TT 3: Focus Session: Entanglement as a Probe for Correlated Quantum Matter

The interplay of quantum fluctuations and correlations in many-body systems can result in novel phases with exciting physical phenomena. Celebrated examples are the fractional quantum Hall effect and quantum spin liquids. A generic property of such phases is their non- local entanglement that manifests itself in topological order and fractionalized particle-like excitations. Excitingly, it has been proposed that such topologically ordered phases might be an ideal building block for a fault-tolerant quantum computer. While recent experiments pinpointed the presence of fractionalized excitations in spin-liquid materials, the characteristic underlying property of non-local entanglement remains elusive and evades a direct experimental probe.

Organizers: Alexander Tsirlin (Augsburg University), Frank Pollmann (Technical University Munich)

Time: Monday 13:30–16:15 Location: H6

TT 3.1 Mon 13:30 H6

Measuring quantum entanglement with neutrons — •Alan Tennant — Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA

The quantification of entanglement without the need for underlying models and theoretical solutions is an open challenge for measurement in condensed matter. This is particularly important in the case of quantum magnets such as spin liquids where we often lack theories that can connect with measurement. Three quantum entanglement witnesses relevant to neutron scattering have been proposed in the form of one-tangle, two-tangle (concurrence), and quantum Fisher information. We have recently applied these to real quantum magnets and found the one-tangle and quantum Fisher information to be particularly promising. I will show how the entanglement witnesses can be determined using experiment and what can be learned from them about the underlying quantum states.

TT 3.2 Mon 14:00 H6

Observation of E_8 particles in Ising chain quantum magnets — •Zhe Wang — Department of Physics, TU Dortmund University, Dortmund, Germany

Near the transverse-field-induced quantum critical point of the Ising chain, an exotic dynamic spectrum consisting of exactly eight particles was predicted [1], which is uniquely described by an emergent quantum integrable field theory with the E_8 Lie algebra, but rarely explored experimentally. By performing high-resolution terahertz spectroscopy of quantum spin dynamics and comparing to analytical calculation of the dynamical spin correlations, we revealed evidence for the E_8 particles in the Ising chain antiferromagnet $BaCo_2V_2O_8$ [2] as well as in the Ising chain ferromagnet $CoNb_2O_6$ [3] under an applied transverse field. In particular, higher-energy E_8 particles were observed above the low-lying two-particle continua, featuring the quantum many-body effects in the exotic dynamic spectrum [2,3].

[1] A. B. Zamolodchikov, Int. J. Mod. Phys. A 4, 4235 (1989).
[2] Z. Zhang et al., Phys. Rev. B 101, 220411 (2020).
[3] K. Amelin et al., Phys. Rev. B 102, 104431 (2020).

15 min. break

TT 3.3 Mon 14:45 H6

Topologically ordered systems on the digital quantum processor — Kevin Satzinger[3], •Yujie Liu[1,2], Adam Smith[4], Christina Knapp[5,6], Michael Knap[1,2], Kirill Schtengel[7], Pedram Roushan[3], and Frank Pollmann[1,2] — [1]Department of Physics, Technical University of Munich, Garching, Germany — [2]Munich Center for Quantum Science and Technology, M{\"u}nchen, Germany — [3]Google Quantum AI, Mountain View, CA, USA — [4]Centre for the Mathematics and Theoretical Physics of Quantum Non-Equilibrium Systems, University of Nottingham, Nottingham, UK — [5]Department of Physics and Institute for Quantum Informationand Matter, California Institute of Technology, Pasadena, CA, USA — [6]Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, CA, USA — [7]Department of Physics and Astronomy, University of California, Riverside, California, USA

In the first part of the talk, we will discuss the experiment on Sycamore quantum processor where we prepare the ground state of the toric code Hamiltonian using an efficient quantum circuit. We measure a topological entanglement entropy near the expected value of ln 2 and simulate anyon interferometry to extract the braiding statistics of the emergent excitations. We further investigate key aspects of the surface code, including logical state injection and the decay of the non-local order parameter. In the second part of the talk. We generalize our protocol to the more general class of string-net states which host doubled topological order, rendering the braiding of non-abelian anyons possible, as a tool to probe and simulate topological quantum field theory.

TT 3.4 Mon 15:15 H6

Robustness of the thermal Hall effect close to half-quantization in a field-induced spin liquid state — •Jan Bruin[1], Ralf Claus[1], Yosuke Matsumoto[1], Nobuyuki Kurita[2], Hidekazu Tanaka[2], and Hidenori Takagi[1,3] — [1]Max Planck Institute for Solid State Research, Stuttgart, Germany — [2]Department of Physics, Tokyo Institute of Technology, Tokyo, Japan — [3]Department of Physics, The University of Tokyo, Bunkyo, Tokyo, Japan

Thermal signatures of fractionalized excitations are a fingerprint of quantum spin liquids (QSLs). In the J_{eff}=1/2 honeycomb magnet α-$RuCl_3$, a QSL state emerges upon applying an in-plane magnetic field $H_{||}$ greater than the critical field $H_{C2} \approx 7$ T along the a-axis, where the thermal Hall conductivity (k_{XY}/T) was reported to take on the half-quantized value k_{HQ}/T. This finding was discussed as a signature of an emergent Majorana edge mode predicted for the Kitaev QSL. The $H_{||}$- and T-range of the half-quantized signal and its relevance to a Majorana edge mode are, however, still under debate.

