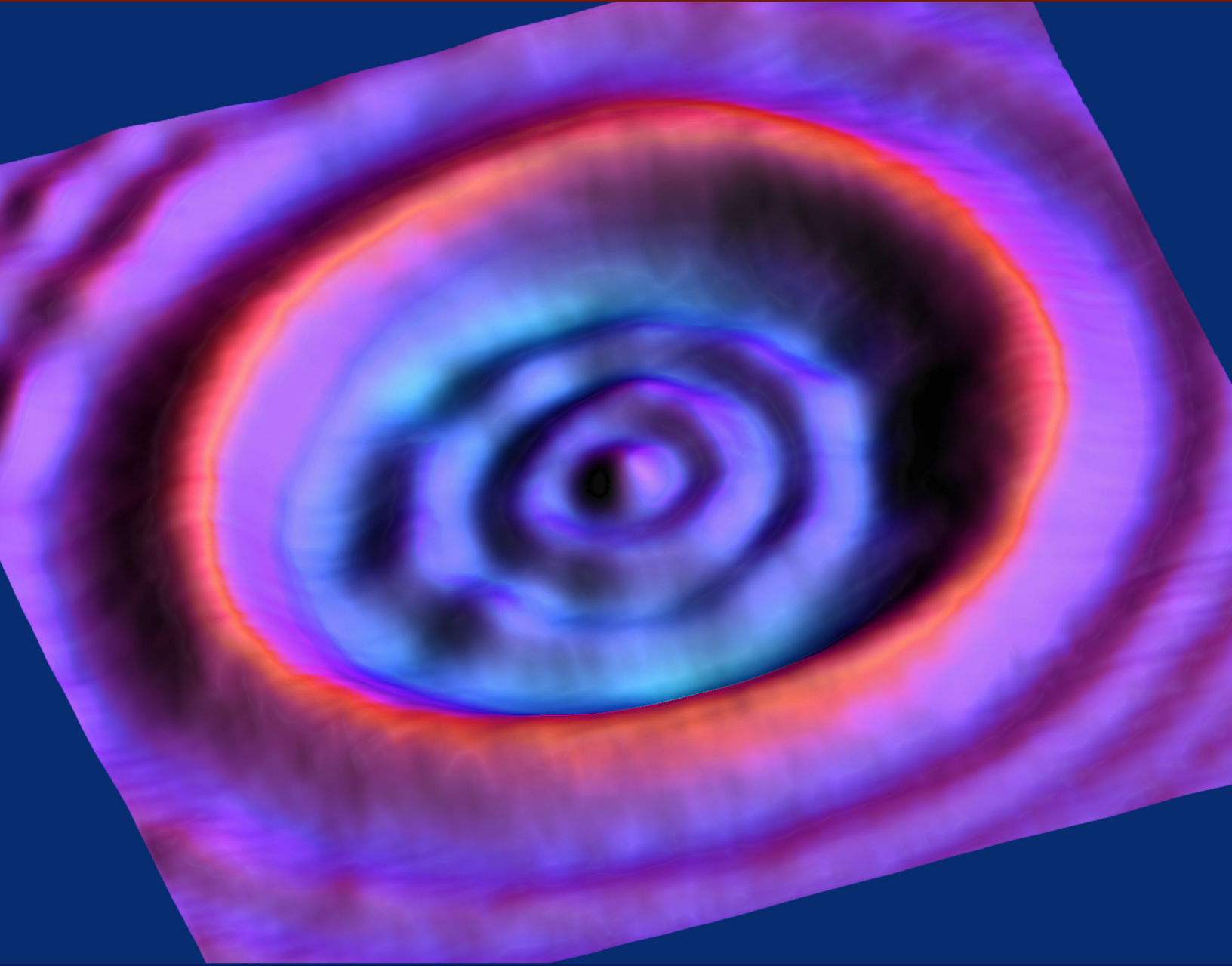


Basic Research Needs for

Quantum Materials



*Quantum Materials—Research to Discover,
Harness, and Exploit Exotic Electronic Properties*

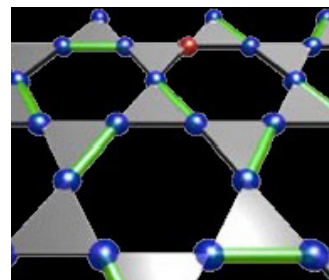
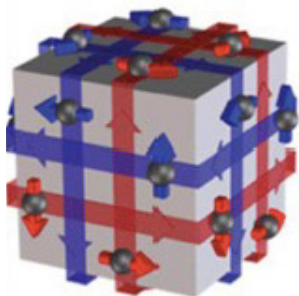
Quantum Materials—Harnessing the potential to revolutionize energy and information technologies

