Experimental Condensed Matter Physics

Portfolio Description

The Experimental Condensed Matter Physics (ECMP) program supports research that will advance our fundamental understanding of the relationships between intrinsic electronic structure and properties of complex materials. The program focus is largely on systems whose behavior derives from electron correlation effects, competing or coherent quantum interactions, and effects of interfaces, defects, anisotropy, and reduced dimensionality. Scientific themes include unconventional superconductivity, magnetism, low-dimensional electron systems, topologically protected states and their spin dynamics, and nanoscale systems. The program also supports research that involves characterization of the electronic states and properties of materials under extreme conditions, such as ultra-low temperatures and ultra-high magnetic fields. Research is also supported on materials phenomena at interfaces with an emphasis on non-equilibrium electronic, structural, and magnetic states between dissimilar materials, as well as the development of experimental techniques that enable such studies. Support for the synthesis of materials required for the broader research activities is also provided. The program will continue to support research that will result in a fundamental understanding of unconventional superconductivity.

Scientific Challenges

The scientific challenges for this program are well summarized in the 2015 Basic Energy Sciences Advisory Committee report, *Challenges at the Frontiers of Matter and Energy: Transformative Opportunities for Discovery Science* (all BES reports can be found at: https://science.energy.gov/bes/community-resources/reports/). Particularly relevant to ECMP are: 1) Mastering Hierarchical Architectures and Beyond-Equilibrium Matter; 2) Beyond Ideal Materials and Systems: Understanding the Critical Roles of Heterogeneity, Interfaces and Disorder; 3) Harnessing Coherence in Light and Matter. The following exemplify the relevance to ECMP in realizing emerging materials properties:

- Synthesize 1-, 2-, and 3-D mesoscale systems;
- Define the important length scales determining structural, charge, spin, and orbital ordering, and understand how they compete;
- Control interface and defect states and spatial and temporal disorder in materials; and
- Control long-range spatial coherence and temporal behavior in structural, charge, spin, and orbital interactions.

These address opportunities in the wide array of strongly correlated electron phenomena included in the program, such as superconductivity, magnetism, topological materials, and quantum effects associated with two-dimensional systems. These also apply directly to ongoing and emerging work in multiscale (nano, meso, and macro) physics in the program. Implied in the above is the development of synthesis and characterization tools required to realize these opportunities. Also implied is close collaboration with theory for guidance and insights in these endeavors.

Also important to this activity are the priority research directions identified in the follow-up BES report on *Basic Research Needs for Quantum Materials*.

Projected Evolution

This activity will include further work to advance our fundamental knowledge of highly correlated systems, including phenomena that occur at the nanoscale, at ultra-low temperatures, and in very high magnetic fields. The program will expand to investigate phenomena that occur in mesoscale structures, where electron confinement results in new materials properties in systems such as semiconducting quantum dots; metallic, magnetic, and ferroelectric nanocrystals; and lithographically patterned graphene sheets. The portfolio can be expected to continue thrusts in electronic structure, new materials, surfaces/interfaces, and development of experimental techniques to enable new physics. Efforts will continue to strengthen research in unconventional superconductivity, including the high-temperature cuprate and iron-based and other highly anisotropic superconductors. In the last few years, the program has increased support for spin physics and nanomagnetism, topological states of matter, and graphene-like materials. Continued growth in research support is expected in the area of quantum materials. Research on conventional superconductors is not a growth area.

Significant Accomplishments

The ECMP activity has a long history of accomplishments. Among these are the discovery of ion channeling and the development of the field of ion implantation, the discovery of metallic and strained-layer superlattices, the establishment of the field of thermoacoustics and thermoacoustic refrigeration and heating, the first observation of superconductivity in a magnetically doped semiconductor (platinum antimony [$PtSb_2$] with ~1% Yb), and design/ construction of the 100 T multishot magnet (now operated by the National High Magnetic Field Laboratory). The 100 T magnet currently holds the world record for long pulse, high magnetic fields in a reusable magnet. In addition, the activity has supported much of the seminal work in the fields of high-temperature superconductors and quasicrystals, efforts now pursued worldwide.