Here we present a comprehensive study of k_{XY}/T in α-$RuCl_3$ with $H_{||}$ up to 13 T and T down to 250 mK, which reveals the presence of an extended region of the phase diagram with $k_{XY}/T \approx k_{HQ}/T$ above H_{C2}. The results are in support of a topological state with a half-quantized k_{XY}/T and suggest an interplay with crossovers or weak phase transitions beyond H_{C2} in α-$RuCl_3$.

TT 3.5 Mon 15:30 H6

Angle-dependent thermodynamic measurements on α-$RuCl_3$ — •Sebastian Bachus[1], David Kaib[2], Anton Jesche[1], Yoshifumi Tokiwa[1], Vladimir Tsurkan[1], Alois Loidl[1], Stephen Winter[2], Alexander Tsirlin[1], Roser Valentí[2], and Philipp Gegenwart[1] — [1]Center for Electronic Correlations and Magnetism, University of Augsburg — [2]Institute of Theoretical Physics, Goethe University Frankfurt

For several years, the field-dependence of the Kitaev material α-$RuCl_3$ has been subject to controversial discussions. Recently, a field-induced Kitaev spin liquid state has been proposed above the critical field for long-range magnetic order. This scenario, however, requires another phase transition towards the partially polarized state upon leaving the spin liquid phase. We utilize a high-resolution alternating field method to precisely determine the magnetic Grüneisen parameter down to 0.5 K in magnetic fields up to 14 T. In combination with specific heat measurements, this allows us to determine the entropy evolution into and out of the presumed topological Kitaev quantum spin liquid regime. We compare our thermodynamic measurements to exact diagonalization results and carefully establish the temperature-field phase diagram. Finally, we discuss implications on the suggested spin liquid phase.

[1] S. Bachus et al., Phys. Rev. B 103, 054440 (2021)
[2] S. Bachus et al., Phys. Rev. Lett. 125, 097203 (2020)

TT 3.6 Mon 15:45 H6

Comparative study of the triangular spin-liquid candidates $NaYbO_2$, $KYbO_2$ and $KYbS_2$ — •Franziska Grussler, Sebastian Bachus, Noah Winterhalter-Stocker, Philipp Gegenwart, and Alexander Tsirlin — Center for Electronic Correlations

and Magnetism, University of Augsburg, Augsburg, Germany

Spin liquid is an entangled state of matter. $NaYbO_2$, $KYbO_2$ and $KYbS_2$ feature the same space group $R\bar{3}m$ as the spin-liquid candidate $YbMgGaO_4$ but evade structural disorder pertinent to that compound. We report a comparative study of the polycrystalline $NaYbO_2$ and $KYbO_2$ and single crystalline $KYbS_2$ including their structural characterization and thermodynamic properties in the milli-K temperature range. The compounds reveal the reduction in magnetic couplings upon replacing Na by K and the enhanced easy-plane anisotropy upon replacing O by S. They show no signs of magnetic order in zero field, but undergo field-induced magnetic order. For $KYbS_2$ a detailed B-T phase diagram is deduced from heat capacity, dilatometry and magnetization measurements for B‖c. By studying specific heat of $NaYbO_2$ and $KYbS_2$ at milli-K temperatures, we conclude that between 0.5 T and 2 T, within the putative spin-liquid phase, magnetic specific heat follows quadratic behavior expected for the gapless Dirac spin liquid. Our observations establish gapless nature of the spin-liquid phase of triangular antiferromagnets but show strong similarities to 120-degree ordered triangular antiferromagnets when B‖c is applied.

TT 3.7 Mon 16:00 H6

Structural and thermodynamic properties of the spin-liquid candidate $Na_2BaCo(PO_4)_2$ — •Vera P. Bader[1], Alexander A. Tsirlin[1], Ivo Heinmaa[2], Raivo Stern[2], Noah Winterhalter-Stocker[1], and Philipp Gegenwart[1] — [1]Center for Electronic Correlations and Magnetism, University of Augsburg — [2]National Institute of Chemical Physics and Biophysics, Tallinn

The first report of $Na_2BaCo(PO_4)_2$ as a spin liquid candidate [1] brought the compound to the fore. One structural prerequisite is fulfilled as the Co^{2+} ions with an effective spin 1/2 form a frustrated triangular lattice. The low temperature properties found in the literature are rather controversial. On the one hand a clear transition is observed in the heat capacity data in zero magnetic field at 140 mK [2]. One the other hand AC magnetic susceptibility data and ZF-μSR measurements indicate a dynamically fluctuating ground state down to 80 mK [3]. The spin-liquid state is highly sensitive to details of the crystal structure and may be suppressed upon structural disorder. Here, we revise both crystal structure and low-T temperature-field phase diagram of $Na_2BaCo(PO_4)_2$. Using high-resolution synchrotron XRD and NMR, we show symmetry lowering and signatures of structural disorder. Moreover, our milli-K heat capacity, thermal expansion and magnetostriction measurements confirm magnetic order in zero field and reveal field-induced phases expected from a nearest-neighbor triangular antiferromagnet.

[1] Zhong *et al.*, PNAS 116 29 (2019)
[2] Li *et al.*, Nat. Commun 11 4216 (2020)
[3] Lee *et al.*, Phys. Rev B 103 024413 (2021)