

Research Activity:**Theoretical Condensed Matter Physics**

Division: Materials Sciences and Engineering
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Portfolio Description:

The Theoretical Condensed Matter Physics activity supports basic research in theory, modeling, and simulations complementing the experimental effort. A current major thrust is in nanoscale science where links between the electronic, optical, mechanical, and magnetic properties of nanostructures and their size, shape, topology, and composition are poorly understood. Other research areas include correlated behavior of two dimensional electron gases, quantum transport, superconductivity, magnetism, and optics. An important facilitating component is the Computational Materials Science Network (CMSN) which enables groups of scientists from Department of Energy (DOE) national laboratories, universities, and (to a lesser extent) industry to address materials problems requiring larger-scale collaboration across disciplinary and organizational boundaries.

Unique Aspects:

New areas of materials science are being identified and studied. New technology is enabling a much closer examination of the existing ones. This healthy progress dictates that new theories be developed and that established ones be reexamined and possibly extended. A very important contribution of the theorist is enforcing a rational, consistent understanding of experimental observations so that we can go forward. Often, this involves working out implications of a theory for a specific material or situation. In materials, this can be an extremely difficult task owing to the very many atoms involved. Theorists have developed many conceptual tools such as quasiparticles, entities defined to examine phenomena at different length scales, or summary statistical approaches to deal with this problem. Further development of such conceptual tools continues to be a very important aspect within this theoretical program. However, for many phenomena now being studied, large scale computation must be used to perform the complex calculations dictated by the fundamental theory or to perform the simulations of systems with many interacting components. The rapid advance in computational capabilities now enables research at such a level of sophistication that computational science has become a "third way of doing science," albeit, at a price. The complexity of such research often dictates larger groups of collaborating researchers from a diversity of disciplines, and one response is CMSN. At present, CMSN consists of four collaborative research projects: Multiscale Studies of the Formation and Stability of Surface-Based Nanostructures; Predictive Capability for Strongly Correlated Systems (an attempt to advance capabilities in many body theory); Dynamics and Cohesion of Materials Interfaces and Confined Phases Under Stress; and Multiscale Simulation of Thermo-mechanical Processes in Irradiated Fission-reactor Materials.

Relationship to Other Programs:

This activity interacts with all the other research activities within the BES Materials Sciences and Engineering Division, driven by mutual interest. Because production supercomputer resources used by the division are administered in this activity, there is an enhanced awareness of opportunity. Within the Office of Science, frequent interaction occurs with the Office of Advanced Scientific Computing Research (ASCR). Information on university grants is shared with the National Science Foundation (NSF), peer reviews are sometimes shared, and on occasion there is joint funding of grants. On the international level, participation in organizing and steering committees is frequent, as are exchanges of experts between foreign and domestic institutions.

Significant Accomplishments:

Consistent with an emphasis on nanoscience, notable achievements in this area have been made within this activity. Research into low dimensional materials has revealed exciting new information and has pointed to new possibilities in creating new tailored materials and devices. Highlights include:

- By judiciously attaching molecules to nanoclusters, one can guide them to assemble in a specified manner. (The rule book remains to be written, but it is under construction.)
- Gold nanoparticles behave much more like their platinum group neighbors in the periodic table including exhibiting interesting catalytic behavior. When passivated by dodecane thiols, they can self-assemble into nanocrystalline superlattices with unique properties.

- Nanocrystalline diamond can form with a bucky ball-like surface reconstruction. The carbon nanoparticles exhibit very weak quantum confinement unlike silicon and germanium.
- Silicon nanotubes can be formed by stabilization with a core of nickel atoms. Unlike carbon, silicon nanotubes are not stable without such help.

Significant progress has also been made in other areas as illustrated by the following examples:

- Dynamic mean-field theory, which is exact for infinite dimensions, has been successfully coupled with three dimensional band theory. The resulting hybrid theory has been used to elucidate the spin polarization of CrO_2 — a famous magnetic recording material that might find new use in spintronics. A competition between quasiparticle behavior and local-moment behavior is found.
- Progress has been made on the question of how to treat core-hole effects in x-ray absorption spectra by a collaborative research team of the CMSN. The team, which focuses on Excited States and Response Functions, brought together experts of all applicable approaches to compare approaches and elucidate the formal relationships among them. What resulted was an excellent prescription for success but with identified places for improvement. This is needed not only for fundamental understanding of the details of x-ray absorption phenomena but for technological applications, e.g., the measurement of the thickness of integrated circuit interconnects.
- The origin of the light-induced conductivity in the transparent oxide $12\text{CaO}\cdot 7\text{Al}_2\text{O}_3$ is traced to electrons excited off hydrogen ions present. To accomplish this, it was first necessary to accomplish calculating the Coulomb gap leading to hopping conductivity.
- A way has been found to see diffraction data for molecules adsorbed on surfaces. The conventional methods of low energy electron diffraction will not work; the molecules produce no Bragg spots because they are randomly distributed on the surface. However, it has been shown that the information is present in the intensity variation of the spots originating from the substrate. The resulting technique has successfully revealed the geometry of small hydrocarbons on a palladium surface.

