Research Statement

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Search for the new phases of matter, development and engineering novel quantum materials has been one of the central focuses of condensed matter physics. These efforts have lead to the discovery of various materials such as unconventional superconductors, topological insulators, quantum spin liquid and *etc.* Traditionally, phases are explored using order parameters based on equilibrium statistical mechanics. This approach, however, cannot provide information on real-space **phase textures** such as electrical phase separation or equilibrium **dynamics** of phase textures that bound to occur as materials' coherence length approaches infinity. Moreover, any point on conventional phase diagram represents a state at its free energy minimum. Such equilibrium phase is just a tip of the iceberg of realizable phases of matter. Studies clearly show that equilibrium and out-of-equilibrium phase textures and their dynamics are crucial to understanding and creating new phases. A few examples include charge density wave (CDW) fluctuation and memory of CDW phase texture in cuprate supercondutors (*1*, *2*), hidden order discovered in nonequilibrium state of dichalcogenides (*3*), and switching noise observed in quenched manganites (*4*). Yet, until recently, dynamics has been associated with soft condensed matter systems to study fluid and particle dynamics because of the experimental limitation to access the relevant spatial and temporal resolution for hard condensed matter systems. **The real time observation of emerging phase textures in and out-of equilibrium** is an under explored and yet the future frontier of the hard condensed matter physics.

In order to observe dynamics, fast probe of real space texture is needed. Synchrotron based **coherent x-rays** are ideal for studying the phase history and dynamics of elementary collective phenomena. Coherent scattering from electronic and magnetic textures result in complex interference (speckle) patterns (Fig. 1). Such patterns encode the complexity of individual phase textures, and therefore provide direct insight into their structure, motion, and stability. We can show, for instance, that dynamical behaviors observed in soft matters are, in fact, also present in hard condensed matter systems (*5*). With the upcoming 4th generation synchrotron facilities and pixelated detectors, we will be able to reach time and spacial resolution of nanoseonds and subnanometers. I will utilize and develop coherent methods such as fast x-ray photon correlation spectroscopy (XPCS) and x-ray lensless imaging to study equilibrium and nonequilibrium dynamics associated with phase transitions.

I would like to focus my first few years at Texas Tech University on studying phase textures and dynamics in oxides and dichalcogenides (see Example 1), studying dissipative dynamics in thermo-quenched manganites (see Example 2), and discovering novel emergent phases in nanoscale functional materials (see Example 3). I hope to collaborate with Dr. Genda Gu at Brookhaven National laboratory and Dr. Anand Bhattacharya at Argonne National Laboratory for the samples, and NTC at Texas Tech University for fabrication. As a long-term project, I would like to develop methods and phase retrieval algorithms for lensless imaging, pushing for nanosecond and nanometer dynamic resolution to study strongly correlated materials (See Example 4). In addition, I would like to implement a table-top laser setup and mentor students in concepts and methods related to lensless imaging (see Example 5)

Example 1 Nature of CDWs in Transition Metal Compounds

Charge density waves (CDW) are ubiquitous in nature and emerge in the vicinity of various electronic orders. For example, CDWs exist in both cuprates and dichalcogenides, in competition with superconductivity. While their CDW formation mechanisms may differ, studies show that they possess similarly layered quasi-2D structure, electron couplings, and pseudogap effects (*6*). Particularly, CDWs are strongly coupled with lattice degree of freedom (*2*, *7*). Uncovering of universal relationship between CDW and lattice can disentangle complex intertwined phases in transition metal compounds. To understand the nature of this coupling, I will monitor speckle textures under both lattice and CDW Bragg peaks simultaneously through the CDW transition to study spacial and temporal extents of their coupling. **Cuprates:** I propose to study $La_{1.8-x}Eu_{0.2}Sr_xCuO_4$ (LESCO), whose low-temperature structural Bragg peak intensity shows a kink at T_{CDW} (*8*) (Fig. 2), indicating some coupling between the lattice and CDW. **Dichalcogenides:** I propose to study TaS_2, that has the most intricate CDW phenomenology of all the dichalcogenides, having three distinct CDW phases coupled with lattice transitions.

Example 2 Equilibrium and Non-equilibrium Dynamics in Manganites

Quenching is a nonequilibrium operation that can result in dissipative dynamics such as domain growth when operated on competing phases. Here, I propose to study $La_{1-x}Sr_xMnO_3$ (LSMO), a perovskite manganite upon thermo-quenching. In LSMO, charge and orbital order (CO/OO) emerges simultaneously at 240K, and is thought to be a precursor for the antiferromagnetic (AF) ordering at 110K. While phase separation in manganites is a well-established concept, conflicting results are reported for the existence of domain fluctuations (*9*, *10*). Recent research consensus indicates that orbital superexchange interaction plays a dominant role in its ordering mechanism. Studying CO/OO domain formations and their fluctuation (if any) in equilibrium and after the onset of quenching will provide additional insights to the ordering mechanism. I will study dynamics, as well as CO/OO domain textures using coherent soft x-rays at orbital and magnetic order Bragg peaks close to their transition temperatures.

