé model, which exhibits, similar to the classical Heisenberg antiferromagnet, a remarkably large and structured ground-state manifold combining continuous and discrete degrees of freedom. This allows for a rich set of order-by-disorder phenomena. Degeneracy lifting by thermal and quantum fluctuations occurs in a highly selective way that, among other interestingeffects, provides a semiclassical route to an emergent Z_2 spin liquid.

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Adiabatic demagnetization refrigeration to milli-Kelvin temperatures with frustrated magnets

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Magnetic frustration triggers an entropy enhancement at low temperatures, due to the multitude of quasi-degenerate configurations. This enhances the magnetocaloric effect of geometrically frustrated magnets compared to that of non-frustrated magnets and ordinary paramagnets in the entire range between zero field and full polarization [1]. More recently itwas shown that the triangular magnet $KBaYb(BO_3)_2$ offers excellent adiabatic demagnetization refrigeration (ADR) performance compared to respective classical paramagnetic salts, i.e., a higher entropy density, lower end temperature and, most importantly, chemical stability, which allows heating and evacuation, as required for UHV applications [2]. A (slightly distorted) triangular magnetic lattice with similar magnetic entropy density is also realized in $NaYbP_2O_7$. ADR curves starting at 2 K in a field of 5 T, measured in the Quantum Design PPMS, indicate a similar base temperature (45 mK) but 30% longer warming time to 2 K (55 minutes) compared to $KBaYb(BO_3)_2$ [3]. The isostructural analogs with Gd spin 7/2 instead of Yb effective spin ½ moments have three times larger magnetic entropy. $KBaGd(BO_3)_2$ shows antiferromagnetic order at $T_N = 263$ mK, with a triangular-shaped peak in specific heat pointing to a distribution of exchange couplings arising from the randomness of K^+ and Ba^{2+} ions [4]. After ADR to 122 mK (under comparable conditions in our PPMS setup), it has a remarkably long warming time of 500 minutes, i.e. 12,5 times longer than its Yb sister compound [4]. In this contribution we also present the first results on the Gd-diphosphate $NaGdP_2O_7$. Despite a zero-field magnetic order at 560 mK, an ADR end temperature of 225 mK is reached. The warming time exceeds two days, i.e., a factor 50 longer compared to its Yb relative, indicating the excellent suitability of this material as precooler in a double-stage ADR setup.

Work supported by the German Science Foundation project 514162746 (GE 1640/11- 1) and the Alexander von Humboldt foundation. We acknowledge discussion and collaboration with A.A. Tsirlin, N. Oefele, F. Hirschberger, K.M. Ranjith, and D. D. Sarma.

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PYROCHLORE MAGNETS

Chair: E. Lhotel

Exploration of fragmentation in Ising pyrochlores with mean-field theory and pressure experiments

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Frustrated magnets are a fascinating class of both theoretical models and materials. They have been a fruitful playground to test the limits of standard paradigms in statistical physics, as well as identify exotic phase transitions. Some of the most striking examples are the holmium and dysprosium titanates, which were proven to be realizations of so-called spin ices. In these materials, Ising-like spins occupy sites of a pyrochlore lattice, pointing in or out of the tetrahedra forming the lattice. They interact ferromagnetically so in the lowest energy configuration the spins satisfy a two in / two out ice-rule. No magnetic order is found down to 50 mK [1], with correlations in the structure factor in the form of characteristic pinch-point patterns [2]. In addition, specific heat measurements show that there is an incomplete release of the entropy expected for Ising degrees of freedom [3]. This points towards a description of spin ices using an emergent field. It can be fragmented into two components following the Helmholtz decomposition: one providing the magnetic monopole charge and the other one a fluctuating background [4]. In titanates spin ices the ground state is empty of monopoles; but in holmium and dysprosium iridate pyrochlores, iridium atoms order antiferromagnetically at about 130 K and provide a staggered local field to the rare-earth spins, promoting a monopole crystal ground state. The physics of dipolar Ising pyrochlores can then be brought together in the form of a fragmentation phase diagram [5].

