Institute for Quantum Matter (IQM)
EFRC Director: Collin Broholm
Lead Institution: Johns Hopkins University
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Mission Statement*: To realize, understand, and control revolutionary quantum materials and structures where quantum effects such as entanglement and coherence find collective macroscopic manifestations.*

The discovery and characterization of quantum materials is one of the grand challenges of twenty-first century physical science. Developed though a deep understanding of their underlying physics, this new class of materials could play an important role in extending the information technology revolution and confronting the unprecedented growth in global energy needs. But despite many important advances, quantum materials continue to present deep fundamental challenges. How can we predict and control the collective properties of 10^{23} electrons in a solid and what novel quantum dominated states of matter and electronic properties may ensue?

With a distinct focus on the discovery and understanding of new materials and artificial structures, the Institute for Quantum Matter Energy Frontier Research Center (IQM) will realize materials and structures where quantum effects such as entanglement and coherence find collective macroscopic manifestations. We shall expose, understand, and control the corresponding physical properties and explore their potential for energy relevant technologies. To accomplish this IQM comprises a collaborative team spanning the materials-by-design triad of materials discovery and synthesis (single crystals and thin films), advanced experimentation (neutron scattering, optical spectroscopies, transport, ultrasound, and high magnetic field techniques) and theory (analytical and numerical). IQM will focus on the discovery of four specific types of quantum matter that have not previously been realized:

Topological magnetic semimetals. While topologically protected 3D Weyl semimetals with linearly dispersing bulk excitations have been documented for inversion symmetry breaking systems, Weyl semimetals induced by collective magnetic order remain hypothetical to date. We shall design, synthesize, and characterize materials with the goal of realizing magnetic Weyl fermions borne of correlations. In related work we will also investigate a new class of materials with quadratic band touchings – the Luttinger semimetal state. Such systems are predicted to be generically strongly interacting and show non-Fermi liquid correlations.

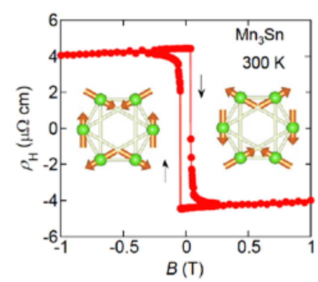

Fig. 1: Hall resistivity at room *T* in Mn_3Sn with spin configurations.

Quantum spin liquids. In a quantum spin liquid, quantum fluctuations destabilize magnetic order, even at *T*=0 K. There are now exactly solvable models with spin-liquid ground states and candidate materials to explore the underlying principles but definitive experimental evidence for a quantum spin liquid and demonstration of its topology remain elusive. IQM will develop new materials and spectroscopies to document emergent fractionalized excitations in quantum spin liquids – including photons and quantum Dirac monopoles – and utilize defects to characterize the underlying quantum spin liquid state.

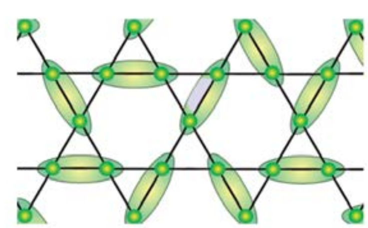
Fig. 2: A valence-bond configuration on a 2-dimensional kagome lattice. In a quantum spin liquid valence bonds resonate.

Topology in Superconductivity. When a superconductor is cooled below Tc, an energy gap opens in the single particle density of states, forming a gap much like that found in an insulator. Consequently, the recent advances demonstrating the crucial importance of topology, and the incompleteness of prior classification schemes, in true insulators should apply to superconductors as well. Recent work by IQM has shown that the traditional superconductor classification scheme, based on spherical harmonics, is incomplete, missing those that require "monopole" harmonics (Fig. 3). IQM will design, synthesize, and characterize materials and nano-scale structures to achieve and document a physical realization of monopole superconductivity.

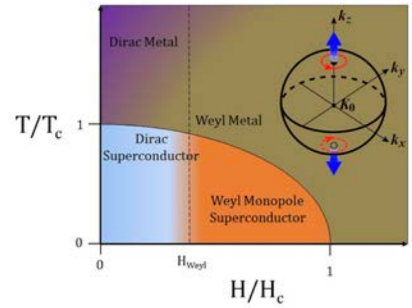

Fig. 3: The monopole superconductor has vorticity and may be realized in a Weyl semimetal.

Axion insulators. Topological insulators (TI) are unique states of matter that – despite an insulating bulk – harbor topologically protected surface states. We shall realize a related interacting magnetic state, the axion insulator. This is a theoretically proposed, but heretofore unrealized state of matter that is similar to a TI in possessing band inversion. However, axion insulators break time reversal symmetry and exhibit a large intrinsic magnetoelectric response that is quantized when inversion symmetry or another select point symmetry is preserved. Such systems are 3D analogs of the 2D quantum anomalous Hall systems and should show a quantized Kerr rotation for the inversion symmetric case and a measurable (and large) dc magnetoelectric response for the inversion symmetry broken state.

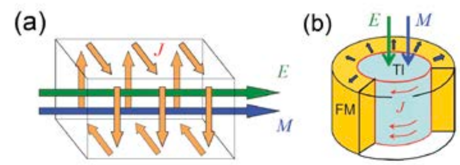

Fig. 4: Connection between magneto-electric coupling and surface current (a). TIs and axion insulators have a quantized surface anomalous hall effect. For TIs the surface states must be gapped by a ferromagnetic cladding layer (b) but this occurs spontaneously in axion insulators.

While each topic presents distinct challenges, there are also deep intellectual connections and cross-cutting methods and techniques so that successes in one area advances others. The unique physical properties of quantum materials present opportunities for breakthrough applications in energy and information. IQM is driven by the fundamental challenges that electronic correlations and topology present but as our understanding of quantum materials matures, we shall also bring their application potential into focus.

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