Quantum Spin Liquids: Fractionalization, Topology, and Confinement

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Quantum spin liquids (QSLs) are exotic quantum states realized in insulating magnets, in which large quantum fluctuations prevent magnetic ordering even at absolute zero temperature despite strong interactions between spins. A powerful framework for understanding QSLs is the resonating valence bond (RVB) picture, which describes a QSL as a quantum superposition of a macroscopic number of singlet configurations. Such a quantum superposition gives rise to strong quantum entanglement extending over the entire system. One of the most striking consequences of this macroscopic entanglement is fractionalization.

Fractionalization is a phenomenon in which the elementary degrees of freedom of a system behave as if they split into multiple quasiparticles. A celebrated example is the fractional quantum Hall effect, where electrons fractionalize into quasiparticles carrying fractional charge. In insulating QSLs, it is instead the spin degrees of freedom that fractionalize, giving rise to emergent particles such as spinons and Majorana fermions. Many QSLs host topological order, a new type of quantum order intimately tied to fractionalization, with deep connections to quantum information science and high-energy physics.

In this talk, I will review representative emergent particles in QSLs, focusing on the Kitaev quantum spin liquid, in which spins fractionalize into itinerant Majorana fermions and localized emergent Z_2 gauge fluxes. Under appropriate conditions, the Majorana excitations acquire a topological gap, giving rise to non-Abelian anyons. Anyons are quasiparticles that can exist only in two dimensions, with exchange statistics distinct from those of bosons and fermions. Non-Abelian anyons in particular, whose exchange transforms quantum states in a non-commutative manner, have attracted great attention as building blocks for topological quantum computation, which promises to dramatically reduce the burden of error correction.

I will further discuss confinement–deconfinement transitions of fractionalized particles. In the deconfined phase, spinons propagate as independent quasiparticles, whereas in the confined phase they are bound together to form conventional magnons. This physics is governed by the dynamics of emergent gauge fields and bears a deep analogy to confinement in quantum chromodynamics, where quarks are

never observed in isolation but are confined within hadrons. QSLs thus provide a rare arena in which the physics of gauge fields and confinement can be directly examined in condensed-matter laboratories.

Finally, I will present the half-integer quantized thermal Hall conductance observed in the Kitaev candidate material α-$RuCl_3$—direct evidence for itinerant Majorana fermions and chiral topological order—as well as a field-induced continuous confinement–deconfinement transition from an antiferromagnetically ordered state to a U(1) quantum spin liquid with a spinon Fermi surface, observed in a triangular-lattice quantum magnet. These results demonstrate that QSLs have evolved from a purely theoretical concept into an experimental platform for a unified understanding of fractionalization, topological order, and confinement—fundamental concepts of modern physics.

For a recent review, see:
Y. Matsuda, T. Shibauchi, and H.-Y. Kee, *Rev. Mod. Phys.* **97**, 045003 (2025).