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

***Mission Statement****: To develop new quantum sensing techniques, scanning qubit microscopy and two-electron EPR spectroscopy, and apply them to investigate relationships between the local and global properties of quantum materials that exhibit strong correlations and/or topological order: exotic superconductors, topological crystalline insulators, and strange metals.*

The EFRC on Quantum Sensing and Quantum Materials (QSQM) will apply new types of quantum sensing to investigate the local and nonlocal quantum observables in three families of quantum materials central to DOE's energy mission: exotic superconductors, topological crystalline insulators (TCIs), and strange metals. Each family presents a compelling mystery: the *origin of chiral or topological behavior* in exotic superconductors, whether *topologically protected corner and hinge states exist in new generations of TCIs*, and the *origin of Planckian dissipation* in strange metals. The two quantum sensing techniques we develop will enable us to unravel the mysteries of these phases in quantum materials:

1. *Scanning qubit microscopy* to investigate localized electronic states and fluctuations.
2. *Two-electron EPR spectroscopy* to investigate electron correlations and interaction mechanisms.

For the first, we are developing a **scanning qubit microscope (SQM)** (Fig. 1), which consists of a single flux qubit integrated into a scanning resonator tip that can be translated over the surface of a material. The state of a qubit is highly sensitive to charge and flux noise, making an SQM a sensitive probe of local charge and spin fluctuations near surfaces or interfaces. A qubit is therefore a bulk-sensitive, non-contact, non-destructive probe that can study low-energy excitations in materials an with unprecedented resolution of 10 kHz. A qubit can detect both electric and magnetic fields, and can be used for quantum manipulation, allowing us swap excitations between the qubit and the material. This SQM will elucidate localized defects in exotic superconductors, fluctuations in strange metals, and localized excitations and boundary modes in TCIs.

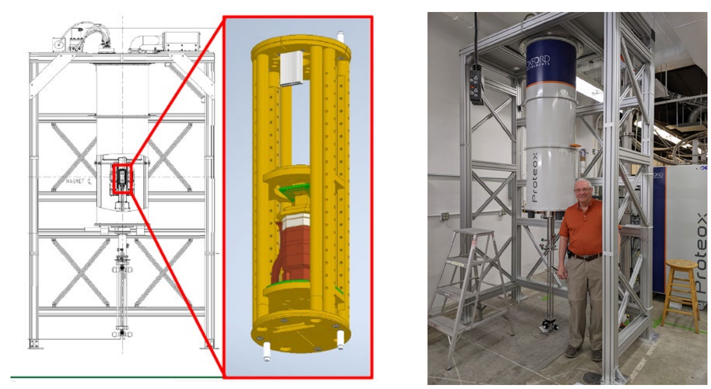


**Fig. 1:** Conceptual layout of a scanning qubit microscope. (left) Dry dilution refrigerator, sensor head, and scanner. (right) Dedicated SQM setup recently installed in the Materials Research Laboratory at the University of Illinois.

For the second technique, we are developing a **two-electron Einstein-Podolsky-Rosen (EPR) spectrometer** (Fig. 2), which uses correlated EPR pairs of electrons to reveal valence band interaction effects. This instrument can be operated either with an ultrafast XUV laser source or with a pulsed ultrafast electron source. The former allows one to coherent pairs of photoelectrons (a technique known as "double photoemission"), revealing the correlation between pairs of electrons in a material. The latter allows one to study scattering between pairs of electrons (at technique known as "Rutherford scattering"), revealing the renormalized interaction mechanism between the electrons. This instrument will therefore reveal a complete picture of the Cooper pairing mechanism in exotic superconductors, the microscopic origin of electron-electron interactions and the degree of correlations in strange metals and TCIs.

Using these techniques, as well as mature approaches in materials synthesis and characterization, the QSQM will be able to address the following profound materials problems:

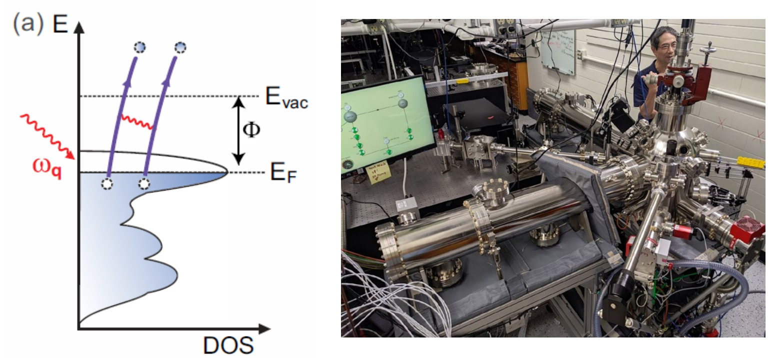


**Fig. 2:** EPR spectrometer under commissioning in the Materials Research Laboratory at the University of Illinois. (left) Illustration of double ARPES, which reveals how electrons are correlated in a material. (right) New setup showing two ARTOF-2 time-of-flight analyzers, which are run in coincidence to identify correlated EPR electron pairs.

**Exotic superconductors**: We aim to identify the pairing bosons and origin of broken symmetries and topological order in exotic superconductors, including chiral *p*-wave superconductors hosting Majorana fermions and $s^{+/-}$ superconductors believed to reside in a proximitized topological phase.

**Topological crystalline insulators (TCIs)**: These are materials exhibiting topological order protected by spatial symmetries. An example is the recently proposed higher-order TIs (HOTIs), which are gapped on all faces but exhibit gapless corner and edge modes. Using our new techniques, we are investigating whether these states exist and whether interactions can gap out such topologically protected modes.

**Strange metals**: Interactions in these materials are so strong the scattering rate, $\tau^{-1} = k_B T/\hbar$, is believed to be “Planckian,” i.e., determined by fundamental constants that set limits on the degree of quantum entanglement allowed in a many-body system. Using our quantum sensing techniques, we will search for hydrodynamic effects and identify the interactions that give rise to this bizarre state of matter.


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