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A step towards emergent QED in $d = 3 + 1$ with high-resolution neutron scattering

Fractional matter coupled to the emergent gauge field in a quantum spin ice

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Recommended with a Commentary by Roderich Moessner, MPI-PKS Dresden

General background— The search for topological phases of matter is one of the central endeavours of condensed matter physics since the field was experimentally founded by Klitzing's discovery of the integer quantum Hall effect. The search for quantum spin liquids in fact predates even this discovery, with Anderson's proposal of a resonating valence bond liquid in the early 1970s. While there is no universally accepted definition of the term quantum spin liquids, it is not uncommon to label as such those spin models whose low-energy description involves an emergent gauge field, by dint of which they also qualify as topological states of matter. There now exists a collection of models which are known to host spin liquid phases, and there is a choice of review articles covering the field [1].

In three dimensions, the effective low-energy theory of a quantum spin liquid can take the form of an emergent quantum electrodynamics (eQED). This is particularly interesting as eQED is not just a copy of the standard QED, but it differs in fundamental respect, such as the existence of both electric and magnetic charges, or a fine structure constant much larger than 1/137, thus realising a strong coupling gauge theory. A frustrated magnet hosting such a quantum spin liquid can thus act as a quantum emulator/simulator of lattice gauge theory.

The experimental search for quantum spin liquids is difficult for a number of reasons. Quite generally, an absence of order, being a negative criterion, is hard to verify as one in principle needs to exclude any conceivable form of order. Moreover, topological features, such as long-range entanglement or topological degeneracies, may be invisible to local probes available in the laboratory. Also, theory support is limited in that the models in question are strongly correlated and often do not lend themselves to controlled solutions.

Considering excitations rather than ground state properties has proven to be a promising avenue, as these tend to have unusual quantum numbers (due to fractionalisation going along with the topological phase of matter) and can therefore exhibit characteristic kinematics in scattering experiments. Indeed, neutrons are a promising experimental probe as they couple in a relatively simple way to the microscopic degrees of freedom, and create excitations of the spin liquid as they scatter off spins inelastically.

Neutron experiments on quantum spin ice— The heart of the preprint being highlighted here [2] are high-resolution low-temperature neutron scattering results on the quantum spin ice candidate material $Ce_2Sn_2O_7$. Spin ice [3] is the name given to a class of magnets on the pyrochlore lattice, which consists of corner-sharing tetrahedra, Fig.1a. For classical Ising spins the ground states are exponentially numerous and defined by the ice rule that two spins point into each tetrahedron and two out, Fig.1b. It is the quantum version, quantum spin ice [4], which is believed to host the eQED. The motivation for an experimental search of QSI has been on for at least two decades [5]. (An in-depth review describing the materials basis and properties QSI materials is contained in Ref. [6].)

In addition to the general obstacles mentioned above, a central practical issue has been the low energy scales involved in the quantum dynamics believed to be well below 1 Kelvin. This happens because connecting two different spin ice configurations requires a resonance move involving six spins around a hexagonal plaquette of the pyrochlore lattice, pictorially depicted as $W_{\hexagon} = |\circlearrowleft\rangle\langle\circlearrowright| + h.c.$. Roughly speaking, this needs to take place 'perturbatively', i.e. violating the ice rules only virtually, so that it corresponds to a high-order process parametrically suppressed with respect to the bare energy scales, themselves typically in the (sub-)Kelvin range in these compounds.

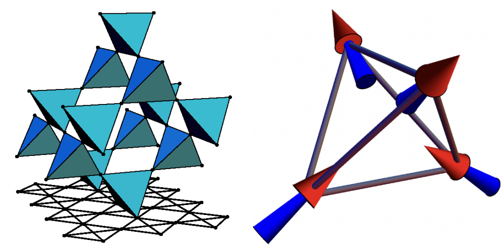

Figure 1: a) Pyrochlore lattice of corner-sharing tetrahedra. b) The ice rule requires two spins to point into each tetrahedron, and two out. The permitted quantum dynamics then involves a resonance move of six spins around a hexagonal plaquette formed by six tetrahedra, $|\circlearrowleft\rangle\langle\circlearrowright|$.

