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Project Title	Theory of fluctuating and critical quantum matter
Senior Personnel	Leon Balents
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1 Executive Summary

The project developed the theory of electronic phenomena in quantum materials in which large fluctuations are present, driven by frustration, strong electronic interactions, topology, or other effects. Theoretical tools and results for specific materials were developed in parallel, allowing the results to be vetted and refined, and providing a resource for experimentalists. The results were reported in 53 publications over the period of the award. The sections below detail the most impactful scientific and technical results.

2 Defining the competition between spin-orbit coupling and Coulomb interaction

Just prior to the start of the award, the physics community discovered topological insulators, in which spin-orbit coupling induces a distinct electron band structure with robust properties, such as boundary protected from scattering, and intrinsic magneto-electric effects. The topological insulator occurs when Coulomb interactions between electrons are negligible. In our work[49], we showed that this spin-orbit physics exhibits an intricate interplay with Coulomb interactions, which dominate in much of transition metal and rare earth compounds. We developed a global phase diagram which describes the combination of these two important effects and defined the platform for many theoretical and experimental works to follow in the community. This work was also central to an influential review article we authored[39].

3 Quantum spin ice

The term “spin ice” refers to a class of magnetic materials with classical two-state moments which experience short-range interactions that force them into a constrained set of configurations which share an identical mathematical description with the positions of protons in water ice. Famously, both water and spin ice consequently exhibit an entropy plateau at low temperature, where these positions remain disordered. In 2011, we collaborated with experimentalists to uncover clear a material, $\text{Yb}_2\text{Ti}_2\text{O}_7$, which contains spin-ice like moments but with pronounced quantum dynamics[45]. We showed how to model such materials, which we dubbed quantum spin ice and how to quantitatively reproduce their dynamics. This kicked off a wave of exploration of quantum spin ice materials, continuing to this day. We made many further theoretical contributions,[44,42,40,30] establishing that this class of materials (of which there are at least a dozen) can host a quantum spin liquid state which is a long-sought goal of the physics community and a potential resource for quantum science.

4 Non-Fermi liquid theory

One of the major open problems in the theory of metals is the nature of metals whose electrons have a very localized character. In some cases, the physical properties of such metals defy the standard Fermi liquid paradigm which describes usual weakly electron liquids. Such non-Fermi liquid metals have exceptional conduction, magnetic, and single-electron properties, which empirically are connected to the emergence of superconductivity and magnetism. In our research, we showed how a local model of strong correlations, known as the Sachdev-Ye-Kitaev model, can be used to describe such unconventional metallic states[25]. This work became a paradigm for many other studies following similar techniques for non-Fermi liquid metals.

5 Thermal Hall effect

A thermal Hall effect is the flow of heat perpendicular to a temperature gradient. If the perpendicular component is large, it can be enabling for technological applications that separate heat from electricity, for example. In an insulator, the thermal Hall effect is considered an indicator of topology, and is sought-after as a probe of quantum physics. In our work, we addressed the dichotomy of heat carried by vibrations of the lattice and by electronic degrees of freedom. It is the latter that are of primary interest for quantum science, but both are generically present. In our work[22], we showed how heat flows back and forth between the two subsystems, and established how such

heat transfer and equilibration is integral to the observation of quantized responses. This is central to the interpretation of thermal Hall experiments in insulators.

6 Moiré materials

In 2019, the discovery of magic angle graphene showed that superconductivity and other emergent states can be created by simply twisting two or more layers of two dimensional materials relative to one another. In this project, we developed some of the fundamental theory for the rapidly growing field of moiré materials. We showed how to construct “continuum models” for these structures, which enable reducing the problem of samples with unit cells of tens of thousands of atoms to an effective Schrödinger like equation whose bands are easily obtained[19]. We initiated the study of moiré magnets, in which magnetically ordered materials are twisted to control their magnetic properties and textures[15,10].

Publications supported by this award

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