In this talk we propose to explore this phase diagram using a combination of theoretical and experimental techniques. First, we developed an extension of the mean field theory first presented in [6]. Using a mapping to a Blume-Capel model, we are able to write a mean-field free energy which includes the entropy of the fragmented phase, and reproduces the qualitative features of the phase diagram explored with simulations. We use this theory to compute observables like specific heat and the monopole concentration across phase transitions. We then present neutron diffraction and specific heat measurements under pressure on the $Ho_2Ir_2O_7$ and $Dy_2Ir_2O_7$ respectively. These experiments proved challenging to interpret, and in particular the AC technique used for the specific heat revealed the importance of the very slow magnetic excitations in spin ice like materials to ensure proper thermalization.

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Quantum fragmented states in pyrochlore oxides

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Since the 2000s, the discovery of spin ices in rare earth pyrochlore oxides has aroused greatinterest. This is indeed a new state of matter, lacking long-range magnetic order, but where the Ising spins, which occupy the vertices of the tetrahedra that form the pyrochlore structure, arrange themselves according to a local organization rule, which stipulates that each tetrahedron must have two incoming and two outgoing spins. This results in a macroscopically degenerate state, associated with a non-zero entropy at zero temperature. An elegant way to describe this state is to consider the Ising spins as the lines of an emerging field, along with a gauge charge defined as the sum of the four spins of a tetrahedron. In this "electrodynamic" description, the spin ice is then a state of zero divergence (or zero charge). More recently, the notion of fragmentation has been proposed, to describe new states where the charge is ordered, but where the spins remain disordered [1,2]. This is what happens, for example, in a moderate magnetic field applied along the [111] direction of spin ices, or in certain compounds as $Ho_2Ir_2O_7$ or $Dy_2Ir_2O_7$ [3,4]. In this presentation, using MC simulations, we shall describe the stability of those fragmented states when the transverse spin components are coupled by additional "quantum" terms. This approach allows describing quantum fragmented states. We observe in particular that such states occupy a large area of the phase diagram. More generally, we shall describe new varieties of fragmented states which appear due to these transverse couplings.

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Entropically-Driven Spin-Liquid to Spin-Liquid Thermal Crossover in a Pyrochlore Magnet

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One of the foremost goals in the study of pyrochlore magnetism is the search for spin liquid phases characterized by magnetic disorder but at the same time strong correlations. These phases are usually found in Hamiltonians possessing a highly degenerate classical ground state manifold preventing the onset of long-range order. However, a degeneracy does not guarantee the realization of a low-temperature spin liquid as the phenomenon known as order-by-disorder may collapse the system into a long-range ordered phase by entropically selecting favorable spin configurations. In this work, we present a spin model on the pyrochlore lattice with Heisenberg and Dzyaloshinskii- Moriya interactions that realizes a novel classical spin liquid at intermediate temperatures, collapsing into another spin liquid phase at low temperatures that is spin-ice-like. Based on a variety of analytical and numerical methods, we argue that the crossover between both phases has an entropic origin, providing the first realization of an order-by-disorder selected spin-liquid. We also investigate the impact of quantum fluctuations on these classical spin liquids and their relevance for non-Kramers pyrochlore materials.

Abundance of hard-hexagon crystals in the quantum pyrochlore antiferromagnet

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We present a novel proposal for potential ground states of the S = 1/2 and S = 1 Heisenberg antiferromagnet on the pyrochlore lattice. The ground-state candidates form a simple family that is exponentially numerous in the linear size of the system. They can be visualized as coverings of hard hexagons, with each hexagon representing a resonating valence-bond ring, breaking various lattice symmetries such as rotation, inversion, and translation. By evaluating a simple variational wavefunction based on a single hard-hexagon covering, we achieve a precise variational energy consistent with density matrix renormalization group predictions and a numerical linked cluster expansion technique carried out at zero temperature. The scenario of a hard-hexagon state is backed up by carefully examining excitations on top of the valence-bond crystal as it provides further evidence of its stability. Our findings have broader implications as they extend to other frustrated magnets, such as the two-dimensional ruby and checkerboard lattices. Our work offers a new perspective, where the frustration effectively decouples unfrustrated motifs – the hard hexagons – in quantum magnets.

