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Statement of Research Interests

My general area of expertise is theoretical condensed matter physics. I explore the collective behaviors of strongly interacting electrons in solid state materials, as well as atoms and molecules in trapped ultra-cold gases. My work is focused on the fundamental understanding of nature, and motivated by the experimental discovery of unconventional physical phenomena. In this regard, I use quantum field theory and computational methods to study quantum phases and phase transitions in diverse contexts: superconductors, heavy fermion (Kondo) materials, frustrated magnets, topological insulators, and ultra-cold atoms. In addition to working by myself, I have a lasting collaboration with theorists and experimentalists at Johns Hopkins University as an adjunct professor. My other active collaborations include NIST/JQI, Pennsylvania State University and Rice University. The following is an outline of my research plans and related accomplishments in three separate areas of my current interest.

1. Topological insulators

All essential physical properties of a material can usually be determined by measurements on a single microscopically small piece of it. For example, local probes can reveal the crystal symmetry and structure of the entire material, or if the material is superconducting or magnetic. However, a class of materials have a non-trivial topology, so that some of their properties cannot be measured by any local probe. The best known example are two-dimensional electron gases subjected to strong magnetic fields in semiconductor quantum wells. This system can establish a quantum Hall state (QHS), which until recently has been the only topological state of matter unambiguously realized in solid state materials. A QHS is electrically insulating but supports special dissipationless currents along its entire boundary that cannot be eliminated without destroying the bulk state. No measurable local property of the bulk reveals that the boundary currents are protected against all possible imperfections of the material; this feature can be observed only by global (transport) measurements. QHS nowadays provide the most precise and accurate standard for resistivity measurements, and the exotic fractional QHS stabilized by interactions among electrons have been identified as a promising platform for building a topological quantum computer.

A new class of materials with non-trivial topology have been discovered recently, and dubbed simply topological insulators (TI). They exist in both two and three-dimensional forms, and behave as insulators in the bulk that have a topologically protected metallic state at the boundary. Unlike QHS, they are shaped by the materials' intrinsic spin-orbit coupling rather than an externally applied magnetic field. Since their theoretical prediction and subsequent experimental discovery a few years ago, the field of topological states of matter has seen an enormous proliferation of studies. Most fundamental problems on TIs have been quickly solved because the first available TIs were conventional band-insulators of weakly interacting electrons and thus amenable to the analysis by highly developed analytical and computational methods of quantum mechanics. At this time, however, the experimental discovery of new materials with strong spin-orbit coupling, such as Kondo insulators and iridium oxides, shifts the focus of the field toward the topological physics of strongly interacting electrons. I have been one of the pioneers in the area of strongly correlated TIs, and currently collaborate with the experimental group of Collin Broholm at Johns Hopkins University which is in a leadership position to carry out neutron scattering experiments on the prominent topological Kondo insulator SmB6. My exploration of correlated TIs has taken three separate directions described below, all of them since my arrival at GMU.

First, I proposed and analyzed a way to experimentally realize novel superconducting and correlated insulating states of matter in quantum wells made from the early TI materials such as Bi2Se3 or Bi2Te3. The
needed interactions among the quantum well electrons can be induced by their immediate proximity to a superconducting material in a gated heterostructure device. Their quantum state can be manipulated by applying a gate voltage. The natural Rashba spin-orbit coupling in the TI quantum well creates an extremely strong momentum-dependent “Zeeman effect” which can lower the energy of induced “inter-orbital” spin-triplet Cooper pairs to the point that they become stable. These Copper pairs are then predicted to form a two-dimensional superconductor bearing a vortex lattice of circulating spin supercurrents, analogous to the well-known Abrikosov vortex lattice in conventional superconductors. A gate-tuned quantum phase transition out of this state is expected to yield a time-reversal-invariant incompressible vortex liquid with fractional excitations, in analogy to the numerically studied transitions of bosonic particles in effective magnetic fields. Both the fundamental physical principles and the essential properties of the available materials (such as the attainable electron densities, the strength of the spin-orbit coupling and induced pairing interactions) promise the feasibility of these quantum states. The fractional TI in this system would naturally have gapped quasiparticles with non-Abelian statistics, and thus be amenable to topological quantum computing applications in the same fashion as envisioned for the elusive non-Abelian fractional QHS.

