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Emergent exotic quasiparticles in quantum spin liquid states

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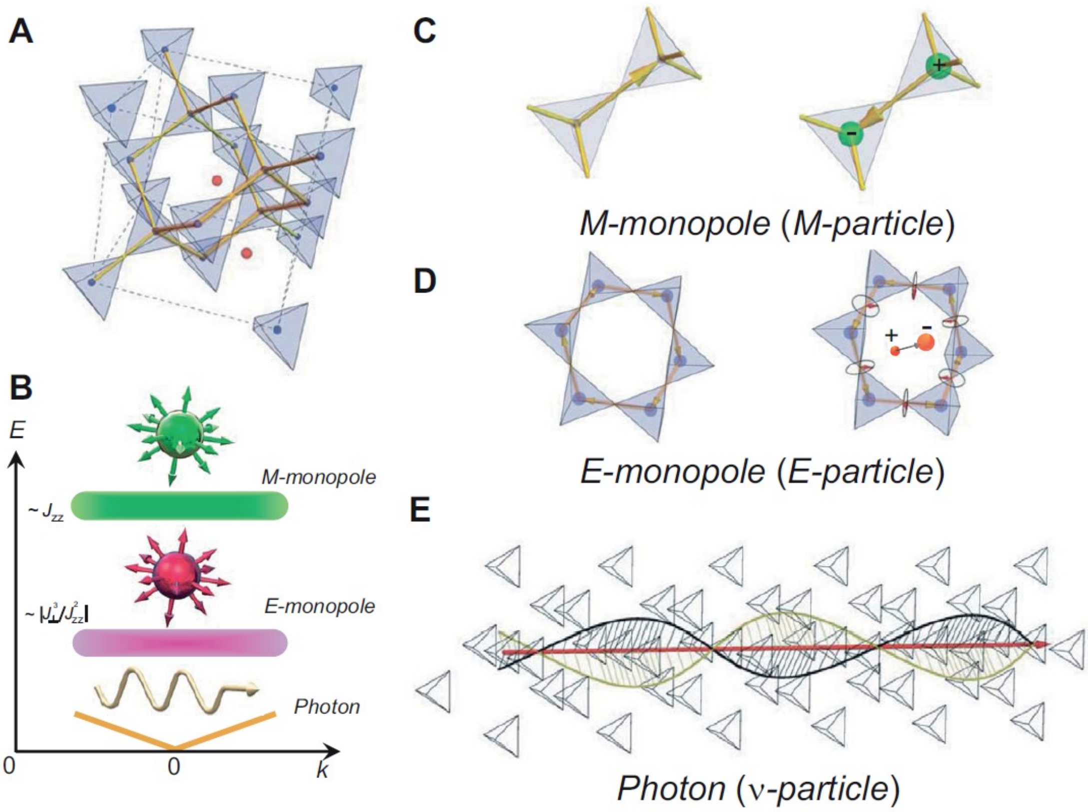
Quantum spin liquid (QSL) is an exotic quantum phase of matter whose ground state is quantum-mechanically entangled without any magnetic ordering. A central, yet poorly understood issue concerns the excitations that characterize QSLs, which are hypothetically associated with the quasiparticle fractionalization and topological order.

A rare earth pyrochlore oxide, where magnetic ions form an array of corner-sharing tetrahedra is one of perfect venues to host QSLs (Fig. A). The magnetic moments residing on the corners exhibit strong geometrical frustration, which produces a range of exotic magnetic excitations (Fig. B). In classical Ising spins with a strong easy-axis anisotropy, frustration results in a spin-ice state with macroscopically degenerate ground states, in which each tetrahedron has the two spins in and two spins out (2-in-2-out) configuration. A spin flip from this classical spin ice manifold can be considered as a pair creation of magnetic monopoles (*M*-particles) with 3-in-1-out and 1-in-3-out configurations (Fig. C), which interact with each other through the static Coulomb interaction. Additional spin interactions such as a transverse exchange term endow the spins with quantum fluctuations, which lead to a QSL state by lifting the macroscopic degeneracy. QSLs show extreme quantum entanglement that is manifested by topological defects and gauge fluctuations. The former can be represented by electric monopoles (*E*-particles, Fig. D), while the latter gives rise to novel excitations such as photons (*n*-particles, Fig. E), which mediates dynamic interaction between *E*- and *M*-particles. The *M*-, *E*- and *n*-particles in the QSL respectively correspond to Dirac-monopoles, electrons, and light in our world. The observation of these particles is a key to understand the QSL state. However, although the *M*-particles have been confirmed by several measurements, neither *E*- nor *n* -particles have yet been seen experimentally.

To reveal the quasiparticle excitations generated by spin degrees of freedom in the quantum magnets the thermal conductivity is a particularly suitable probe because of the following reasons. The specific heat often contains very large nuclear Schottky contribution at low temperatures. On the other hand, thermal conductivity is not contaminated by such local excitations, providing a highly sensitive probe for itinerant excitations [1][2][3]. In fact, low energy exotic spin excitations in QSLs are clearly detected by the thermal conductivity. Here we report highly unusual heat conduction generated by spin degrees of freedom in a QSL state of the rare-earth pyrochlore magnets, $Yb_2Ti_2O_7$ and $Pr_2Zr_2O_7$, both of which host spin-ice correlations with strong quantum fluctuations.

In the disordered spin-liquid regime of $Yb_2Ti_2O_7$, the thermal conductivity exhibits a nonmonotonic magnetic field dependence, which is well explained by the strong spin-phonon scattering and quantum monopole excitations. We show that the excitation energy of quantum monopoles is strongly suppressed from that of dispersionless classical monopoles. Moreover, in stark contrast to the diffusive classical monopoles, the quantum monopoles have a very long mean free path. We infer that the quantum monopole is a novel heavy particle, presumably boson, which is highly mobile in a three-dimensional spin liquid. [4]

We also report highly unusual heat conduction generated by the spin degrees of freedom in a QSL state of $Pr_2Zr_2O_7$. Above 0.2 K, the thermal conductivity shows a two-gap behavior, which is consistent with the gapped excitations of *M*- and *E*-particles. At lower temperatures, the thermal conductivity unexpectedly shows a dramatic enhancement, indicating the presence of another type of excitations. These low-lying excitations inside the monopole gaps can be attributed to emergent photons, i.e. *n*-particles, coherent gapless spin excitations in a spin-ice manifold. [5]



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