*This work was partly supported by the Deutsche Forschungsgemeinschaft under grants SFB 1143 (project-id 247310070) and cluster of excellence ct.qmat (EXC 2147, project-id 390858490)

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METALLIC MAGNETS

Chair: J. Reuther

Magnetic and Optical Properties of Metallic Pyrochlore Iridate $Pr_2Ir_2O_7$

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Iridium pyrochlores ($A_2Ir_2O_7$, A = Y, rare-earth elements) are of current interest as they are predicted to give rise to many exotic topological phases [1-3]. Iridium exhibits large spin-orbital coupling (SOC) due to its heavy nature and relatively small (as compared to 3*d* transition metals) onsite electronic correlation (*U*). In iridates, SOC, *U*, and crystal field effect show a comparable strength. Setting a new balance between theserelevant energies can derive novel topological phases [1-3]. However, many proposed phases have not been observed yet; therefore, much more experimental efforts are required in this direction. In the pyrochlore lattice, the tetrahedral arrangement of A and Ir cations causes geometrical frustration which often leads to exotic magnetic states. Thephysical properties of pyrochlore iridates show an interesting evolution with A-site element: from magnetic insulating to complex metallic phases [4]. When the A^{3+} ion is magnetic, there is a possibility of *f-d* exchange interactions between Ir^{4+} and A^{3+} ions which naturally introduces complicated magnetic interactions in pyrochlores [5,6]. $Pr_2Ir_2O_7$ is of special interest as the Pr^{3+} has larger A-ionic size and reside magnetically at the A-site. $Pr_2Ir_2O_7$ exhibits paramagnetic (PM) metallic behavior [6,7] and it seems to be close to the interaction-driven AFM quantum critical point tuned by the A-site which could be located between two larger Pr^{3+} and Nd^{3+} ions [7,8].

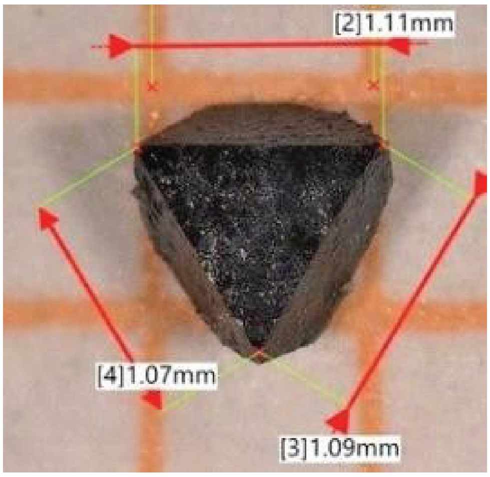

Figure.1 shows the crystal image of Pr2Ir2O7.

We have grown $Pr_2Ir_2O_7$ in the single-crystal form using the flux method as shown in Fig. 1. The chemical composition of crystals has been analyzed using energy dispersive analysis of x-ray. Temperature-dependent magnetization data for $Pr_2Ir_2O_7$ show that the magnetization increases with decreasing the temperature without any bifurcation between M_{ZFC} and M_{FC} branches of magnetization which reveals PM behavior. The temperature-dependent reflectivity $R(\omega)$ spectrum of $Pr_2Ir_2O_7$ reveals a plasma edge-type nature and the $R(\omega)$ in the far-infrared range increases interestingly with lowering the temperature suggesting its metallic character. The optical conductivity $\sigma(\omega)$ spectra reveal an absorption structure around ~ 0.13 eV which significantly develops with lowering the temperature. Furthermore, the position of IR-modes shows a small variation around ~ 30K where the resistivity of $Pr_2Ir_2O_7$ shows a small upturn.

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Dynamic generation of scalar chirality and topological Hall effect in spiral magnets

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YMn_6Sn_6 is a Kagome metal with a ferromagnetic order in-plane and a complex noncollinear arrangement between the planes. Several phase transitions occur in magnetic field, and the nature of some of the emerging phases had not been previously understood. Moreover, in one of those phases a topological Hall effect had been reported, despite the fact that underlying crystal lattice is centrosymmetric, does not break the chiral symmetry, and does not allow for Dzyaloshinskii-Moriya asymmetric exchange. By combining thorough magnetic, transport and neutron scattering experiments with first-principle calculations and mean-field theory modelling, we were able to identify all magnetic phases, which include several different spiral phases and a co-planar fan-like structure. We also propose a plausible explanation for the topological Hall effect. In our scenario, it emerges from skyrmionic fluctuations in the same way as C_2 nematic order emerges from spin fluctuations in the absence of long-range magnetic order emerges in Fe-based superconductors. In agreement with the experiment, this topological phase appear only in in-plane finite magnetic fields, the amplitude of the effect grows approximately linearly with temperature, and is the strongest near the phase boundary.