What is thus required is not only a very low-temperature set-up but also, in order to probe the quantum dynamics of the expected excitations, a concomitantly high energy resolution. This is achieved in the present set-up with measurements at 170 mK and an energy resolution in the μeV range. Not all that long ago, such parameters would have sounded fanciful.

The inelastic neutron scattering signal (Fig. 4 of the preprint) is presented as a scattering intensity as a function of energy transfer, integrated over a window of wavevectors $|\mathbf{Q}| \in [0.3, 1.1]\text{Å}^{-1}$. This takes the form of a peak with an asymmetric lineshape, with a gap of around 10 μeV and a linewidth about an order of magnitude larger.

The second basic component of the preprint consists of a comparison to available theories for this model. As mentioned above, no exact results are available, nor indeed are the parameters of the Hamiltonian describing this material known/agreed upon.

The treatments available from theory are either effectively long-wavelength [7], short-distance [8] or mean-field [9]. The authors present the best fit combining these sources of information, for two different scenarios, depending on whether the QSI phase hosts zero or π flux through the hexagonal plaquettes of the pyrochlore lattice. Specifically, firstly, the approximate solutions of the scattering cross-section in the 0- and π-flux cases provide a functional form for the respective lineshapes which can be fit to the experimental lineshape as a whole; and secondly, corrections due to the effect of the long range of the Coulomb interactions between the fractionalised excitations is taken into account near the onset of the scattering above the gap. The latter incorporates the physics of the so-called Sommerfeld enhancement [10], first studied under the heading of electron diffraction and Bremsstrahlung, but it has also appeared in the contexts of semiconductors [11] and dark matter [12].

By thus fitting the parameters in the theory to the experimental results, the authors extract characteristic energies in the model Hamiltonians: a leading energy scale of 50-70 μeV; and a subleading one within a factor 2 of 10μeV between the two scenarios. These scenarios, however, do not just differ quantitiatively: the π-flux spin liquid mean-field theory yields a two-peak structure, more pronounced than found in experiment but a less pronounced version of which could have the appearance of the asymmetrical peak seen in experiment; the 0-flux theory by contrast does have an asymmetric single line, but one which is still not broad enough on the high-energy side.

Why I like this preprint— Overall, this work reflects nicely how the field has advanced qualitatively of late. It has moved way beyond statements like "QSLs have broad features in neutron scattering" towards identifying concrete new physics in the data–in this case, in particular, noting that the onset of the scattering may reflect the physics of Sommerfeld enhancement. This reinforces the prospect of identifying phenomena such as (emergent) Cerenkov radiation in the future: the best way to pin down eQED will likely be to identify a range of specific physical phenomena with characteristic fingerprints in experiment.

This work therefore also shines a light on the way ahead of us yet, before we can claim eQED to have been realised in QSI. Despite the availability of quite a range of experimental results using a variety of probes, no consensus has yet been reached on what are the model Hamiltonian parameters describing $Ce_2Sn_2O_7$. This may very well be related to issues about variations between samples of nominally the same compound, and how e.g. preparation conditions impact the purity/nature of defects in the final sample. Achieving this may take some time, as has turned out to be required in related endeavours such as the search for Majorana zero modes for topological quantum computation, or the persisting uncertainty regarding the model parameters for $RuCl_3$

So, regarding the next steps, one can of course always dream of even more detailed experimental results – e.g. inelastic neutron scattering in the conditions achieved here, but with high wavevector resolution – but for the moment, this work puts the ball firmly back in the theorists' (and chemists') court. What is needed is a reliable description of the actual sample under consideration – not only fixing parameters of a model Hamiltonian but also understanding nature, level and influence of disorder; and then to provide an unambiguous analysis of the response functions being measured.

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