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The excitation spectrum of the U(1) Dirac spin liquid and its relevance to new Yb-based triangular lattice antiferromagnets

Quantum Electrodynamics in 2+1 Dimensions as the Organizing Principle of a Triangular Lattice Antiferromagnet
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Recommended with a Commentary by Joel E. Moore, University of California, Berkeley, and Lawrence Berkeley National Laboratory

The possibility of liquid-like ground states in triangular-lattice magnets has attracted attention at least since the work of Anderson fifty years ago, which introduced the concept of a spin liquid and argued that one might exist deep within the Mott-insulating phase of the Hubbard model on this lattice. While later work is generally accepted to have shown that the actual state deep in that phase has long-ranged three-sublattice order, new materials and theoretical studies have clarified where the long-sought triangular lattice spin liquid–indeed, several distinct kinds of such liquids–might be found. The theoretical paper by Wietek, Capponi, and Läuchli [1] that is cited in the header is an example of ongoing efforts to understand how the signatures of one kind, the U(1) Dirac quantum spin liquid, can be detected in real and numerical experiments. This question is highly topical in light of recent experiments, chiefly using inelastic neutron scattering, on a number of Yb-based triangular lattice compounds; four examples are Refs. [2–5], which are believed to have lower levels of chemical disorder than revealed in earlier Yb materials [6]. Another observation is spin specific heat that scales with the square of temperature at low temperature [5], consistent with expectations for independent Dirac spinons. As work has continued on spin liquids more or less unabated for decades, it is impossible in a brief article to give a full and fair perspective, and readers may wish to consult longer treatments for background. The focus here will be on explaining why the fairly technical paper [1] is a timely step toward understanding how the excitation content of this phase is visible in (numerical or real) experiments.

Anderson's original resonating valence bond proposal would now be viewed as an example of a $\mathbb{Z}_2$ spin liquid, which is a gapped topological phase that is known to appear in dimer models on the triangular lattice [7]. Another kind of gapped topological spin liquid, the chiral spin liquid, seems to appear in the Hubbard model close to the Mott transition, when additional interactions beyond nearest-neighbor Heisenberg coupling destabilize the three-sublattice order [8, 9]. The appearance of this state is believed to be driven primarily a four-spin coupling term [10], and yet another kind of spin liquid, with a Fermi surface of spinons, appears when this coupling is further enhanced. As a feature of frustrated magnetic models is that small changes in the Hamiltonian can lead to major changes in the ground state, and the interactions in any given material and their anisotropies may be fairly far from those in the Hubbard model, it is not too surprising that the spin liquid that is suggested by most experiments on the new Yb-based compounds is none of these. Most experiments have been interpreted in terms of nearest-neighbor J_1 and second-neighbor J_2 couplings, with values that in some cases have been extracted from fits to the neutron scattering spectra at high magnetic fields.

In the U(1) Dirac spin liquid, there is a gapless Dirac-like spectrum of spin excitations, interacting through an emergent gauge field whose importance we return to momentarily. Various computational and theoretical techniques have been applied to estimate where this phase appears in phase diagrams and even how it should look in inelastic neutron scattering experiments, which measure the dynamical spin structure factor $S(\mathbf{q}, \omega)$. Methods used include exact diagonalization of small systems, variational Monte Carlo based on trial wavefunctions for the phase, density matrix renormalization group (DMRG), and analytical methods like Schwinger-boson mean-field theory. One weakness of these methods is that none of them is both unbiased and fully two-dimensional; DMRG, for example, is typically carried out on cylinders that are very long in one direction but small in the other, with a circumference of around six or eight spins, meaning that estimating $S(\mathbf{q}, \omega)$ involves both an interpolation in $\mathbf{q}$ and an extrapolation to the thermodynamic limit. Considerable computational effort has been devoted to the phase diagram of the $J_1 - J_2$ model on the triangular lattice, which appears to support some kind of spin liquid phase for an intermediate range of J_2/J_1, beginning at around 0.06-0.08 in the isotropic case, and in modeling $S(\mathbf{q}, \omega)$ in that phase.

Another weakness of current theory, which the paper by Wietek et al. begins to address, is that just staring at either experimental or numerical spectra does not reveal much of the exciting gauge physics that this phase is expected to contain. In addition to the gapless spin excitations, there should be an emergent dynamical U(1) gauge field so that the overall theory is a form of three-dimensional electrodynamics (QED_3). Note that in a 2D material with charged Dirac fermions like graphene, the electromagnetic field still lives in three spatial dimensions. In the Dirac spin liquid, the spin excitations are neutral but still interact through a kind of gauge field, and the existence of such emergent gauge fields in correlated matter has been a holy grail since at least the early days of high-temperature superconductivity. Soon after influential mean-field theories of the Hubbard model were developed by Affleck and Marston, and Kotliar and Liu, it became clear that incorporating beyond-mean-field corrections led to a kind of gauge field that is expected to acquire dynamics and have various important effects on the observable low-energy properties of the state.

Similar analytic methods (see for example a series of papers by Michael Hermele and collaborators for the U(1) case) yield many possiblities for spin liquids, on many different lattices, with Abelian or non-Abelian emergent gauge fields. However, it remained difficult to understand how the gauge field would affect microscopic spectra measured numerically or experimentally–in other words, the differences between a simple model of Dirac spinons with no interactions at low energy, versus the full theory with monopoles and other gauge excitations, were somewhat unclear. An important step in clarifying the consequences of the gauge fields was the relatively recent identification of the quantum numbers of the key excitations by Song et al. [11], which applied some of the considerable progress in recent years in analyzing band structures to bands of spinons. The goal of the Wietek et al. paper [1] is to compare the properties of different kinds of excitations in QED_3 from a model parton wavefunction, such as monopoles and fermion bilinears, with the spectrum from exact diagonalization of the $J_1 - J_2$ Hamiltonian in the putative spin liquid regime.

The key results are captured in Figure 4, which shows that the "zoo" of low-lying excitations from exact diagonalization of 36 sites can be recognized as excitations predicted by QED_3 because of their high overlap with different kinds of excitations in the model wavefunction obtained by Gutzwiller projection of partons. In their words, "We observe that almost every eigenstate in the dense low-energy ED spectrum has significant overlap with only one of the various excitation ansatz types." A caveat mentioned by the authors is the possibility that QED_3 only describes a quantum critical point in the model between conventional and valence-bond-solid phases, rather than an extended phase. Either way, a challenge for extending this study to larger systems and real experiments is that in exact diagonalization, one has direct access to excited-state wavefunctions, while in neutron scattering spectra and estimates of them using time-dependent DMRG, one instead probes the dynamics of observables. But if it is possible to extend this study and find distinct observable signatures of the various kinds of excitations predicted by the gauge theory, then the rich physics of this type of quantum spin liquid will finally be amenable to experimental characterization.

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