Center for Novel Pathways to Quantum Coherence in Materials (NPQC)
EFRC Director: Joel Moore
Lead Institution: Lawrence Berkeley National Laboratory
Class: 2018 – 2022

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.

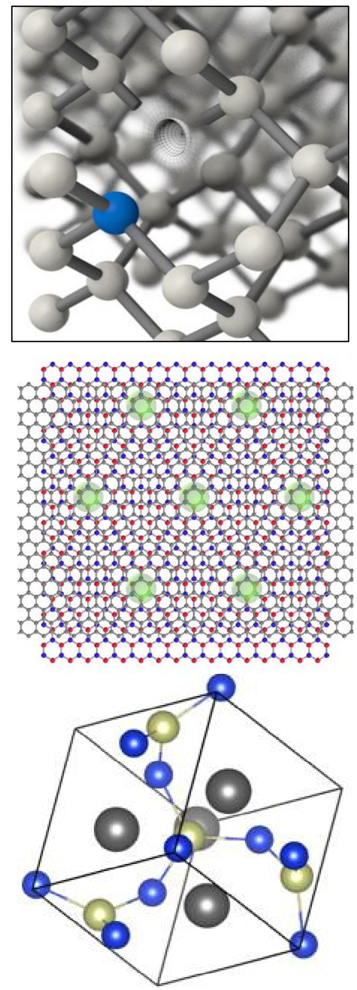

Figure 1. Illustrations of research directions for the three thrusts of this EFRC. *From top to bottom*: a nitrogen-vacancy (NV) center in the diamond lattice used for quantum sensing; 2D layers of trilayer graphene and boron nitride form a superconducting moiré superlattice; crystal structure of LaIrSi, an optically active topological material.

This includes developing the power to manipulate coherence involving *many* two-level systems in realistic solid-state environments. New pathways will also come from applying advanced tools and concepts based on coherence to understand complex materials that could eventually provide alternate qubit, sensing, or optical technologies. Success in these basic goals requires an integrated approach via the EFRC and will provide new material approaches to a variety of quantum information science challenges.

Advances in quantum materials, including two-dimensional materials and topological materials, lead to remarkable new kinds of defects in both real space and momentum space. Major outcomes of this Center will include new approaches to solid-state quantum sensing and quantum spectroscopy, controllable crossovers between coherent and incoherent transport, and understanding the unconventional properties of a variety of new materials classes. These have the potential to open new frontiers in quantum information science, electronics, and optics. The work in this EFRC is aligned with BES Basic Research Needs for quantum materials, transformative experimental tools, and synthesis science.

The Center conducts research in three major thrust areas:

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. Conventional wisdom holds that 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, we will investigate 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 microscopic magnetic storage of information and the nonlinear optical response of quantum materials.

Thrust 2 – Quantum coherence in engineered surfaces: 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. 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.

Thrust 3 – Coherence and defects in correlated and topological materials: New materials with enhanced response functions 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.

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