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μSR study in metallic frustrated magnets Ho(In,Cd)Cu_4

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Metallic frustrated magnetic systems are less explored compared to the insulating frustrated magnets. $HoCdCu_4$ and $HoInCu_4$ are rare-earth intermetallic compounds in which Ho moments are arranged in a fcc cubic lattice (fcc lattices are considered to be a frustrated lattice). Both of the compounds exhibit antiferromagnetic long-range magnetic ordering at around 8 K and 760 mK respectively [1,2]. We have studied these two compounds by utilizing Muon Spin Relaxation / Rotation (μSR) technique. Our detailed μSR results indicate that even though in both of the compounds the Ho-moments are arranged in a fcc lattice but their static and dynamic magnetic properties are quite different. In $HoCdCu_4$, there is a drastic reduction of the Muon asymmetry below the ordering temperature which suggests that the Muon is experiencing a large local magnetic field produced by the Ho-moments, whereas for $HoInCu_4$, the Muon asymmetry neither show any reduction nor show any oscillations but follows similar features often found in quasi-static magnetic ordering. As far as the dynamics are concerned (which can be estimated from the relaxation rate λ in the paramagnetic state), the critical slowing down of spin-fluctuations started just above the ordering in the $HoCdCu_4$ compound, on the contrary, in case of $HoInCu_4$, λ started to increase far above the ordering temperature with reducing temperature. This observation suggests that there is short-range correlations in the $HoInCu_4$ compound in its paramagnetic state which is a signature of frustrated magnets but such a signature of frustration is absent in $HoCdCu_4$. Thus our detailed study indicates that $HoInCu_4$ can be considered as a highly frustrated magnet whereas $HoCdCu_4$ is a non-frustrated magnetic system.

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Nature of frustration-induced symmetric skyrmion lattice --- Effects of three-dimensionality, magnetic anisotropy and long-range RKKY interaction

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The skyrmion is a swirling noncoplanar spin texture whose constituent spin directions wrap a sphere in spin space, characterized by an integer topological charge. In magnetically ordered state, skyrmion is usually stabilized as a periodic array called the skyrmion lattice (SkL). While the SkL state was discussed at an earlier stage for non-centrosymmetric magnets interacting with the antisymmetric Dzyaloshinskii-Moriya (DM) interaction, it was theoretically proposed in 2012 that the "symmetric" SkL is also possible in certain class of frustrated *centrosymmetric* magnets without the DM interaction, where the size of constituentskyrmions can be varied from very small to infinitely large (corresponding to the continuum limit) by tuning the extent of frustration, while both *skyrmions* and *antiskyrmions* are equally possible due to the underlying *chiral degeneracy*, possibly leading to the unique electromagnetic response [1]. In Ref. [1], the SkL was identified in a rather simplified statistical physical model, i.e., the frustrated J_1-J_3 (J_1-J_2) isotropic Heisenberg model on the triangular lattice, as a triple-q state stabilized under magnetic fields and thermal fluctuations. Subsequent experiment has observed the SkL for centrosymmetric triangular-lattice metallic magnet, e.g., Gd_2PdSi_3 [2].

Of course, real material possesses various perturbative interactions not taken into account in a simplified model of Ref.[1], e.g., three-dimensionality (interplane coupling), magnetic anisotropy, quantum fluctuations, and long-range RKKY interaction in case of metals, etc. Indeed, experiment suggests that SkL can be stabilized even at $T=0$, where the effect of certain perturbative interactions, e.g., the magnetic anisotropy, was argued to playa role [2,3]. Here, we wish to extend the earlier theoretical calculation on the SkL formation [1] by systematically investigating the effects of various perturbative interactions which more or less exist in real materials, including the interplane coupling [4,5], the magnetic anisotropy [6], and the long-range RKKY interaction expected in metals [5,7] by extensive Monte Carlo simulations, within the classical Heisenberg-like model on the triangular (or stacked- triangular) lattice. Especially, we explore possible phase structures of the model under finite magnetic fields and at finite temperatures, to find that the SkL state is stabilized for appropriate parameter range even under those perturbative interactions, together with a variety of multiple-q states [4-7]. In particular, the SkL state is stabilized even at $T=0$ under the Ising-like magnetic anisotropy of moderate strength [6], consistently with the earlier calculation [3]. Interestingly, the SkL state of the 3D RKKY model turns out to be quite novel, exhibiting an intriguing *replica-symmetry breaking* (*RSB*) phenomenon [5]. On the basis of the obtained phase structures, we discuss a unified picture of the frustration-induced symmetric SkL together with a variety of multiple-q states encompassing the SkL state.

