# TT 18: Correlated Electrons: Spin Systems and Itinerant Magnets – Frustrated Magnets 2 (jointly with MA)

Time: Monday 15:00–18:30 Location: H 3005

TT 18.1 Mon 15:00 H 3005

**Semionic resonating valence bond states** — •Mohsin Iqbal[1], Didier Poilblanc[2], and Norbert Schuch[1] — [1]JARA Institute for Quantum Information, RWTH Aachen, 52056 Aachen, Germany — [2]Laboratoire de Physique Theorique, C.N.R.S. and Universite de Toulouse, 31062 Toulouse, France

Ground state of Heisenberg antiferromagnet (HAFM) on kagome lattice forms a Z2 topological spin liquid. However, the topological nature of the spin liquid is not entirely clear. We propose semionic resonating valence bond (RVB) states as an ansatz to characterize the topological order using the formalism of Projected Entangled Pair States (PEPS). In contrast to normal resonating valence bond state (proposed in earlier studies as another ansatz) which is in the phase of Kiteav toric code, semionic RVB states carry the topological order of double semion model.

Within PEPS formalism one can extend the ansatz and construct semionic simplex RVB states. Variational calculations show that semionic simplex RVB states give relatively lower energy for HAFM on kagome lattice compared to simplex RVB states and make a better candidate to describe the topological order.

TT 18.2 Mon 15:15 H 3005

**Exotic magnetization plateaus in a quasi-two-dimensional Shastry-Sutherland model** — Gregor Foltin[1], •Salvatore R. Manmana[2], and Kai P. Schmidt[1] — [1]Lehrstuhl f. Theoretische Physik 1, TU Dortmund, D-44221 Dortmund — [2]Institut f. Theoretische Physik, Georg-August-Universität Göttingen, D-37077 Göttingen

We find unconventional Mott insulators in a quasi-2D version of the Shastry-Sutherland model in a magnetic field. In our realization on a four-leg tube geometry, these are stabilized by correlated hopping of localized magnetic excitations. Using perturbative continuous unitary transformations (pCUTs, plus classical approximation or exact diagonalization) and the density matrix renormalisation group method (DMRG), we identify prominent magnetization plateaus at magnetizations $M = 1/8$, 3/16, 1/4, and 1/2. While the plateau at $M = 1/4$ can be understood in a semiclassical fashion in terms of diagonal stripes, the plateau at $M = 1/8$ displays highly entangled wheels in the transverse direction of the tube. Finally, the $M = 3/16$ plateau is most likely to be viewed as a classical 1/8 structure on which additional triplets are fully delocalized around the tube. The classical approximation of the effective model fails to describe all these plateau structures which benefit from correlated hopping. We relate our findings to the full 2D system, which is the underlying model for the frustrated quantum magnet $SrCu(BO_3)_2$.

TT 18.3 Mon 15:30 H 3005

**Weyl spin liquids** — •Kevin O'Brien, Maria Hermanns, and Simon Trebst — Institute for Theoretical Physics, University of Cologne, 50937 Cologne, Germany

Topological semimetals – the gapless cousins of topological insulators – have attracted much recent interest. They exhibit bulk features such as gapless Weyl nodes that can be characterized by topological invariants. In addition, they possess gapless surface modes, also called Fermi arcs, which are intimately connected to the bulk features and, thus, topologically protected.

Here we discuss the emergence of such a topological semimetal in three-dimensional generalizations of the Kitaev model. These models describe the fractionalization of spin-orbit entangled moments into Majorana fermions and a $\mathbb{Z}_2$ gauge field. We demonstrate that the Majorana fermions form a Weyl superconductor for the Kitaev model on the recently synthesized hyperhoneycomb structure of $\beta$-$Li_2IrO_3$ in the presence of an external magnetic field. We discuss the topologically protected bulk and surface features of this state, which we dub a Weyl spin liquid.