While I continue to examine the properties of this setup, my immediate focus has turned to the Kondo insulator material SmB$_6$ (samarium hexaboride), which is considered to be the first serious candidate for a natural strongly correlated TI and hence attracts a lot of interest in the field. This second line of my TI research involves a close collaboration with experimentalists at Johns Hopkins. So far, they measured the detailed dispersion of a collective exciton mode in SmB$_6$ using inelastic neutron scattering, and I provided a quantitatively accurate theoretical interpretation of the results using perturbative quantum field theory. The existence and coherence of this mode in a three-dimensional crystal is a testimony to very strong interactions among electrons. Going beyond the bulk experiment, I begun analyzing the consequences of such strong interactions on the dynamics of the topologically protected metallic boundary of this material. The same theoretical methods that explain the observed bulk mode also predict a variety of unconventional states of matter that can settle at the SmB$_6$ boundary. Depending on the detailed interface properties between the SmB$_6$ crystal and its surrounding, the possibilities range from two-dimensional non-Fermi liquid metals and magnetically ordered states to exotic algebraic spin liquids. My immediate plan is to explore these preliminary predictions in greater detail and characterize the observable properties of these states. Most of these states of matter are potentially realistic, and their discovery in correlated TIs would undoubtedly revolutionize this young field. Even more interesting are the exotic quantum states that could be realized in quantum wells made from SmB$_6$. This two-dimensional quantum system is very similar to the TI quantum well described above, but contains natural strong Coulomb interactions among the “heavy” electrons from the samarium’s f-orbitals and thus does not require artificially engineered correlations by a superconducting proximity effect. A double-gated SmB$_6$ quantum well could be driven through a quantum phase transition between vortex lattice exciton condensates and exotic fractional incompressible quantum liquids. A part of my long-term plan is to explore this physics and propose its concrete experimental realizations. I will also continue and expand my direct collaboration with experimentalists at Johns Hopkins. Among them are Peter Armitage who studies the SmB$_6$ surface states by AC optical conductivity measurements, and Tyrel McQueen who grows SmB$_6$ crystals and characterizes their various properties.

My third line of research in the field of TIs is purely theoretical. It seeks to characterize and classify the phenomenology of all possible fractional TI states of matter. The Rashba spin-orbit coupling, responsible for the existence of TIs, is an example of a static Yang-Mills gauge field presented to electrons in real materials (dynamical non-Abelian Yang-Mills gauge fields have been first identified in high-energy physics as mediators of the weak and strong nuclear interactions). This gauge field produces a peculiar spin-dependent “magnetic field” that gives rise to phenomena similar to those arising from ordinary magnetic fields. In particular, I predicted the existence of incompressible quantum liquids that arise from the Rashba spin-orbit coupling and have fractional quasiparticles analogous to the ones found in the experimentally observed fractional QHS.
prediction follows from my extension of the well-known Chern-Simons effective field theory of fractional QHS. There is a large number of works that aim to classify the exotic fractional states of matter, where quasiparticle excitations carry a fraction of the fundamental electron's charge and spin. This is an integral part of our understanding of nature. Similar classification of phenomena have led to the discovery of quarks in high-energy physics (which are an example of fractional quasiparticles), and the quantitative descriptions of continuous phase transitions in all areas of physics. The classification of fractional quantum states is far from being complete, and it seems that an entire new world of such states awaits discovery in correlated TIs. The major practical problem is how to experimentally detect such states when they may be completely insulating and no local probe is adequate. A part of my fundamental research aims to find some solutions to this problem.