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SPIN CHAINS AND VAN DER WAALS MAGNETS

Chair: A. Mahajan

Inversion symmetry breaking in frustrated spin systems

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Magnetic orders in frustrated spin systems are often accompanied by the inversion symmetry breaking, leading to the multiferroicity and magnetoelectricity. Also, presence or absence of the inversion symmetry can have significant influences on magnetic properties as well as their coupled electronic phases. In this presentation, we discuss the structural inversion symmetry breaking in several van der Waals magnets based on optical techniques including the optical second-harmonic generation. The topics include (i) linear magnetoelectricity in ultrathin $MnPS_3$, (ii) multiferrocity in atomically thin NiI_2, and (iii) defect-induced inversion symmetry breaking in Fe_3GeTe_2 and its influence on the magnetic orders. If time allows, we will discuss the dynamic multiferroicity observed in oxide heterostructures particularly involved with acoustic phonons.

Interaction Scales in a 2D Van der Waals magnet $Cr_2Ge_2Te_6$

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We investigate thickness-dependent transformation from a paramagnetic to ferromagnetic phase in $Cr_2Ge_2Te_6$ (CGT) in both its bulk and few-layer flake forms. In bulk CGT, 2D Ising-like critical transition occurs at $T_C = 67$ K with out-of-plane magnetic anisotropy. Few-layer CGT on an $hBN/SiO_2/Si$ substrate displays the same T_C but also exhibits a new critical transition at T'_C =14.2 K. Critical scaling analysis reveals critical exponents corresponding to the new transition differs significantly from those in bulk and do not conform to the known universality classes. Density functional theory (DFT) and classical calculations reveal a competition between magnetocrystalline and dipolar anisotropy emerges with reduced dimensions. The observed behavior is caused by minor structural distortions at lower dimensions, which modify the balance between spin orbit coupling, exchange interactions and dipolar anisotropy. This triggers a new critical crossover at T'_C. Our findings signify the emergence of a complex interplay of short and long-range interactions below T'_C as dimensionality decreases.

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Tunable magnetic frustration in $PbM_2Ni_6Te_3O_{18}$ (M = Mn, Fe, Co, Zn)

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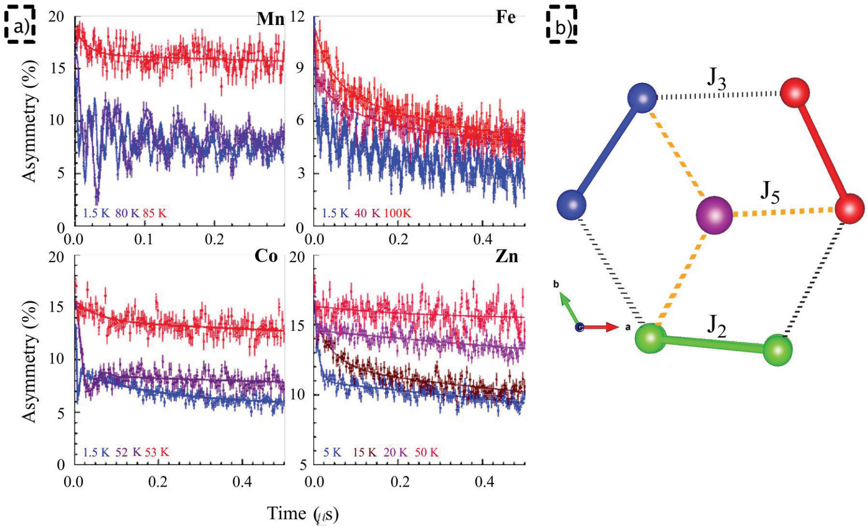

Caption of the figure : a) Zero-field muon decay asymmetry measured at various temperatures below and above T_N for $PbM_2Ni_6Te_3O_{18}$, where M = Mn, Fe, Co, and Zn. b) View along $\hat{c}$ showing the in-plane antiferromagnetic J_2, ferromagnetic J_3 and J_5 exchange pathways between the three colored Ni-chains and the M-dimer (purple) at the centre.