In a world of technologies built on quantum materials, computers will work a million times faster than today's supercomputers while using a fraction as much energy. Electricity will be generated, transmitted, and used with almost no losses. Smart building materials, fabrics, and electronic devices will change their properties on demand to satisfy our needs. The astounding effects of quantum mechanics will enable materials properties and functions that seem like science fiction today.

The magic of quantum materials results from electronic interactions beginning at the atomic and subatomic scale—where solid matter loses its conventional order and takes on wavelike properties, and where quantum phenomena such as interference, tunneling, fluctuations, entanglement, and topological effects are found. Based on our everyday experience, it is difficult to develop an intuitive understanding of these quantum mechanical effects. In materials research, quantum materials challenge current theory and have a level of complexity that requires sophisticated, powerful tools and methods to synthesize, understand, and manipulate them.

The potential benefits of quantum materials to energy, quality-of-life, and the economy are staggering. A report from a Basic Research Needs workshop held in 2016 identifies four priority research directions that will advance our capabilities to design, characterize, and synthesize quantum materials and tailor their properties to address the world's most pressing technological needs. The full report can be downloaded from <https://science.energy.gov/bes/community-resources/reports>.

What is a quantum material? Quantum materials are solids with exotic physical properties that arise from the interactions of their electrons, beginning at atomic and subatomic scales where the extraordinary effects of quantum mechanics cause unique and unexpected behaviors.



(Left) Topological insulators, whose surfaces conduct electricity with low losses, could enable a new generation of energy-efficient electronics. (Center) In superconducting materials, electrons form a collective wave through the material that completely eliminates electrical resistance and magnetic fields (allowing a cube of magnetic material to levitate above a superconductor). Superconductors could revolutionize motors and the electrical grid. (Right) In quantum

spin liquids, electron spins become entangled in a quantum fluctuating state, a medium that supports collective excitations called quasiparticles. These exotic quasiparticles could transform future information storage and processing capabilities.

(Left) Courtesy of Lawrence Berkeley National Laboratory.

(Center) Courtesy of Oak Ridge National Laboratory.

(Right) Courtesy of Oleg Tchernyshyov, Johns Hopkins University.

Priority Research Directions

- **Control and exploit fluctuations in quantum matter for the design of bulk materials with novel functionality**

Key question: *Looking beyond the standard paradigms of simple metals and semiconductors, how do strongly-interacting electrons organize themselves in quantum materials, and how can this be controlled for energy-relevant technologies?*

One effect of quantum mechanics is spontaneous “quantum fluctuations” that break down conventional order in solids. The resulting material properties, coupled with extreme sensitivity to external perturbations, could advance technologies ranging from power management and transmission to quantum computing and novel sensors. To realize these envisioned applications of quantum materials, we need to understand their complex phase diagrams, response to quenched disorder, quantum entanglement, and quantum phase transitions.

- **Harness topological states for groundbreaking surface properties**

Key question: *Building on recent advances in the field of topological insulators, what new topological states of matter can be realized, what are their signatures, and how can these be used for energy-related applications?*

Topological insulators manifest distinct electronic properties in a protected surface region. These materials offer potential breakthroughs for energy, electronics, and computation because they support switchable electrical currents on their surfaces with dramatically lower energy loss. Research is needed to understand and harness the unique properties of dissipationless electron transport and fractional quasiparticles that underlie their potential utility.

- **Drive and manipulate quantum effects (coherence, entanglement) in nanostructures for transformative technologies**

Key question: *How can the extraordinary properties of coherent quantum states be controlled and utilized for energy-related applications?*

Nanostructured quantum materials can be manipulated using new excitation techniques to create electronic properties that do not exist in thermal equilibrium. The formation of quasiparticles and extraordinary quantum effects such as coherence and entanglement offer a path to ultra-fast, ultra-energy efficient computing. Research is needed in quantum transport and nonequilibrium properties of heterogeneous, nanostructured quantum materials to reveal and exploit these fundamental properties.