The solid-state bulk crystals and heterostructures are just one group of promising systems that could realize fractional TIs and other novel forms of matter. I will also look into the other candidate systems, such as strained graphene and ultra-cold atoms. Both are emerging platforms for engineering artificial gauge fields, including even the non-Abelian ones. In addition to insulating topological states, my interests broadly include topological superconductors and magnetic Mott insulators. I anticipate studying many such systems by field-theory methods in the long run.

2. Ultra-cold atoms

Trapped gases of cold atoms are a non-traditional condensed matter system where interactions between particles can produce non-trivial collective behaviors. Atoms and simple molecules numbering up to millions can be trapped by magnetic and optical means in a small volume at a very low density, and cooled to incredibly low temperatures (picokelvins above the absolute zero) where quantum mechanics dominates their collective motion. An entire research field of “quantum simulation and engineering” has emerged in atomic physics after a series of technological advances: laser and evaporative cooling, optical lattices and artificial gauge fields, etc. At the same time, interacting atoms give rise to various correlation phenomena that cannot be observed in any solid state material, such as the tunable universal crossover between the weak and strong-coupling superfluidity (or superconductivity).

My work in this field has been motivated by the fundamental discovery and characterization of novel correlated states of matter, as well as the attempts to indirectly understand some aspects of high-temperature superconductivity in copper oxide materials. My early work was the first to identify a zero-density quantum critical point as the origin of the universal (system-independent) properties of the mentioned crossover between different regimes of superfluidity\textsuperscript{9-10}. It considered both uniform\textsuperscript{9} and lattice\textsuperscript{10} systems of atoms, and made some quantitative predictions that have been confirmed in numerical studies\textsuperscript{11}. My follow-up work analyzed fermionic superfluidity in rotating traps and provided some new insight into the quantum vortex lattice melting and the long-standing problem of “re-entrant” superconductivity in high magnetic fields\textsuperscript{12-13}. Lastly, I have been exploring unconventional lattice insulators and superfluids of resonantly interacting fermionic atoms in the crossover regime. My collaborators and I predicted the existence of novel states of matter known as pair density-waves (PDW)\textsuperscript{14}. This line of my research is currently funded by the NSF and supports the work of one of my graduate students at GMU.

PDW states are superfluids or Mott insulators of atomic Cooper pairs that spontaneously break the translation symmetry of the underlying crystal lattice. I discovered that they arise quite generally from pairing instabilities among attractively interacting fermionic atoms in ordinary band insulators with multiple bands\textsuperscript{14}. This effect of spatially modulated superfluidity is typically very weak, but strictly speaking wins over the conventional uniform superfluidity at the lowest temperatures. The physical mechanism responsible for the PDW states involves inter-band pairing and thus has peculiar connections to solid state multi-band superconductors, such as iron-based superconductors and possibly cuprate superconductors (which may reflect Cooper pairing on
the Fermi surface reconstructed by a “hidden order”). A special case of PDW states are the well-known Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) states, proposed a long time ago to describe magnetized superconductors in magnetic fields that create a strong Zeeman effect. Spin-orbit coupling is another agent capable of stabilizing PDW phases, which I begun exploring very recently.

My main short-term goal is to map out the phase diagram of PDW and FFLO superfluids in simple tight-binding lattices with two or more bands. This work is mostly conducted numerically by calculations on the GMU’s superconducting cluster, and the method is based on the typical mean-field approximation in the quantum field theory of attractively interacting atoms. The main goals are to understand the evolution of PDW states due to variations of the model parameters, and design realistic experimental setups that could create and detect such states. We are mainly motivated by the desire to understand the fundamental physics of spontaneous spatial modulations in superfluid states, a general phenomenon that is seen in various high-temperature superconductors.

Our preliminary results indicate a broad range of stability for lattice FFLO states in two spatial dimensions. This is an important result because FFLO states have remained elusive in all experimental searches so far. Some theoretical studies have shown that FFLO states are hardly stable in two or three dimensions, while their one-dimensional version is stable in a large portion of the phase diagram even though it lacks a true long-range order of spatial oscillations. Our study now shows an experimentally practical route to stabilizing FFLO states in multiple spatial dimensions, and we expect to gain a qualitative understanding of the full phase diagram in the nearest future.