TT 18.4 Mon 15:45 H 3005

**Orphan glassiness in a disordered spin liquid** — •Jorge Armando Rehn[1], Arnab Sen[2], and Roderich Moessner[1] — [1]Max Planck Institute for the Physics of Complex Systems, Dresden — [2]Indian Association for the Cultivation of Science, Kolkata

The random dilution of non-magnetic impurities in systems presenting a classical spin liquid phase leads to interesting new physics: certain spins in direct proximity to vacancies are known to be fractionalized, and to create an extended spin texture on its neighborhood. A mapping of the pure spin system to a distribution of fluxes living on a dual bipartite lattice enables understanding of the thermal excitations as emerging Coulomb charges. Using this mapping it is also possible to interpret the diluted system in terms of charges, which are not entropically generated, but induced by the vacancies. The effective picture obtained at low temperatures for the diluted system neglects entropically generated charges and considers only the randomly placed long ranged interacting charges induced by the vacancies. A study of this effective model and the possibility of a glassy phase in this system will be presented on this talk.

TT 18.5 Mon 16:00 H 3005

**Majorana metals and quantum spin liquids** — •Maria Hermanns, Kevin O'Brien, and Simon Trebst — Institute for Theoretical Physics, Cologne, Germany

One of the most intriguing phenomena in strongly correlated systems is the fractionalization of quantum numbers – familiar examples include the spin-charge separation in one-dimensional metallic systems, the fractionalization of the electron in fractional quantum Hall states or the emergence of monopoles in spin ice.

In this talk, I will discuss the fractionalization of magnetic moments in spin-orbit entangled j=1/2 Mott insulators, in which the emergent degrees of freedom are Majorana fermions. The latter form metallic states whose precise character intimately depends on the underlying lattice structure. The origin of such dichotomous states is elucidated by a family of exactly solvable Kitaev-type models of frustrated quantum magnets in three dimensions, which might be realized in a class of recently synthesized Iridate compounds. In particular, these models provide the first analytical tractable examples of long sought-after quantum spin liquids with a spinon Fermi surface and even an entire new class of quantum spin liquids – so-called Weyl spin liquids, in which the fractionalized degrees of freedom form a topological Weyl-superconductor.

TT 18.6 Mon 16:15 H 3005

**Magnetic monopoles in diluted quantum spin ice** — •Olga Petrova[1], Roderich Moessner[1], and Shivaji Sondhi[2] — [1]Max Planck Institute for the Physics of Complex Systems, Dresden, Germany — [2]Princeton University, Princeton, NJ, USA

Typical spin ice materials can be modeled using classical Ising spins. The geometric frustration of the pyrochlore lattice causes the spins to satisfy ice rules, whereas a violation of the ice constraint constitutes an excitation. Flipping adjacent spins fractionalizes the excitation into two monopoles. Long range dipolar spin couplings result in Coulombic interactions between charges, while the leading effect of quantum fluctuations is to provide the monopoles with kinetic energy. We study weakly diluted spin ice including the leading effects of quantum mechanical fluctuations. We find that a missing spin gives rise to hydrogenic excited states in which a magnetic monopole is bound to the vacancy at various radii. We compute the properties of these states via a mapping to a single particle problem that is defined on the Bethe lattice. These quantities are then used to obtain an expression for the dynamic structure factor, that can be measured in neutron scattering experiments directly.

TT 18.7 Mon 16:30 H 3005

**Monte-Carlo Study of Polarization Plateaux in Hexagonal Water Ice** — •Matthias Gohlke, Frank Pollmann, and Roderich Moessner — Max Planck Institute for the Physics of Complex Systems, Dresden, Germany

We study the hexagonal phase Ih of water ice in an external electric field at low temperatures using a Worm Monte Carlo algorithm. We observe polarization plateaux when the field is aligned along the [001] and [1-10] directions. In each case, one plateau occurs at intermediate polarization with finite entropy. The remaining degrees of freedom can be mapped to dimer models on the honeycomb and the square lattice, respectively. Upon slightly tilting the external field, we observe a Kasteleyn transition to a plateau with saturated polarization and vanishing entropy. This transition is checked analytically using the Pfaffian method and compared to the Monte Carlo results.

