Research Statement

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Overview

My research interests are focused on the discovery and understanding of quantum materials, through a wide range of experimental approaches, from material synthesis, to device fabrication, to transport and magnetization measurements, to X-ray and neutron scattering. As elaborated in a recent US Department of Energy (DOE) workshop [1], quantum materials are "solids with exotic physical properties, arising from the quantum mechanical properties of their constituent electrons", and present enormous technological and economic potential. Exploring these systems prompts deeper understandings of the interplay of symmetry, topology, dimensionality, disorder, and strong correlations in macroscopic observables, and is considered by the National Science Foundation (NSF) as one of its 10 big ideas: the quantum leap. My research experience on high-T_C superconductors, charge density wave conductors, and quantum magnets has provided me with a unique track record in tackling the following problems: understanding the nature of superconductivity in high-T_C superconductors and topological superconductors, understanding the nature of itinerant electrons on geometrically frustrated lattices, and searching for novel phases in metallic frustrated magnets. These are some of the most pressing problems that both NSF and DOE have been actively supporting in recent years.

Past & ongoing research

My previous research has focused on some important classes of quantum materials: high-T_C superconductors, charge density wave (CDW) conductors, and quantum magnets.

1. High-T_C superconductors

My work on cuprates has resolved the controversy surrounding the occurrence of the Kosterlitz-Thouless (KT) transition in cuprate superconductors [2-3], and provided the first experimental evidence that the intrinsic dynamics in the KT critical regime and the low temperature ordered phase are correlated [4], confirming a forty-year old theoretical prediction. I have also studied the vortex phase diagram of the underdoped cuprates at high magnetic field (H) and zero temperature (T) limit. Through a carefully designed study, as reflected in the choice of material, probes that couple to the vortex matter directly, and an unprecedented range of H and T, I have established a unified perspective on the vortex phase diagram of underdoped cuprates [5], and more importantly, discovered an unanticipated state of matter: hidden order of Cooper pairs [6].

Recently, I have been studying the phonon dispersion relation in a newly discovered iron-based high-T_C superconductor, $Ca_{0.73}La_{0.27}FeAs_2$, the parent compound of the CaLa112 family [7-8], using inelastic X-ray scattering, and I hope to gain insights on the role of phonons and coupling between lattice and spin/charge degrees of freedom in iron-based high-T_C superconductors [9].

2. Charge density wave (CDW) conductors

CDW materials have also been a focus of my research. During my PhD, I mainly studied the dynamics across the CDW transition in nanoribbons of quasi-1D systems, such as $NbSe_3$, using noise spectroscopy [10-11]. At Duke, I have been studying the nature of CDW and its interplay with SC in the one-dimensional superconductor $Ta_4Pd_3Te_{16}$, at both ambient and high pressure, using synchrotron X-ray scattering and the de Haas-van Alphen oscillations measurements [12].

3. Quantum magnets

Following recent advances in the field of quantum magnetism, I joined Duke University and worked on field- and pressure-tuning of quantum magnets and mapping of their phase diagrams, with techniques such as magnetization measurements and X-ray/neutron scattering. One of the systems I studied is doped Shastry-Sutherland systems, in which a Resonating Valence Bond (RVB) superconductivity was predicted but has so far evaded experimental realization. In this system, I have found an unexpected, rich impurity-related phenomenology [13], which also intrigued me to extend the study to high pressure.

Beyond the Shastry-Sutherland systems, I have studied the quantum spin liquid candidate $YbMgGaO_4$ using magnetization measurements and neutron scattering, and the results resolved the controversy over the nature of the spin liquid state in this material [14]. Meanwhile, I have also been working on the synthesis and characterization of new quantum magnet systems. The importance of material synthesis for the discovery of new quantum materials cannot be overstated, and it continues to be a critical aspect of my research interests.

Future research

My experience working in very different fields has placed me in a good position to tackle some of the most pressing problems in condensed matter physics.