Recent accomplishments in the program include:

- First observation of charge-neutral quasiparticles which may provide new insights into the mechanism responsible for high-temperature superconductivity.
- First demonstration of current-driven manipulation of magnetic skyrmions at room temperature in commonly used magnetic materials.
- The detailed nature of the hidden order parameter in the heavy-fermion superconductor (URu_2Si_2) was revealed, 30 years after it was first discovered.
- Direct observation of giant magnetic anisotropy in non-rare-earth-based materials.
- Demonstration of a very large coercivity enhancement in V_2O_3/Ni bilayers driven by nanoscale phase coexistence.

Unique Aspects

This activity continues to support research on electronically complex and quantum materials that impact a wide range of topics including unconventional superconductivity, magnetism, and low-dimensional electron systems. The research on magnetism and magnetic materials focuses on hard magnet materials, such as those used for permanent magnets and in motors; on spin-orbit and exchange coupling, important for information technologies; and on spin-polarized electron transport, particularly in nanometer-scale structures. The superconductivity portfolio comprises a concerted and comprehensive energy-related basic research program. Research on the properties of materials in high magnetic fields utilizes the 100 Tesla multi-shot magnet (designed and built by BES), now located at the National High Magnetic Field Laboratory at Los Alamos National Laboratory. Internationally, this activity holds a position of world leadership in the areas of magnetism, superconductivity, materials characterization, two-dimensional electron gas materials, and nanoscale science. New, exciting areas launched within this activity include studies on interfacial effects in magnetism, topological insulators, skyrmions, and iron-based superconductors.

Mission Relevance

Improving the understanding of the electronic behavior of materials on the atomistic scale is relevant to the DOE mission in energy, as these structures offer enhanced properties and could lead to dramatic improvements in technologies for energy generation, conversion, storage, delivery, and use. Specifically, research efforts on the fundamental mechanisms of superconductivity, the physics of low-dimensional systems, and understanding charge-orbital-spin interactions provide the scientific underpinnings for a broad range of energy technologies. This activity also supports basic research in semiconductor and spin-based electronics of interest for the next-generation information technology and electronics industries.

Relationship to Other Programs

The research in this activity is aimed at building a fundamental understanding of the electronic behavior of materials as a foundation for future energy technologies. Improving the understanding of the physics of materials at the nanoscale will be technologically significant, as these structures offer enhanced properties and could lead to dramatic improvements in technologies for energy generation, conversion, delivery, and utilization. This activity also supports semiconductor and spintronics research of fundamental interest to the information technology and electronics industries.

These research efforts are closely coordinated with other core research activities in BES, including: Physical Behavior of Materials on superconductivity and magnetism; Synthesis and Processing Science on single crystal and thin film growth; X-ray and Neutron Scattering on advanced scattering techniques; and Theoretical Condensed Matter Physics on superconductors, nanostructures, and low-dimensional systems. This research activity also sponsors—jointly with other core research activities and the Energy Frontier Research Centers program, as appropriate—program reviews, principal investigators' (PI) meetings, and programmatic workshops.

The Program also works with agencies outside of BES.

- Nanoscience-related projects in this activity are coordinated with the Nanoscale Science Research Center user facilities and reviews in the BES Scientific User Facilities Division. BES further coordinates nanoscience activities with other federal agencies through the National Nanotechnology Coordination Office (NNCO), which provides technical and administrative support to the National Science and Technology Council (NSTC) Subcommittee on Nanoscale Science, Engineering, and Technology (NSET) for the National Nanotechnology Initiative (NNI).

- Predictive materials sciences activities and the associated theory, modeling, characterization, and synthesis research are coordinated with other federal agencies through the NSTC Subcommittee on the Materials Genome Initiative (MGI).
- The program has also supported topical studies by the National Research Council (NRC) of the National Academies, including *Condensed-Matter Physics and Materials Physics: The Science of the World Around Us, Assessment of and Outlook for New Materials Synthesis and Crystal Growth, Optics and Photonics: Essential Technologies for our Nation,* and *High Magnetic Field Science*. The program is jointly supporting, with NSF, the NRC study *Frontiers of Materials Research: A Decadal Survey*. The 2020 assessment is expected to be complete by September, 2018.
- This program and the National Science Foundation (NSF) support the NRC Condensed Matter and Materials Research Committee (formerly the Solid State Sciences Committee), which is charged with assessing the state of the field and advising federal agencies on research priorities. Additional interactions with the NSF include joint support of National Academies studies in relevant areas and ongoing communication about research activities.
- The program also participates in interagency coordination groups such as the Interagency Coordination Committee on Ceramics Research and Development and the Federal Interagency Materials Representatives (FIMaR).