Quantum Sensing and Quantum Materials (QSQM)
EFRC Director: Peter Abbamonte
Lead Institution: University of Illinois, Urbana-Champaign
Class: 2020 – 2024

Mission Statement: *To develop three new quantum sensing techniques—scanning qubit microscopy, two-electron Einstein-Podolsky-Rosen (EPR) spectroscopy, and nonlinear x-ray optics—and use them to study local and nonlocal quantum observables in quantum materials.*

The EFRC on Quantum Sensing and Quantum Materials (QSQM) will apply new types of quantum sensing technique to measure and correlate local and nonlocal quantum observables in three families of quantum materials central to DOE's energy mission: exotic superconductors, topological crystalline insulators, and strange metals.

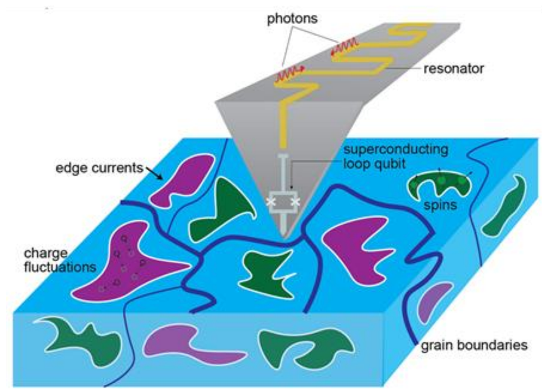

Figure 1 Conceptual illustration of a scanning qubit microscope, which consists of a tip-mounted flux qubit that may be scanned in close proximity to a heterogeneous quantum material.

To carry out this mission, we plan to develop three new, cutting-edge quantum sensing instruments. The first is a **scanning qubit microscope (SQM)**, which consists of a single flux qubit integrated into a tip that may be scanned over the surface of a material, as illustrated in Fig. 1. The state of a qubit is exceedingly sensitive to charge and flux noise, making an SQM a highly sensitive probe of local charge and spin fluctuations near surfaces or interfaces.

The second instrument is a **two-electron EPR spectrometer**, which uses correlated Einstein-Podolsky-Rosen (EPR) pairs of electrons to reveal hidden global interactions in materials. This instrument, illustrated in Fig. 2, can be operated in two different modes. In the first, double photoemission, the sample is illuminated with ultrafast XUV photon pulses that eject correlated electron pairs from the surface. The angle-and energy-distribution of these pairs can be used to reconstruct the anomalous Green's function of the material. In the second, two-electron Rutherford scattering, time coincident ultrafast electron bunches are scattered off one another near a material surface, revealing the renormalized interaction between quasiparticles.

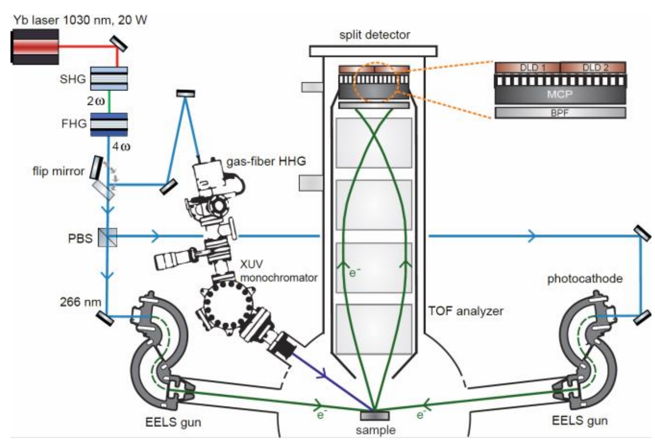

Figure 2 Conceptual illustration of a two-electron, time-of-flight, Einstein-Podolsky-Rosen spectrometer, which uses coherent pairs of electrons to detect valence band phenomena in quantum materials.

The third, **x-ray four-wave mixing** instrument uses correlated pairs of photons to measure the nonlinear optical response of materials at nonzero momentum. Illustrated in Fig. 3, this experiment is carried out at a free-electron laser facility, such as the LCLS facility at SLAC National Accelerator Laboratory. This instrument will directly measure the global geometry of Hilbert space of a material, revealing previously undetected topological phenomena, and will also identify new broken symmetries in materials that reveal exotic and previously unobserved phases of matter.

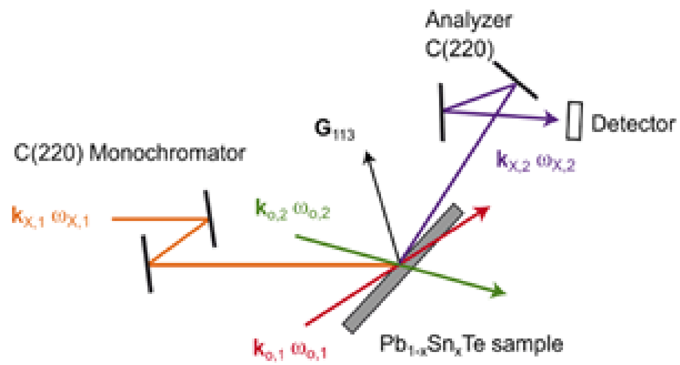

Figure 3 Conceptual illustration of an x-ray four-wave mixing experiment, which uses coherent pairs of photons to measure the nonlinear optical properties of quantum materials at nonzero momentum.

The new quantum sensing techniques we develop will enable us to unravel the most compelling mysteries of quantum materials. Scanning qubit microscopy will allow us to detect not only localized electronic states but also sources of dissipation and dephasing in materials over a wide frequency range. It will measure the frequencies of excitations and fluctuations in materials with unprecedented sensitivity. It will enable us to determine whether corner states and hinge states exist in higher-order topological insulators, whether new types of zero-energy states emerge at domain walls in unconventional superconductors, and reveal how strange metals screen charge.

Two-electron EPR spectroscopy will improve our scientific understanding of all materials in which interactions play a nontrivial role, including magnetic materials, strange metals, doped Mott insulators, interacting topological phases, and charge and spin density wave materials. It can directly reveal the pairing boson in most unconventional superconductors, as well as the mechanism behind other types of Fermi surface instabilities in quantum materials.

Nonlinear optics is widely known to be a highly sensitive probe of broken symmetries in materials. However, such measurements have always been restricted to small momenta. Our momentum-resolved x-ray nonlinear optics instrument will allow us to detect new categories of phenomena including the predicted nonlinear axion optical response in topological crystalline insulators, and whether charge carriers in strange metals flow independently or via collective hydrodynamic transport.

Together, these schemes will provide new knowledge about interacting and topological materials, facilitate the discovery of new materials, and define new directions for future spectroscopic probes.

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