Quantum electrodynamics in a piece of rock

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Gauge theories, such as quantum electrodynamics, are a cornerstone of high energy particle physics. They may also describe the physics of certain unassuming materials. Recent theoretical work moves this idea closer to reality.

Refers to: Song, X.-Y., He, Y.-C., Vishwanath, A. & Wang, C. From spinon band topology to the symmetry quantum numbers of monopoles in Dirac spin liquids. Preprint at *arXiv* http://arxiv.org/abs/1811.11182 (2018) | Song, X.-Y., Wang, C., Vishwanath, A. & He, Y.-C. Unifying Description of Competing Orders in Two Dimensional Quantum Magnets. Preprint at *arXiv* http://arxiv.org/abs/1811.11186 (2018).

A quantum spin liquid (QSL) is an insulating state of matter believed to appear in materials such as Herbertsmithite (pictured). QSLs are notorious for their absence of signatures in magnetic measurements — they have no magnetic ordering at the lowest temperatures. Hidden under the apparently-inert exterior of such a state is the emergence of a gauge theory, a cousin of the Standard Model of particle physics. A gauge theory can be defined as a theoretical framework in which forces are described in terms of curvatures. That a gauge theory emerges at low energies is a statement about the patterns of long-range quantum entanglement in the ground state. One concrete consequence of this emergence is the fractionalization of quantum numbers: the low-energy excitations of a QSL can have a charge or spin which is a fraction of that of the constituent electrons. No single electron has ever been split apart, but when many of them get together, the excitations can behave as if they are fractions of an electron. The price for these remarkable phenomena is that the gauge theory is strongly interacting, and, like other strongly-interacting theories, hard to study. In two recent papers [1, 2], Xue-Yang Song and co-workers describe how to overcome a long-standing theoretical impasse in the study of QSLs.

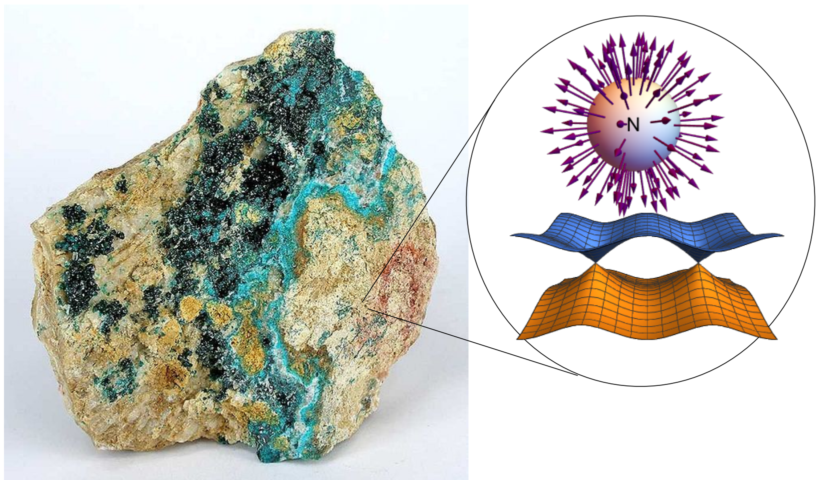

Figure. Herbertsmithite (left) is believed to host a Dirac spin liquid [10] (with a representative part of the band structure shown on lower right). The quantum numbers of emergent monopoles (upper right) clarify the experimental signatures of this state.