The pentanary oxides $PbM_2Ni_6Te_3O_{18}$, where M = Mn, Fe, Co, Zn, allow magnetic frustration to be tuned by changing the transition metal ion M. These compounds contain Ni^{2+} zigzag chains along the *c*-axis which order antiferromagnetically below T_N, in addition to a kagome-like interchain structure in the *a*-*b* plane which becomes magnetically frustrated when coupled ferromagnetically. The competition between the ferromagnetic interchain exchanges J_3 and J_5 turns out to be crucial in determining the magnetic structures. By direct comparison of the muon-spin rotation (μSR) asymmetry, we demonstrate that when M = Mn, the larger M moment allows the M–Ni exchange J_5 to dominate over the interchain (Ni–Ni) exchange J_3 and suppresses magnetic frustration (see Figure 1b). But as J_5 weakens (M = Fe, Co) and vanishes (M = Zn), J_3 becomes increasingly significant and turns the system into a strongly frustrated one within the kagome-like structure. These results demonstrate beautifully how the nature of the magnetic ground state, whether fully ordered or strongly frustrated, can be constructed by the choice of a single magnetic ion in an isostructural family of materials containing zigzag chains.

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Possible realization of floating phase in S = 5/2 highly frustrated spin chain systems

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Highly frustrated magnets (HFMs) exhibit a wide variety of novel quantum spin liquid states in which the spins are strongly correlated and do not order even at T = 0 K. While the spin liquid states are generally seen in a few model HFMs with S = ½, it is rarely noticed in the large spin S = 5/2 systems. Herein, we present the investigation of a few potential S = 5/2 frustrated spin chain (FSC) materials: $Bi_3FeMo_2O_{12}$ (BFMO) and $K_3FeMo_4O_{15}$ (KFMO). While tuning the ratio of the next nearest neighbor (NNN) and nearest neighbor (NN) coupling ($\alpha = J_2/J_1$), the S = ½ FSC system exhibits the Kosterlitz-Thouless transition from the commensurate gapless phase to fully dimerized gapped phase [1], and the S = 5/2 FSC system shows the transitions from the commensurate gapless phase to the partially dimerized phase and incommensurate floating phases [**2**]. A large region of floating phase has been theoretically predicted for the S = 5/2 FSC model when the α value > 0.4. Experimentally, it is yet to be explored. With this motivation, we have investigated two compounds, BFMO [3] and KFMO, having the well-separated S = 5/2 FSCs through magnetic, heat capacity, and electronic structure calculations. The electronic structure calculations show that the α values for BFMO and KFMO are close to 1. No magnetic long-range order (LRO) is noticed even at 150 mK temperatures, despite the relatively large antiferromagnetic Curie-Weiss temperature θ_{CW}. The temperature-dependent magnetic heat capacity follows the power law behavior, indicating that the compound exhibits gapless spinon excitations. According to the S = 5/2 FSC theoretical model's quantum phase diagram, the BFMO and KFMO systems should be the candidates for the floating phase with gapless excitations.

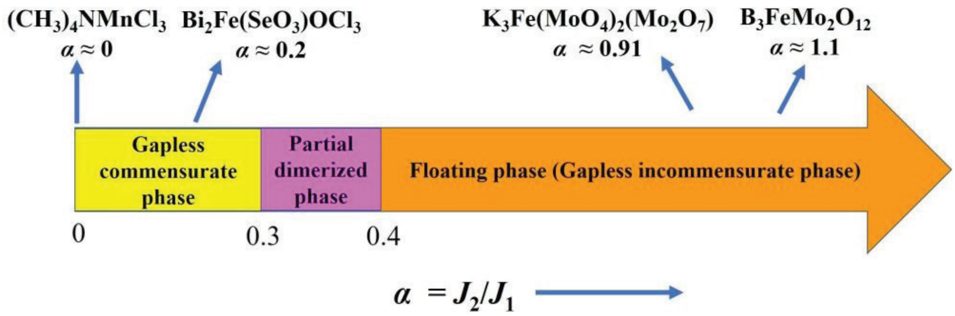

Figure 1: (Colour online) The Quantum phase diagram of the S = 5/2 FSC model [2]. Our compounds BFMO and KFMO are placed in the floating phase region.