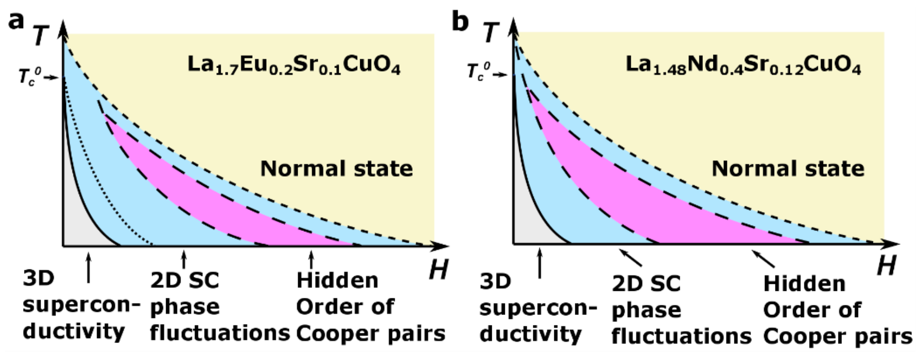

Fig. 1: Schematic *T*-*H* phase diagram of striped La-214 cuprates. A magnetic field (H) perpendicular to CuO2 planes suppresses the 3D superconductivity (gray) and leads to the decoupling of CuO2 layers; the decoupling field (dotted line) is higher in $La_{1.7}Eu_{0.2}Sr_{0.1}CuO_4$ because of its weaker stripe correlations. However, strong SC phase fluctuations (blue) persist in the planes, corresponding to a SC state with $T_C = 0$. The hidden order of Cooper pairs (pink), appears to compete with the $H = 0$ superconductivity. Reproduced from Ref. [6].

1. High-T_C superconductors

Figure 1 shows the schematic *T*-*H* phase diagram that I have established with transport measurements [6]. Much remains to be done to understand the nature of the hidden order phase and the high-field normal state. Transport measurements, mostly sensitive to the vortex matter and SC order, suggest that the hidden order of Cooper pairs originates from rearrangement of the SC order in the plane. However, little is known about the role of the charge/spin stripes, and the evolution of this phase with doping.

(1) I plan to establish my own sample growth capability. Some simple but powerful technique, such as flux method, will be used to grow single crystal samples for this study. If needed, I will also apply to use the NSF-funded user facility PARADIM at Cornell University. Moreover, I will also establish external collaborations with groups such as Sara’s at Duke, where a state-of-the-art optical floating zone furnace is available to grow high quality single crystals. Once samples are available, I plan to explore the doping-dependence of the hidden order phase in striped cuprates.

(2) Tunnel diode oscillator (TDO) measurements, which were successfully used in my previous work to detect small magnetization change in Mg-doped SCBO [12], are valuable tools for transport studies and magnetization studies. It is capable of detecting possible rearrangement of the spin stripes, which is especially useful in a large diamagnetic background of 2D SC phase fluctuations. I will continue my collaboration with Dr. David Graf of NHMFL, and more importantly, develop an in-house capability for TDO experiments. The magnet field required for such a study is not very high, and a 14 T (or even 9 T) magnet that is commercially available is enough. If higher field is needed, I will apply for magnet time and conduct the experiments at the National High Magnetic Field Laboratory (NHMFL).

(3) My study on $La_{1.7}Eu_{0.2}Sr_{0.1}CuO_4$ suggested that the high-field normal state crossovers from an ln(1/*T*)-dependent insulating phase to a metallic phase at *H* above 55 T [5]. Therefore, I plan to study and confirm the metallic behavior of resistivity at high *H*. Moreover, quantum oscillation has been observed in some of the "cleaner" cuprates, such as YBCO [15], but not in La-based cuprates, because they are often insulatinglike or not metallic enough. If the metallic behavior is confirmed at the fields, I plan to perform torque magnetometry measurements and search for de Haas–van Alphen (dHvA) oscillation with *H* up to 100 T. To perform these studies, I will apply for magnet time at the Pulsed Field Facility at Los Alamos National Laboratory and establish collaboration with local scientists.

(4) I plan to apply for beamtime in national neutron user facilities (ORNL/NCNR) and perform neutron scattering measurements. The temperature and field range are well within the reach of the sample environment capability in these Neutron facilities. Detection of stripe correlations using neutron scattering has provided the first evidence of intertwined orders of spin, charge, and SC [16]. A carefully designed study, guided by the phase diagram [6] obtained from the transport measurements, could provide crucial information on the rearrangement of the strips.