- **Design revolutionary tools to accelerate discovery and technological deployment of quantum materials**

Key question: *What new methodologies and tools are needed to advance synthesis of quantum materials and our ability to probe and predict their properties?*

The remarkable properties of quantum materials present immense challenges to existing experimental and theoretical capabilities. The development of new methodologies and tools will accelerate the discovery of new quantum materials and advance the ability to probe, predict, and exploit their remarkable properties.

Summary

Human society progresses as we learn to create and use new materials. Continuing advances in the ability to manipulate and tune materials have led to the discovery of exotic states where quantum mechanics reigns, producing incredible properties beyond those found in conventional materials. These properties lead to materials offering profound benefits—superconductors that transport electrical charge without resistance and enable the creation of super-powerful magnets; topological materials with surfaces that conduct electricity without losses while the bulk is insulating; and quantum spin liquids that could become platforms for ultra-fast, ultra-efficient quantum computing.

The capability to create and control quantum materials will be a true materials revolution, with transformative effects on energy production and use, transportation, and information technology. There is a world-wide effort to realize the potential of these materials. The research directions outlined in this report will increase understanding of the fundamentals of quantum materials and will establish the capabilities required to design, create, understand, and use them.

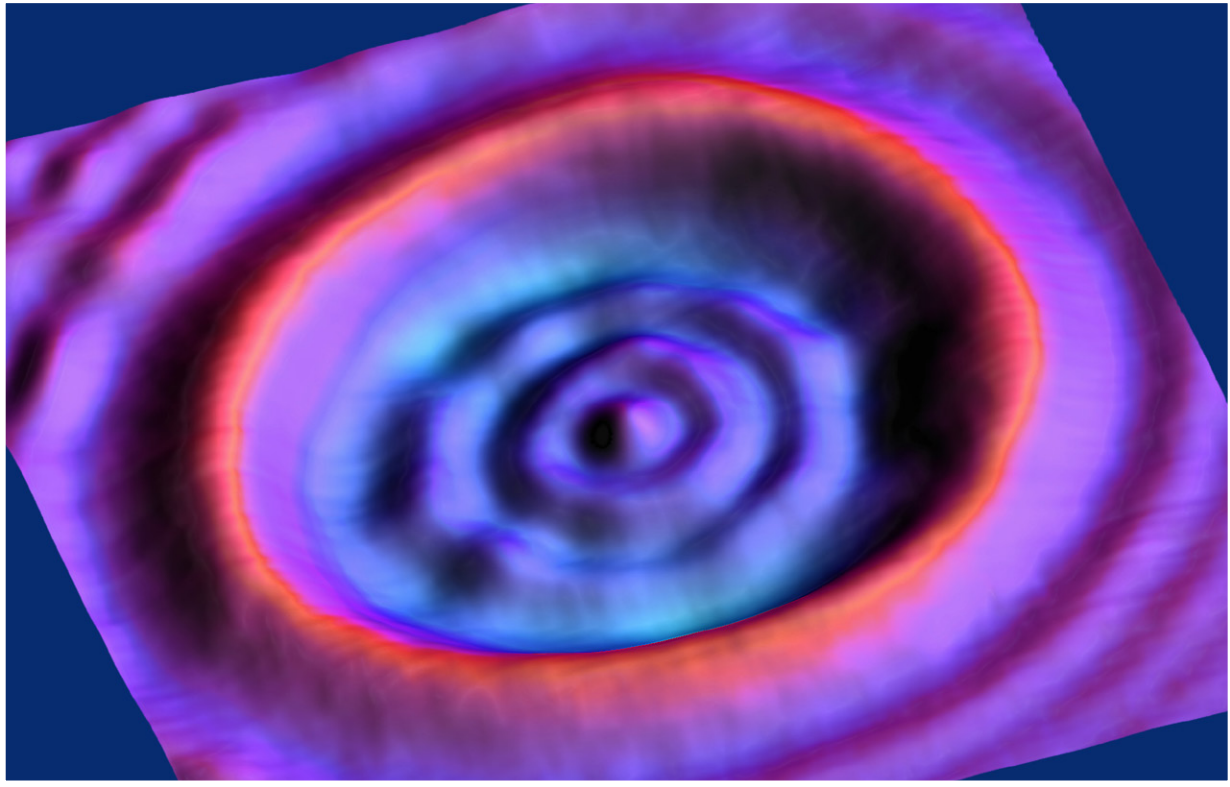


Image courtesy of Lawrence Berkeley National Laboratory.

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