My long-term goal is to explore insulating PDW states of matter, which are possibly related to the puzzling “pseudogap” state of high-temperature superconductors. The existence of strongly correlated insulators of Cooper pairs is clearly predicted by the field-theoretical renormalization group and perturbative calculations that I carried out recently. The insulating state of lattice fermions generally exhibits the same crossover between the weak and strong-coupling regimes, just like the superconducting phase. This is especially true in two spatial dimensions where a continuous phase transition out of a superconducting phase is guaranteed to produce either a metallic ground state or a correlated Cooper-pair insulator. The analogous phase transition out of a PDW superfluid can stabilize an unconventional PDW Mott insulator of Cooper pairs that breaks the lattice symmetry. This part of the project will be done in collaboration with the numerical expert M. Rigol at Penn State University. We will perform numerical spectroscopy by exact diagonalization, and track the evolution of the “pseudogap” from zero to finite temperatures in a simple model system. I will also apply non-perturbative field theory methods to qualitatively predict PDW orders that arise from quantum fluctuations of Cooper pairs in multi-band lattice potentials. Some of our predictions will be directly testable in experiments. One of our goals is to better understand high-temperature superconductors: the atomic system very transparently exposes the pairing “charge” fluctuations near the transition, allowing theorists to identify unambiguous experimental signatures of such fluctuations. Applied to cuprates, these insights might be able to shed some light on the debate about the nature of their “pseudogap” state. Another goal is to seek new exotic states of quantum matter. Quantum fluctuations of topological defects are extremely influential in two spatial dimensions, and possibly lead to the hypothesized but still unobserved exotic deconfined quantum critical points in the phase diagram. Of course, the experimental accessibility of this system provides a special motivation for this investigation.

The ability to study correlated states of matter with cold atoms is developing very rapidly, therefore I will likely continue to frequently place my research in this context. I am particularly interested in the progress on artificial gauge fields engineered by the Raman coupling to internal atomic states or via non-optical means utilizing an atom-chip. Artificial magnetic fields and spin-orbit couplings involving bosonic atoms have already been demonstrated in a laboratory, promising a practical route to cold atom quantum Hall effects. Since coming to GMU, I have discussed and collaborated with I. Spielman (NIST), who pioneered this technique, and hope to theoretically accompany his planned studies on vortex lattice melting transitions and topological insulators. Some of my most recent work on correlated topological insulators is placed in the cold atom context, where it derives its motivation from the pioneering experiments in the Spielman's group.
3. High temperature superconductors

My broader research interests include other open problems of strongly correlated electrons, especially high-temperature superconductivity in copper-oxide and iron-based superconductors. I made several contributions to this field. My most notable work addressed the measured Nernst effect and subgap features in the electron density of states in cuprates, by exploring the quantum dynamics of vortices in the presence of nodal quasiparticles. My work on iron-based superconductors has scrutinized two separate phenomena: the phase diagram and pairing symmetry of multi-band superconductors, and the universal scaling of various observables in the superconducting phases that feature nodal quasiparticles. The problem of cuprate superconductivity is almost thirty years old and unsolved despite a historic effort that largely shaped the modern condensed matter physics. The world-wide front of superconductivity quickly shifted to the new problem of iron-based superconductors upon their discovery, but it turned out that these materials are even more complicated than cuprates while probably not being an equally great platform for new physical paradigms. The progress in both areas depends heavily on the future experimental developments and technology improvements. So, my long-term goal is to continue following the activities in this field and make new contributions to it when good opportunities arise. In the meanwhile, I am slowly developing several ideas for theoretical investigations of unconventional phases in multi-band superconductors, as well as a new (probably computational) approach to renormalization group that could map the phase diagram of competing orders in high-temperature superconductors by adapting to different types of emergent dynamics at different length-scales.

References