2. Topological superconductor

With a strong background in unconventional superconductivity, I plan to expand my research to topological superconductors. Topological superconductors [17] and topological matters [18] in general, have been the center of the condensed matter research in recent years, because of their significant scientific and technological potentials. There have been two major pathways in realizing topological superconductors: (1) intrinsic topological SC materials in which the pairing parity is either odd or ill-defined; and (2) artificially engineered hybrid structures in which SC is introduced into topological non-trivial materials by the proximity effect. More recently, a gate-tuned transition from a two-dimensional topological insulator to an intrinsic superconductor has been demonstrated in monolayer WTe_2 [19], which offers potential for developing topological superconducting devices in a single material instead of hybrid structures. I am particularly intrigued by the fate of the helical edge states once the system becomes superconducting, and the nature of the SC phase itself in this system. I plan to study this and related systems using approaches like transport measurements and noise spectroscopy. Non-local transport, for example, is a particularly useful method to examine the helical edge state in the SC phase. I also plan to study the (topological) insulator to superconductor quantum phase transition in more detail, and compare its universality class with what was obtained in conventional and high-T_C superconductors. To get samples, I plan to develop my own device fabrication capability and fully utilize the state-of-the-art facilities at the Nano Tech Center at TTU. I will also actively seek collaboration opportunities with other experts in the field.

3. Metallic quantum magnets

Metallizing quantum magnets have been considered as one of the major pathways to realize new quantum states of matter [1]. Two approaches are generally adopted. First, traditional wisdom involves injecting mobile charge carriers into quantum spin liquids, or other frustrated quantum magnets, such as valence-bond solid. It is expected that the Resonating Valence Bond superconductivity would emerge. However, experimental situations have been difficult, because of the strong tendency for the doped charge carriers to be localized. My previous work on Mg-doped SCBO represents progress along this line [13]. Some promising material, such as a copper oxide kagome antiferromagnet, $Cu_5V_2O_{10}(CsCl)$ (averievite), has also emerged recently [20]. The second approach, namely searching for metallic materials featuring frustrated lattices, has attracted more and more attention in the last decade. This has been explored with both f-electron materials [21-22] and d-electron kagome metal [23]. While the kagome antiferromagnet herbertsmithite is found to host the quantum spin-liquid state [24], the kagome metals (semimetals), on the other hand, hold the key to some topologically nontrivial electronic states, such as "high-temperature fractional quantum hall states" [25]. For example, Fe_3Sn_2, an old material, featuring a spin-orbit-coupled ferromagnetic kagome lattice, has been "rediscovered" to show frustrated ferromagnetism [25] and signature of kagome-derived Dirac fermions [23].

Despite significant progress in the recent years, the field is still in its early age, and much remains to be done. I plan to pursue the study of metallic quantum magnets, using both approaches mentioned above. I will start with materials like Fe_3Sn_2, which are straightforward to grow with techniques like flux method. Because of the vital importance of the material development in this field [26], an important direction of my future research will be the synthesis and doping of promising materials. Once the single crystals of target material are successfully grown, it will be studied using an extensive arsenal of techniques: transport measurements, magnetization measurements, and X-ray/neutron scattering techniques. I hope to better understand the nature of itinerant electrons on various geometrically frustrated lattices; and discover novel properties, such as unconventional SC and fractional statistics, with systematic studies on a family of materials, using probes that are sensitive to different degrees of freedom.

<u>Science education</u>

Looking forward to my role as a faculty, I would like to take on more active roles in promoting science education with broader impact. I will actively recruit minority students and establish a culture of diversity and inclusion in the group. One of the best ways to promote science education is to better prepare the science educators. To this end, I would also like to extend my efforts beyond the university by building relations with local high schools, and actively recruit high school science teachers and expose them to the most recent developments in science and technology. I will also actively recruit high school student interns and expose them to scientific research at an early age. Meanwhile, I will provide guidance and help for them to apply for internship, scholarship and exchange opportunities. Finally, I will actively participate in outreach programs that will bring science to the general public, especially underprivileged groups.

<u>Conclusions</u>

My main research goal is to discover and understand novel quantum materials, with a particular focus on unconventional and topological superconductors, and metallic quantum magnets. In this regard, my research interests are complementary to those of several faculty members at Texas Tech University Physics. I am looking forward to achieving my research vision, playing an active role in science education and participating in department service and other broader impact activities at TTU.

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