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KAGOME AND HYPERKAGOME MAGNETS

Chair: S. Blundell

Magnetic frustration in the garnet hyperkagome lattice

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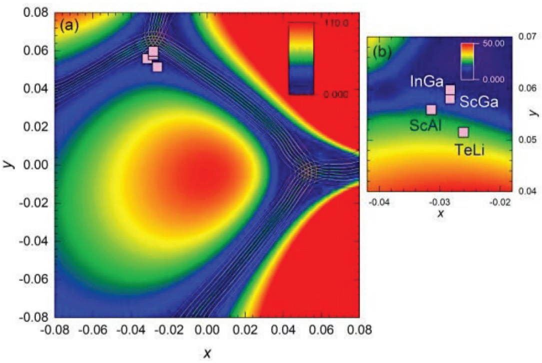
Amongst geometrically frustrated architectures is the hyperkagome lattice, which consists in a twisted spatial arrangement of corner-sharing triangles and which can be found in rare-earth (R) garnets $R_3B_2C_3O_{12}$ [1]. Mean-field calculations on a hyperkagome lattice, for an effective anisotropic pseudospin S = ½ (characterized by general g_{xx}, g_{yy}, and g_{zz} Landé factors), generate a very rich magnetic phase diagram indeed, encompassing complex phases, including disordered ones, when magnetic anisotropy departs from the strong Ising case [2]. Tuning the rare-earth magnetic anisotropy in garnets is the key to exploring this phase diagram, and can be achieved through appropriate distortions of the rare-earth oxygen environment, the latter being controlled by the B and C ionic size.



Caption of the figure : (a) Variations, with the surrounding oxygen (*x*O, *y*O) coordinates, of the energy (in meV) of the first CEF excitation for a Dy^{3+} in its dodecahedron. The boundaries delimiting the different Ising phases are marked by contour lines. (b) Enlargement of (a) around a set of experimental data displayed as pink squares (the higher the energy of the first CEF excitation, the stronger the Ising anisotropy).

In dysprosium garnets (R = Dy), our neutron scattering results show that the Ising character of Dy^{3+} is weakened by larger ions on the C site (Figure 1), but even in $Dy_3In_2Ga_3O_{12}$, where dipolar interactions should be the weakest because of the large Dy-Dy distance, multiaxial (**k** = 0) magnetic ordering is still observed around T_N = 1.1 K [3]. $Dy_3Ga_5O_{12}$ remains somewhat of a mystery, as it is the only Dy garnet with a subkelvin T_N (360 mK). An extensive investigation of the magnetic phase diagram and magnetic excitations of $Dy_3Ga_5O_{12}$ will be presented, allowing one to understand the unique interplay between magnetic exchange, dipolar interaction and XY anisotropy specific to this compound [4].

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Signature of half-moons in a Schwinger boson theory of the J_1, $J_2 = J_3$ kagome antiferromagnet

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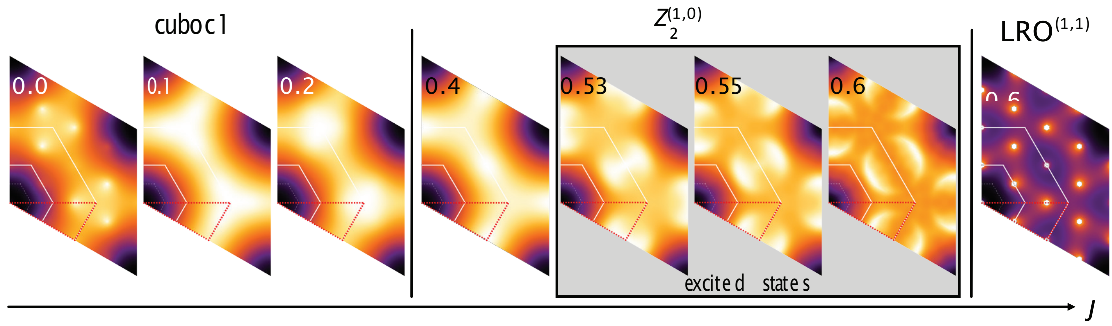

Figure 1: Evolution of the structure factor *S(q)* in function of the competition of the magnetic coupling parameters. Eventually half-moon physics emerges in a Z_2 fluxed quantum spin liquid.