**15 min. break.**

TT 18.8 Mon 17:00 H 3005

**Comparison between dynamical permeability and permittivity in $Dy_2Ti_2O_7$ at low temperatures** — •Steffen Harms[1], Christoph P. Grams[1], Martin Valldor[2], and Joachim Hemberger[1] — [1]II. Physikalisches Institut, Universität zu Köln, Cologne, Germany — [2]Max Planck Institute for Chemical Physics of Solids, Dresden, Germany

$Dy_2Ti_2O_7$ if one of the well known spin-ice compounds in which magnetic monopoles are emergent [1]. It was predicted, that these monopoles carry electric dipole moments [2] and therefore the monopole dynamics can be seen in the dielectrical response $\varepsilon^*(\nu)$.
Recently published data exhibits the speeding up of a dielectric relaxation process reaching a relaxation rate of up to $\nu_0 = 100$ kHz near the critical-endpoint of the (H,T)-phase diagram [3]. This process can be associated with the hopping of magnetic monopoles and should among other contributions also be seen in the magnetic ac-susceptibility.
Here we present a comparative broadband study of complex permittivity and permeability in the mK range in order to disentangle the different contributions to the dynamic response in the spin-ice $Dy_2Ti_2O_7$.

Funded through the Institutional Strategy of the University of Cologne within the German Excellence Initiative and research grant HE-3219/2-1.

[1] C. Castelnovo et al., Nature 451, 42 (2008).
[2] D. I. Khomskii, Nature Communications 3, 1 (2012).
[3] C. P. Grams et al., Nature Communications 5, 4853 (2014).

TT 18.9 Mon 17:15 H 3005

**Groundstate Entropy and Monopole Heat Transport in dilute Spin Ice** — •S. Scharffe[1], G. Kolland[1], M. Valldor[1,2], O. Breunig[1], J. F. Welter[1], P. Laschitzky[1], and T. Lorenz[1] — [1]II. Physikalisches Institut, Universität zu Köln, Germany — [2]Max-Planck-Institut für Chemische Physik fester Stoffe, Dresden, Germany

The spin ice $Dy_2Ti_2O_7$ is a geometrically frustrated spin system consisting of corner-sharing tetrahedra. An Ising anisotropy aligns the spins along their local easy axes in the {111} directions. Possible groundstates are given by the "ice-rule": two spins point into and two out of each tetrahedron. This behavior is analogous to the hydrogen displacement in water ice, revealing a residual entropy for $T \to 0$ K. Anomalous excitations are created by single spin flips and are discussed as magnetic monopoles which contribute to the magnetic heat transport in spin ice[1, 2]. Here, specific heat and heat transport measurements of the pure spin ice and the diluted reference materials $(Dy_{1-x}Y_x)_2Ti_2O_7$ are presented. We extract $c_{\mathrm{mag}}$ and demonstrate how the residual entropy of the pure spin ice varies with increasing non-magnetic Y-dilution. Additionally, we show that the monopole contribution $\kappa_{\mathrm{mag}}$ to the total heat transport also correlates with the degree of Y-dilution. The extraction of $\kappa_{\mathrm{mag}}$ and $c_{\mathrm{mag}}$ enables us to calculate the magnetic diffusion coefficient $D_{\mathrm{mag}}$ of the spin-ice materials which is strongly suppressed in the diluted systems for $T < 1$ K.

This work was supported by the DFG via project LO 818/2-1.

[1] Kolland *et. al.*, Phys. Rev. B, **86**, 060402(R) (2012)
[2] Scharffe *et. al.*, J. Magn. Magn. Mater. (in press, arXiv:1406.4037).

TT 18.10 Mon 17:30 H 3005

**Non-linear susceptibility of spin ice from the Wien effect** — •Vojtěch Kaiser[1,2], Steven T. Bramwell[3], Peter C.W. Holdsworth[2], and Roderich Moessner[1] — [1]Max-Planck-Institut für Physik komplexer Systeme, Dresden, Germany — [2]École normale supérieure de Lyon, Lyon, France — [3]London Centre for Nanotechnology, University College London, London, UK

We give predictions for the non-linear magnetic response of the emergent Coulomb fluid of magnetic monopoles in spin ice. To this end, we combine the increase of the monopole density due to the second Wien effect with the magnetization dynamics of spin ice. Non-linearities that occur thanks to this coupling between monopoles and spins manifest themselves in computer simulations and are explained by a simple kinetic model. At longer times, spin ice magnetizes which renders the density increase transient unless the field direction is changed periodically. Strikingly, for certain frequencies the non-equilibrium non-linear response due to the Wien effect in spin ice is indistinguishable from an electrolyte. Studying the response to harmonic driving with large amplitude allows us to define a non-linear susceptibility of spin ice as a potential experimental signature of these phenomena.