Example 3 Quantum Confinement

Interfaces and boundaries of strongly correlated systems are under intense research because they possess electronic properties that are distinct from the bulk materials. This is especially apparent when the sample size becomes comparable to domain size of the underlying orders. In manganites, where multiple phases phase-separate, it is a question whether the phase domains spatially organize themselves to further reduce frustration at the boundary during magnetic phase transition. In addition, nanoscaled systems can easily be driven out of equilibrium with small external perturbations. I will study such finite size effect by combining nanofabrication and coherent x-ray scattering. To start, I propose to study a quasi-1D $La_{1-x-y}Pr_yCa_xMnO_3$ (LPCMO) strip fabricated from a thin film using ion implantation (*11*). LPCMO is known to host phase-separated regions of FM and AF/CO domains below its charge ordering and above its metal-insulator transition temperature. Theoretical calculation suggests the formation of edge states, such as edge stripes induced by magnetic field (*12*). Such stripe state can open various pathways toward ultralow-power integrated circuits (*13*). The phase texture of CO domains will be revealed via resonant diffraction pattern obtained at Mn abortion edge.

Example 4 Bragg CDI

Bragg coherent diffractive imaging (BCDI) is a lensless imaging technique that maps out a crystal's strain and domain textures in real space. It is a robust method where we can obtain real-space images of a sample from a single detector image, allowing for fast and high-resolution bulk 3D imaging. In collaboration with I. Robinson at the X-ray Scattering Group and CSX-1 beamline at NSLSII, BNL, I have been commissioning the capability of BCDI in the soft x-ray energy range using a magnetic phase domains (Fig. 3). This field is suitable for a long-term investment because technological improvements will continually provide faster and higher resolution images. Using this technique, we can image CDW and magnetic domain evolution in example 1 and 2 in real time.

Example 5 Tabletop Laser Setup for Lensless Imaging

A tabletop laser system is a simple, yet practical system to learn optics for undergraduate, provide hands on training of graduate students, test samples, and examine new methods of lensless imaging. It teaches basic concepts in optics such as light interference, dispersion, and diffraction. Yet, robust enough to demonstrate cutting edge coherence imaging methods such as in-flight holography and Fresnel CDI (*14*, *15*). A standard setup includes a laser source, a sample stage equipped with transnational and rotational axes, and a CCD or a photon counting detector to accumulate photon diffraction patterns. The system will be built inside an noise isolation hatch on an optical table. This set up can image with up to 0.5 μm resolution for a wide range of samples from nanoparticles to biological samples. When equipped with a polarizer and an analyzer, it will image magnetic domains using magneto-optical Kerr or Faraday effects.

As an upgrade to the system, I will equip a pump-probe system using a Ti-Sapphire laser and study driven, nonequilibrium dynamics in these systems. A cost estimate for the basic system is $50,000, and the upgraded system will cost an additional $100,000.

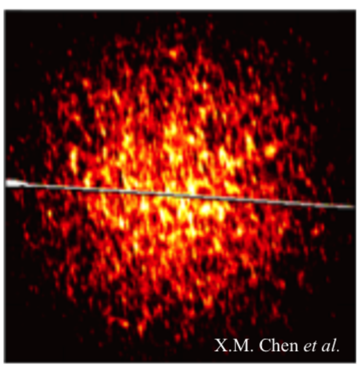

Figure 1: A typical speckle diffraction pattern on CCD camera when coherent x-rays are used (shown is CDW Bragg peak in LBCO)

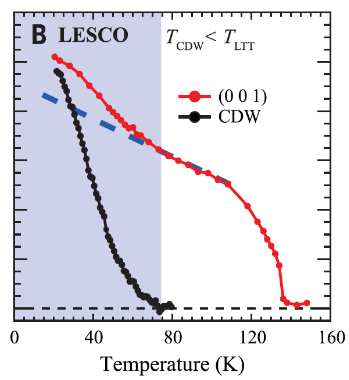

Figure 2: The scattering intensity of LESCO lattice and CDW Bragg peaks compared (borrowed from (*8*))

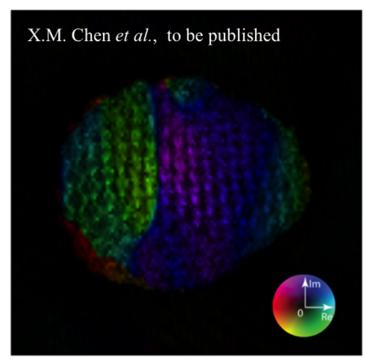

Figure 3: Real-space reconstructed image of the magnetic domains in antiferromagnetically ordered artificial lattice using Bragg CDI

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