We study the kagome antiferromagnet for quantum spin-1/2 with first J_1, second J_2, and third J_3 neighbor exchanges define along the natural axes of the lattice instead of the more common diagonals of the hexagons , along the $J_2 = J_3 = J$ line.

We use Schwinger boson mean-field theory for the precise determination of the phase diagram, and two different rewritings of the Hamiltonian to build an intuition about the origin of the transitions. The spin liquid obtained at $J = 0$ remains essentially stable over a large window, up to $J \simeq 1/3$, because it is only weakly frustrated by theJ term. Then, at $J \simeq 1/2$, the intermediate Z_2 spin liquid condenses into a long-range chiral order because of the change of nature of the local magnetic fluctuations. As a side benefit, our Hamiltonian rewriting offers an exact solution for the ground state of our model on a Husimi cactus.

Tracking this chiral QSL for larger **J** when it becomes an excited state, one can see the emergence of half-moon patterns reminiscent to classical systems probing local ferromagnetism and disordered ground states.

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Classical Nematic Spin Liquid in the $S = \frac{5}{2}$ Heisenberg Kagome Antiferromagnet $Li_9Fe_3(P_2O_7)_3(PO_4)_2$

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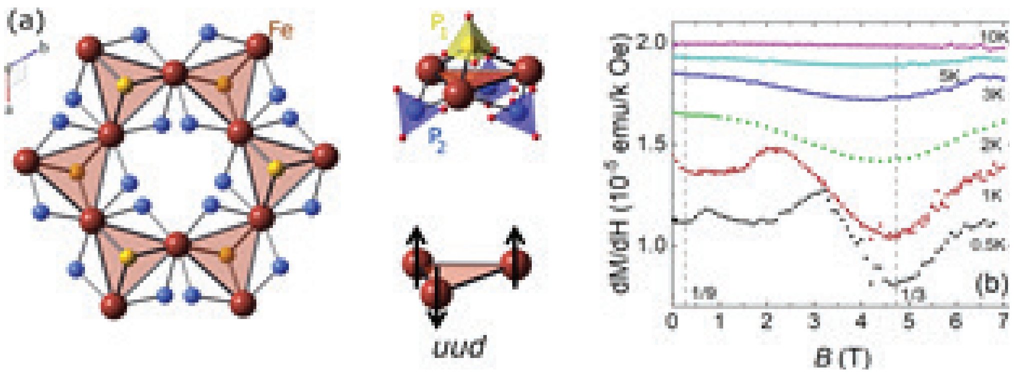
The kagome lattice occupies a central place in the field of magnetic frustration. Very early on, pioneering theoretical studies highlighted its specificity even at a classical level [1]. Nevertheless, some of the well-established numerical results obtained many years ago on the classical kagome Heisenberg antiferromagnetic (KHAF) model could not be verified due to the lack of experimental candidates.

This motivated us to look at the magnetic properties of a new classical (S=5/2) Heisenberg kagome antiferromagnet, the layered monodiphosphate $Li_9Fe_3(P_2O_7)_3(PO_4)_2$ [LiFePO] (Fig. 1), using magnetization measurements and ^{31}P nuclear magnetic resonance [2]. Thanks to the moderate exchange interaction (J~1K) between spins, we could experimentally investigate the phase diagram of the classical model under applied fields which hosts nematic spin liquid, VBC, incompressible plateaus or superfluid phases [3,4]. Here, we evidence the highly sought-after 1/3rd magnetization plateau in a kagome compound (Fig. 1). A moderate ^{31}P NMR line broadening reveals the development of anisotropic short-range correlations, concomitantly with a gapless spin-lattice relaxation time T1~kBT/ħS, which point to the presence of a semiclassical nematic spin-liquid state predicted for the KHAF model [3,4].



Caption of the figure: (a) Structure of the LiFePO kagome compound. Fe^{3+} ($S = 5/2$) ions form regular corner-sharing triangles. (b) Evolution of the derivative *dM/dH* with *T* showing the appearance of the 1/3 magnetization plateau (dashed line). The classical nematic spin-liquid phase emerges below $T^* = 5$ K.

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