TT 18.11 Mon 17:45 H 3005

**Field Induced Phases and Possible Multimagnon Bound States in the Frustrated Quantum Spin Chain Linarite** — Britta Willenberg[1], Manfred Reehuis[1], Markus Schäpers[2], Anja U.B. Wolter[2], Stefan.-Ludwig Drechsler[2], Satoshi Nishimoto[2], Bernd Büchner[2], Kirrily C. Rule[3], Bachir Ouladdiaf[3], and •Stefan Süllow[4] — [1]HZ Berlin, Berlin, Germany — [2]IFW Dresden, Dresden, Germany — [3]The Bragg Institute, ANSTO, Australia — [4]IPKM, TU Braunschweig, Braunschweig, Germany

A neutron diffraction and NMR study of the field induced phases of linarite $PbCuSO_4(OH)_2$ is presented for magnetic fields $H \parallel b$ axis at temperatures down to 1.7 K. A two step spin flop transition is observed, transforming the helical magnetic ground state into a collinear structure. As well, a magnetic phase with sine-wave modulated moments parallel to the field direction was detected, enclosing the other long-range ordered phases. The propagation vector of this 3D spin density wave phase shifts with increasing magnetic field. Theoretical calculations imply that linarite possesses an $xyz$ exchange anisotropy. Within this model a coexistence of 2-, 3-, and 4- magnon bound states is predicted to be present in linarite.

TT 18.12 Mon 18:00 H 3005

**High-temperature heat transport in coupled quantum spin chains** — •Christian Hess[1], Oleg Mityashkin[1], Ashwin Mohan[1], Chinnathambi Sekar[1], Gernot Krabbes[1], Bernd Büchner[1], Romuald Saint-Martin[2], and Alexandre Revcolevschi[2] — [1]Institute for Solid State Research, IFW Dresden, 01069 Dresden, Germany — [2]Laboratoire de Physico-Chimie de L'Etat Solide, Université Paris-Sud, 91405 Orsay, France

We present high-temperature heat conductivity data up to $T \sim J/2k_B$ for the compounds $SrCuO_2$ and $CaCu_2O_3$, which represent spin-1/2 realizations of the isotropic Heisenberg spin chain and of a weak-rung two-leg spin ladder, respectively. In both cases, the high-temperature heat conductivity is suppressed with increasing temperature, which indicates a thermally activated scattering process. Indeed, the analysis of the data reveals a perfect description of the temperature dependence of the mean free path $l_{\mathrm{mag}}$ by just two scattering processes, viz. (i) a temperature independent scattering off boundaries that dominates at low temperature, and (ii) thermally activated high-temperature scattering $l_{\mathrm{mag}} \sim \exp(-T^*/T)$. Interestingly, for the Heisenberg spin chain the energy scale $k_BT^*$ of the activated scattering is comparable with typical phonon energies, suggestive of spinon-phonon scattering. However, in the weak-rung spin ladder, which can be viewed as a pair of weakly coupled spin chains, the energy scale of the activated scattering is clearly beyond the phonon energies in the system and $k_BT^* \sim J$. These findings suggest that the weak interchain coupling introduces a new, magnetic type of scattering.

TT 18.13 Mon 18:15 H 3005

**Spin structures of S = 5/2 antiferromagnetic triangular lattices: $AAg_2M[VO_4]_2$** — •Angela Möller[1], Clarina R. de la Cruz[2], Ngozi E. Amuneke[1], and Joshua Tapp[1] — [1]Department of Chemistry and TcSUH, University of Houston, United States — [2]Quantum Condensed Matter Division, ORNL, Oak Ridge, United States

The $AAg_2M[VO_4]_2$ compounds present a unique series for studying structure-property relationships. The size of the A cation ($Ba^{2+}$, $K^+$, $Rb^+$, or $Ag^+$) controls i) the inter-layer distances between the magnetic triangular lattices (M, here $Mn^{2+}$ or $Fe^{3+}$) and ii) the distortion of the non-magnetic vanadate units. The crystal and magnetic structures were refined from neutron diffraction data under applied fields (ORNL, HB2A) and reveal the complex magnetic phase diagrams of frustrated S=5/2 triangular lattices with axial and XY-anisotropy, respectively [1].

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[1] N. E. Amuneke, et al., Chem. Mater. 26, 5930 (2014).