Mission Relevance:

The program's ultimate purpose is to understand the properties of existing materials and to reveal new materials that are more efficient in producing, storing, and using energy. To this end, the programs in this portfolio have the common goal of achieving a basic understanding of matter at all scales ranging from atomic to bulk. The experimental and theoretical programs work closely together, but there are also more independent modes of research. The theorists try to establish a theoretical basis for experimentally observed results, which almost always suggests further experiments, and thus leads to new results. New experiments and experimental techniques are suggested. New science is also produced by simulating processes on computers. "Computer experiments" can be performed which are difficult or impossible to perform in the laboratory. They are also much easier to dissect and to vary the conditions in order to isolate the effective mechanisms. For example, the behavior of the surface layers of materials sliding on each other and a new understanding of the role of lubricants has been obtained in this way. Other examples include investigations into the behavior of electrons flowing in nano wires and nanotubes and in the properties of matter at extreme conditions of temperature and pressure.

Scientific Challenges:

The close relationship between the experimental and theoretical programs dictates that many challenges are common to both. Examples are exploring the behavior of complex systems, investigating nano-scale systems, and understanding superconductivity. New ways of conceptually visualizing and characterizing phenomena will broaden our horizons. Stripes occurring in cuprate superconductors and two dimensional electron gasses are excellent examples. Bridging length scales is a major thrust. The tactic of dividing up the effects in materials according to the length scale at which they occur has greatly facilitated our understanding. But for theorists, this creates the problem of how to pass needed information between the different constructs used at the different length scales. Only in that way can one calculate parameters rather than make phenomenological fits. Such is the basis for improved understanding and greater precision of our modeling. It is a continuing major goal on which limited progress has been made. Bridging time scales is similarly important, but far less progress has been made. Basic theory improvements are also needed. For example, density functional theory is our most computationally tractable many body theory, but it defines many functionals both for the ground state or ensemble energy and separately for the properties that must be determined. Whereas knowledge of the exchange-correlation functional for the ground

state energy is reasonably advanced, knowledge of all other functionals is still quite rudimentary. Other many body approaches, although far more computationally intensive, provide important information and require further development. Improvements are also needed in our computational tools. Materials theory is a very heavy consumer of computer resources even if not so visibly as other disciplines. (This is because materials theory deals with many dissimilar problems rather than a few overarching ones.) The materials community could make very productive use of vast increases in computational capability. Because the phenomenal growth due to hardware improvements is actually overshadowed by those due to clever algorithm design, further improvements in “tool development” will significantly impact future development of science in a qualitative way.

Funding Summary:

Dollars in Thousands								
<u>FY 2007</u>	<u>FY 2008</u>	<u>FY 2009</u>						
23,208	25,832	36,190						
<table style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="text-align: left;"><u>Performer</u></th> <th style="text-align: right;"><u>Funding Percentage*</u></th> </tr> </thead> <tbody> <tr> <td>DOE Laboratories</td> <td style="text-align: right;">54%</td> </tr> <tr> <td>Universities</td> <td style="text-align: right;">46%</td> </tr> </tbody> </table>			<u>Performer</u>	<u>Funding Percentage*</u>	DOE Laboratories	54%	Universities	46%
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*Based on FY2007

The program provides funding for >100 university grants. The program supports research at Lawrence Berkeley National Laboratory, Brookhaven National Laboratory, Ames Laboratory, Argonne National Laboratory, Oak Ridge National Laboratory, Los Alamos National Laboratory, Lawrence Livermore National Laboratory, and National Renewable Energy Laboratory. Programs at the national laboratories are multi-investigator efforts on problems that require extensive participation by experimental and theoretical scientists. Many of the research efforts at national laboratories involve interfaces with the university and industrial communities and with user facilities. Additionally, about \$1.68M is provided for projects of the CMSN.

Projected Evolution:

Materials will be modeled with ever-greater sophistication, realism, and complexity. Needs and opportunities will drive the effort inexorably in this direction. Science at the nanoscale will continue a major thrust, although it is only one of many. A cooperative effort between the BES Chemical Sciences, Geosciences, and Biosciences Division and ASCR seeks to enhance our capabilities to model and simulate at the nanoscale. The CMSN will be enhanced to bring together teams adequate to address the more complex problems envisioned. Large scale computing will continue to be an important aspect of the research, but a new balance will have to be achieved in the allocation of resources, which will impact all BES activities.