Center for Novel Pathways to Quantum Coherence in Materials (NPQC)
EFRC Director: Joel E. Moore
Lead Institution: Lawrence Berkeley National Laboratory
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Mission Statement*: To expand dramatically our understanding and control of coherence in solids by building on recent discoveries in quantum materials along with advances in experimental and computational techniques.*

The fundamental importance of the two-level system or qubit was recognized in the early days of quantum mechanics. An obvious way to maintain the quantum coherence of a qubit is to embed it in a perfect low-temperature vacuum. However, this is not the only way; a two-level system in a defect state in a solid (Figure 1), or a superposition of interband states at one value of momentum in an ideal crystal, can maintain quantum coherence for a remarkably long time even at room temperature. To fully exploit the potential of quantum-based sensing, communication, and computation, we must find new pathways to protect and use quantum coherence in solid-state environments that are closer to ambient temperatures. This includes developing the power to manipulate coherence involving *many* two-level systems in realistic solid-state environments.

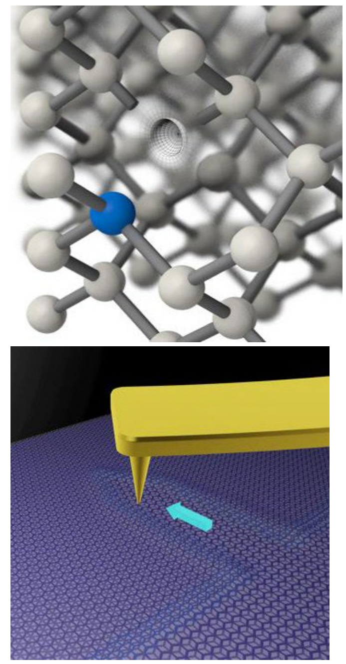

Figure 1. Illustrations of research directions for the thrusts of this EFRC. *From top to bottom*: a nitrogen-vacancy (NV) center in the diamond lattice used for quantum sensing; controlled writing of one-dimensional boundary in atomically thin 2D materials.

The research in this Center will dramatically expand our control and understanding of coherence in solids by building on fundamental materials discoveries in recent years. Advances in quantum materials including two-dimensional materials and strongly correlated materials lead to remarkable new kinds of defects, boundaries, and interfaces. Common threads are the need to understand defects in complex material environments, the use of high-resolution optical techniques and other cutting-edge experimental tools, and the role of inhomogeneity in various types of quantum materials.

The Center conducts research in two linked major thrust areas. Each thrust involves an integration of synthesis, characterization, and theory, and takes advantage of unique national laboratory capabilities.

Thrust 1 – Defects, disorder, and many-body entanglement for quantum spectroscopy

The ability to interrogate quantum materials and to measure their coherent properties is crucial for both the fundamental and applied sciences. Harnessing many-body entanglement can significantly enhance such quantum sensing technologies. The goal of this thrust is to theoretically predict, computationally optimize, and experimentally create, characterize, and develop novel defect-based quantum sensing platforms. In addition to the platforms themselves, NPQC investigates sensing protocols that utilize many-body interactions, non-equilibrium driving pulses, and quantum information inspired techniques (e.g., error correction) to improve sensor performance.

In combination, these enhanced sensing methods will open new doors to directly image the nanoscale transport properties of heterostructures, the nature of correlated states at ultrahigh pressures, and other important materials properties. NPQC research has already demonstrated improved control over the creation and probing of defect ensembles, and begun to apply the improved sensors to important problems in the physics of quantum materials, such as those arising in Thrust 2.

Thrust 2 – Coherent transport and switching in engineered surfaces and layered materials

Two of the most significant achievements of the last decade in materials physics are deeper understanding of the importance of topological order in materials and dramatic improvement in our ability to engineer 2D materials with atomic precision. Thrust 2 is an outgrowth of these achievements, as it focuses on atomically precise 2D material combinations that enable new types of topological and correlated quantum coherence. Research in this thrust explores atomically engineered topological interfaces that promise to find new examples of topological protection and improve coherent transport to the point that it becomes technologically relevant. An example of such an interface from previous NPQC work is the creation of Luttinger-liquid behavior at mirror twin boundaries in a 2D dichalcogenide.

This thrust is also aimed at exploiting the new complex quantum states that are predicted to arise when 2D materials are combined in ways that take advantage of topological protection and many-body correlations. Superconductivity can emerge for particular arrangements of 2D sheets. Layered crystals made from 2D sheets can use magnetic intercalants to create ordered states that imprint directionality on transport properties in a switchable fashion. New materials in this family have the potential to become transformative technologies: ultra-fast electronics on time-scales of quantum processes, ultra-sensitive sensors based on electronic phase transitions, and the ability to encode information at the nanoscale. The purpose of this thrust is to address a key challenge in realizing the potential of these materials: understanding the role of defects, disorder and heterogeneity in determining response functions. The goal is not only to mitigate their potential deleterious effects, but to investigate how they may be used to control and manipulate electronic properties.

An important benefit of research in NPQC is its role in training junior personnel to become productive scientists in this field at the intersection of quantum materials and quantum information science applications. Further information about NPQC research and activities is provided at the website below.

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