Abstract

The **main objective** of this project is to spatially map the electronic and magnetic properties of tunable 2D Wigner crystal (WC) and quantum spin liquid (QSL) systems down to the atomic scale. WCs are insulating charge-ordered lattices of electrons that form at low electron density, whereas QSLs are frustrated Mott insulators that have no magnetic order down to T = 0 but that exhibit long-range quantum entanglement between spin centers. A central objective for WC systems is to directly image WC electronic wavefunctions and spin textures, as well as their behavior in the presence defects. We seek to visualize how WCs respond to strain, including pinning thresholds and glassy relaxation dynamics. Visualizing WC melting behavior and mixed phase coexistence is also a high priority. For QSLs a central objective is to image the behavior of charge-neutral spin-1/2 spinon excitations. These are notoriously difficult to characterize since they typically don't respond to applied fields. We will use new scanned probe techniques to image spinon quantum interference as spinons scatter off 2D surface structures, and we will test predictions that doping QSL systems should induce novel non-Fermi liquid ground states. We will test whether it is possible to observe gapped QSL behavior in materials whose properties appear to be described by the Kitaev spin model. Our overall **technical approach** is centered around the use of 2D materials in single-layer and bilayer electrical devices that are compatible with cryogenic atomically-resolved scanned probe microscopy. This creates opportunities to tune charge carrier density in WCs and QSLs through electrostatic gating, as well as to induce lateral E-fields and current density via side gates and contacts. We will probe these systems in new ways, such as through the use of scanning tunneling potentiometry and scanning tunneling microscopy-based electron spin resonance (STM-ESR). We will also use Kelvin probe force microscopy (KPFM) techniques to overcome the electrostatic perturbation induced by a metallic scanned-probe tip. **Anticipated outcomes** if successful include the mapping of WC charge order near melting transitions where solid and liquid phases are predicted to coexist in complex stripe and bubble patterns. We will similarly visualize mixed-phase QSL systems that combine novel liquid and solid spin phases detected through spinon quantum interference and spin-polarized tunnel current. This includes spinon Friedel oscillations and spinon-based RKKY-like coupling between spin defects. Use of hybrid magnetic/QSL structures will allow us to visualize and manipulate QSL-based Majorana fermion edge-states. These results are expected to **impact DoD capabilities** in the critical technology areas of Microelectronics, Advanced Materials, and Quantum Science. The ability to spatially manipulate Majorana fermions represents an important step toward braiding them, and would be an impactful result in the area of Quantum Science. Performing STM-ESR measurements on finite Wigner "molecules" would be a useful step toward analyzing the effects of quantum decoherence on these novel electron-based qubit networks and would also help to advance the topic of Quantum Science. The ability to tune 2D materials between antiferromagnetism and QSL order would be a useful advancement for the DOD-relevant area of spintronics. Nanoscale spatial characterization of the nonlinear I-V response of WCs (i.e., depinning) would also help to advance the DOD priority area of Microelectronics (including efforts to improve fast switching and low power performance). Our characterization of novel heterostructures that combine different single-layer materials would have a positive impact on DOD capabilities in the priority area of Advanced Materials.