Experimental Condensed Matter Physics

Portfolio Description

This activity supports experimental condensed matter physics research, emphasizing the development of a detailed understanding of the relationship between the electronic structure and the properties of complex materials, both in bulk materials and thin films. Nanoscale structures and phenomena, and the impact of those structures on mesoscale properties, are core elements of the program. The focus is on systems whose behavior derives from strong correlation effects of electrons, anisotropy, or reduced dimensionality. Scientific themes include superconductivity, magnetism and spin physics, low dimensional electron systems, and nanoscale systems. Also supported is the development of techniques to characterize the electronic states and properties of materials under extreme conditions, such as in ultra-low temperatures (milli-kelvin) and in ultra-high magnetic fields (100 Tesla). As required to drive the discovery of new phenomena, this activity supports growth of single crystals of new materials.

Unique Aspects

This activity continues to support research on electronically complex materials, an area that impacts a wide range of other topics including superconductivity, magnetism, magnetoresistivity, 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 exchange biasing, which is used to stabilize the magnetic read heads of disk drives; and on spin-polarized electron transport, particularly in nanometer-scale structures. The combined projects in superconductivity comprise a concerted and comprehensive energy-related basic research program. Research on the properties of materials in high magnetic fields utilizes the 100T multishot magnet (designed and built by BES), now located at the National High Magnetic Field Laboratory (NHMFL) at Los Alamos National Laboratory (LANL). This activity also supports research that involves using photoemission to investigate correlated electron systems. Internationally, this activity holds a position of world leadership in the areas of magnetism, superconductivity, materials characterization, 2D electron gases, and nanoscale science. New, exciting areas launched within this activity include studies on the evolution of condensed phase phenomena from ultra-cold atoms, topological insulators, and magnetic superconductors.

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 research of fundamental interest for information technology and electronics industries in the fields of semiconductor and spintronics research.

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 growth; X-ray and Neutron Scattering on photoemission studies of correlated electron systems; and Theoretical Condensed Matter Physics on 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.

- There are active interactions with the DOE Office of Energy Efficiency and Renewable Energy (EERE) through workshops, program reviews, PI meetings, and communication of research activities and highlights.
- 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 Science and Technology Council (NSTC) Nanoscale Science, Engineering, and Technology Subcommittee that leads the National Nanotechnology Initiative.
- 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.
- The program has also supported topical studies by the National Research Council, including "Assessment of and Outlook for New Materials Synthesis and Crystal Growth", "Optics and Photonics: Essential Technologies for our Nation," and "High Magnetic Field Science".
- This program and the National Science Foundation (NSF) support the National Academy of Sciences' 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 Academy studies in relevant areas and ongoing communication about research activities.

Significant Accomplishments

This 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 100T multishot magnet (now operated by the NHMFL). The 100T 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:

- The observation of Bose condensation of excitons doped double layer semiconductor structures.
- The characterization of BCS (Bardeen, Cooper, and Schrieffer), two-gap superconductivity in magnesium diboride (MgB_2).
- The first observation of the fractional quantum Hall effect in graphene.
- The first observation of the Hofstadter's butterfly energy spectrum in graphene and h-boron nitride moire superlattices.
- STM imaging of the formation of heavy fermions in cerium-cobalt-indium ($CeCoIn_5$).

Mission Relevance

Improving the understanding of the electronic behavior of materials on the atomistic scale is relevant to the DOE mission, 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 in understanding 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.

Scientific Challenges

Among the immediate ongoing scientific challenges for experimental condensed matter physics are: the solution of the mechanism for high-temperature superconductivity; the understanding of novel quantum effects and of "emergent phenomena," that is, new phenomena that emerge when the complexity of a system grows with the addition of more particles; understanding the influence of interfaces in determining the electronic properties of materials; and discovery and characterizations of topological states in materials. Low temperature physics continues to be important for the advancement of physics by providing the experimental conditions necessary to observe phenomena such as Bose–Einstein condensates, the quantum Hall effect, and superconductivity. High-magnetic-field research coupled with low temperature physics led to the discovery of the quantum and fractional quantum Hall effect and to the general area of novel quantum effects. The availability of very high magnetic fields over useable time scales offers the promise of both increasing the fundamental understanding of matter and of observing the effects of very high magnetic fields on materials properties. Developing and understanding matter and materials at the nanoscale is a critical need because electronic, optical, and magnetic devices continue to shrink in size.

Projected Evolution

This activity will include further work in developing a fundamental understanding of highly correlated systems and understanding phenomena that occur at the nanoscale, at low temperatures, and in very high magnetic fields. The program will expand to investigate phenomena that occur in mesoscale structures. The confinement of electronic behavior in mesoscale architectures (such as semiconducting quantum dots; metallic, magnetic, and ferroelectric nanocrystals; and lithographically patterned graphene sheets) results in new materials properties. Mesoscale science offers the opportunity to tune the degree of confinement to any arbitrary level and to connect multiple confined systems expressing different charge, spin, and mechanical degrees of freedom to produce new phenomena. The portfolio can be expected to continue thrusts in electronic structure, new materials, surfaces/interfaces, and development of experimental techniques, including the growth of thin films and single crystals to enable new physics. Efforts will continue to strengthen research in unconventional superconductivity, including the high-temperature cuprate superconductors, magnesium boride, and iron pnictide superconductors. In the last few years, the program has increased support for spin physics and nanomagnetism, topological states of matter, and graphene. Recently, the program has begun to explore whether cold atom research can provide insight into open questions about correlated electron behavior in condensed matter systems.