Like all ground states of matter, QSLs can be categorized by their low-energy excitations, which can be gapped or gapless. The best theoretical understanding is of the gapped cases but candidate QSL materials (such as Herbertsmithite, 2D organic salts and $YbMgGaO_4$) so far seem mostly to be gapless (for a detailed review, particularly of the experimental situation, see Refs. [3, 4]). A gapless QSL without a Fermi surface, called a Dirac spin liquid, is special, and is a candidate ground state for several simple models as well as several materials (such as Herbertsmithite and $Ba_8CoNb_6O_{24}$). A Dirac spin liquid is described in terms of spin-half fermions with a massless Dirac dispersion, coupled to an emergent photon field. This gauge theory is just like the Quantum Electrodynamics of particle physics textbooks, except that it is in 2D and at strong coupling, and therefore not yet perfectly understood. The fermions of a Dirac spin liquid, called spinons, are neutral under ordinary electromagnetism. Where in this sophisticated description is the ordinary spin? In terms of the gauge theory variables, the actual spin degree of freedom is a composite object, like a hadron in quantum chromodynamics (QCD), which is made of two or more quarks.

One achievement of Song et al. [1, 2] is to demonstrate (building on earlier work [5]) that in 2D systems the Dirac spin liquid plays the role of a 'parent' state, in terms of which the whole phase diagram may be understood. This description builds on the understanding of QSLs in 1D, where gauge theory is less exciting than in higher dimensions, for example because there are no propagating photons. Earlier work has shown that in 1D, the analogous role of the parent spin liquid state is played by the Luttinger liquid [6]. In particular, an ordered state neighbouring the Luttinger liquid in the phase diagram has a symmetry-breaking pattern that is determined by the quantum numbers of the operators by which the Hamiltonian of the parent state is perturbed to get there.

To show how the Dirac spin liquid acts a parent state, Song et al relied on the fact that it is the deconfined phases of a gauge theory that can describe QSLs. Deconfinement means that charges can be separated at finite energy cost, like in electromagnetism and unlike in QCD, which confines quarks. The deconfined phase of a gauge theory in two spatial dimensions can be understood by making an analogy to the familiar quantum mechanics of a particle in a double-well potential. The apparent ground-state degeneracy of the double-well system is lifted by quantum tunnelling events (called bounces), which move the particle from one minimum of the potential to the other. Notice that the degeneracy would not be lifted if only even bounces were allowed, in which the particle tunnels out and back. In the deconfined phase of the gauge theory, the analogue of the two-level degeneracy is the masslessness of the emergent photon. The analogues of the processes mediated by the tunnelling events are called monopole operators, because the relevant field configuration is exactly a magnetic monopole in Euclidean spacetime [7]. The spectrum of spinons determines which tunnelling events (analogous to even bounces) are possible, and therefore determines whether the spin liquid state is stable.

An aspect of the spin-liquid tunnelling problem that is missed by the crude double-well analogy is that, in a gauge theory, the tunnelling events can carry other quantum numbers, such as charge or angular momentum. The contribution of Song et al. in Ref. [1] is to systematically identify the quantum numbers of the monopole operators under the symmetries of various physically-relevant lattices, building on earlier numerical work [8] by exploiting a decade's progress on free-fermion band topology. In Ref. [2], Song et al. then use this information to identify the nearby ordered phases that result when the gauge theory is confined by proliferating these monopoles, producing a detailed picture analogous to the Luttinger liquid understanding in 1D.

Does this help us know where and how to look for quantum spin liquids in experiments and in numerics? It does. The main idea is to identify the QSL by how it gets destroyed: the pattern of order in phases that neighbour the QSL encodes the quantum numbers of the monopole operators that were condensed to get to them. In addition, the monopole quantum numbers clarify the experimental signatures of such a Dirac spin liquid state, by telling us at which reciprocal lattice vectors various excitations should appear in light-scattering or neutron-scattering experiments.

This phenomenon of emergence of gauge theory in a material has been called [9] an "anti-GUT" (Grand Unified Theory), in the following sense. In a GUT, when we probe the theory at higher energies (for example by raising the temperature), the interactions describing electromagnetism and the weak and strong forces are unified into one big gauge group. In contrast, a spin liquid can be seen by a higher-energy probe to be made simply from interacting spins, with no gauge fields in sight. It is instead at lower energies where the gauge group is enlarged, and where these beautiful ideas are relevant to condensed matter.

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