Quantum Sensing and Quantum Materials (QSQM)

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Lead Institution: University of Illinois
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Mission Statement*: To apply advanced scattering and scanning probe spectroscopy techniques to study charge dynamics in quantum materials.*

The modern understanding of quantum materials is based on measuring a few fundamental Green's functions, which describe how excitations propagate in many-body systems. These include the one-electron Green's function, spin susceptibility, and charge susceptibility. While the first two are well measured by techniques like angle-resolved photoemission (ARPES), scanning tunneling microscopy (STM), and inelastic neutron scattering (INS), no equivalent probe has existed for the charge response. The mission of the QSQM is to measure this charge response in various quantum materials, with meV energy resolution and either spatial or momentum resolution. We aim to focus on the following phenomena:

Strange metals. First discovered in copper-oxide superconductors, the strange metal phase appears to be a universal state of matter found in a wide range of materials, including ruthenium oxides, heavy fermion systems, organic molecular crystals, and twisted van der Waals materials. Its defining feature is a universal scattering rate governed solely by fundamental constants, known as Planckian dissipation. We are using momentum-resolved electron energy-loss spectroscopy (M-EELS), along with other techniques, to explore the possibility of conformal symmetry in these materials, which would suggest a quantum critical and universal phase.

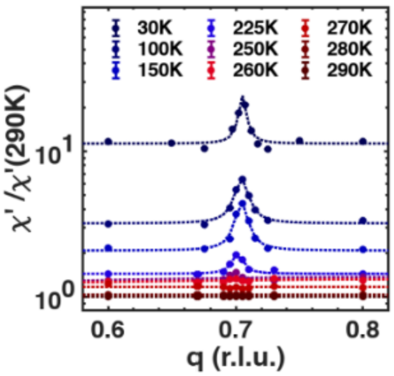

Figure 1 – Susceptibility divergence near the CDW ordering transition in $ErTe_3$. Predicted originally in the 1970's, this effect was measured for the first time this year with momentum-resolved EELS.

Altermagnets. Originally believed to be a type of antiferromagnet, altermagnets are now considered a distinct class of materials characterized by unique symmetry. The QSQM is investigating the predicted paramagnon polaron excitation, a new collective mode thought to be exclusive to the altermagnetic state.

Charge density wave materials. Although widely studied, the charge density wave (CDW) instability remains poorly understood. A CDW resembles a superconductor, but breaks a spatial symmetry rather than $U(1)$ gauge symmetry. The CDW is believed to result from a divergence in charge susceptibility at nonzero momentum, though this prediction has never been tested. The QSQM is investigating the behavior of the charge susceptibility near CDW transitions (Fig. 1), focusing on selenide and telluride materials, to gain deeper insights into this unique phase of matter.

Interacting topological phases. The first three-dimensional topological materials identified were topological insulators and Weyl semimetals, where topology is reflected in the single-particle energy band structure and surface states. Researchers are now exploring how topology manifests in strongly interacting many-body systems, where it appears that the relevant excitations are collective modes. The QSQM is employing M-EELS, scanning microwave impedance microscopy (MIM), and scanning single-electron transistor (SET) measurements to investigate collective modes in a variety of interacting topological materials. These include noncentrosymmetric materials with topological phonon band structures, ordered ferroelectrics displaying skyrmion and vortex phases, and two-dimensional fractional Chern insulators.

Quantum Fisher information. Quantum entanglement is a fundamental property of a many-body system, but measuring it experimentally has proven challenging. Recently, it was suggested that the charge response can serve as a measure of quantum Fisher information (QFI) in a many-body system, reflecting both wave function geometry and the density of entanglement. The QSQM is utilizing momentum-resolved scattering techniques to quantify the QFI in quantum materials. We have recently demonstrated that the simple insulator LiF adheres to theoretically predicted bounds, and we are now extending these measurements to more exotic materials, such as strange metals.

Technique development. In addition to conducting pioneering measurements on materials, the QSQM is developing the next generation of instruments that will serve as platforms for future experiments. We are implementing new strategies to enhance the accuracy and speed of momentum-resolved electron energy-loss spectroscopy (M-EELS) measurements. One approach involves using ARPES-type hemispherical analyzers, which enable parallel momentum and energy readout. This is being achieved by integrating a small Scienta SES-100 analyzer with an Ibach-type high-resolution EELS spectrometer and a eucentric sample goniometer. Simultaneously, we are exploring time-of-flight techniques using pulsed electron beams, which will allow for fully three-dimensional measurements, simultaneously measuring energy and two momentum directions in parallel.

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