BPA News

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Materials in a New Era—1999 Solid State Sciences Committee Forum Summary

by Thomas P. Russell, Chair, Solid State Sciences Committee

The 1999 Solid State Sciences Committee Forum, entitled "Materials in a New Era," was held at the National Academy of Sciences in Washington, D.C., on February 16-17, 1999. This article is a summary of the discussions. A more detailed account of the forum appears in *Materials in a New Era: Proceedings of the 1999 Solid State Sciences Committee Forum*, soon to be available from the Board on Physics and Astronomy. The agenda for the forum appears on Page 5 of this newsletter.

The forum was designed to launch the decadal report *Condensed-Matter and Materials Physics: Basic Research for Tomorrow's Technology*. This report, part of the series *Physics in a New Era*, reviews some of the outstanding accomplishments in materials research over the last decade and indicates some of the emerging areas where there is true excitement in the field from the perspective of basic science potential and in terms of societal impact.

The first day of the forum focused on the national political environment surrounding materials science, the funding constraints under which materials scientists must operate, and the changing roles of government laboratories, industry, and academic institutions in promoting materials science.

Unlocking Our Future

Laura Rodriguez, a staff member in the office of Representative Vernon Ehlers (R-MI), set the stage from a national perspective with the keynote presentation on the recently issued study *Unlocking Our Future: Toward a New National Science Policy*. This report, the result of a House of Representatives study headed by Rep. Ehlers, was aimed at developing a national science policy appropriate for the 21st century. The study finds that the federal government, scientists, and educators must address several issues: (1) Our science policy is outdated. (2) The American public does not understand science and its practice. (3) Scientists are politically clueless. It is evident that our nation needs to improve its science, mathematics, engineering, and technology education; to develop a new concise, coherent, and comprehensive science policy; and to make its scientists socially responsible and politically aware. The report makes four major recommendations:

1. Continue to push the boundaries of the scientific frontier by supporting interdisciplinary research, maintaining a balanced research portfolio, and funding more innovative "risk-taking" projects.

2. Support private research efforts, an essential component of a healthy U.S. R&D portfolio, by encouraging young, start-up companies, making the R&D tax

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BPA Meets in Washington

The BPA held its Spring meeting in Washington, D.C., on April 26. Board Chair Robert C. Dynes, chancellor of the University of California at San Diego, opened the meeting with the announcement that the membership of the Board will rotate on July 1. New members of the Board include Anneila Sargent of Caltech, Peter Wolynes of the University of Illinois, William Bialek of NEC Princeton Laboratory, Cherry Murray of Lucent Technologies, and Gordon Baym of the University of Illinois. Anthony Tyson of Lucent Technologies was reappointed. The first BPA meeting that new members will attend will be the Fall meeting, which will take place at the Academies' Beckman Center on November 6-7, 1999.

In closed session, Dynes discussed a review of the Board's program by its parent Commission on Physical Sciences, Mathematics, and Applications. CPSMA member Jerry Gollub outlined the results of the review; CPSMA member Daniel Kleppner participated in the discussion.

The open sessions began with discussion of various subjects related to astronomy. In the afternoon, several guests spoke on topics ranging from NASA's perspective on astronomy issues to the latest developments in algorithms for image compression using wavelets. On the next day, selected projects being carried out under the auspices of the BPA were reviewed.

Astronomy Topics

John Huchra, co-chair of the Committee on Astronomy and Astrophysics, reported that the committee is planning to send a letter report to the NSF Astronomy Division following up the McCray report on ground-based optical and infrared astronomy. The letter addresses the continuing need for an effective program to facilitate construction of instrumentation for the new generation of optical telescopes now in operation. The CAA is also completing a

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The Board on Physics and Astronomy is a continuing interdisciplinary body with expertise spanning the various subfields of physics, astronomy, and astrophysics. It serves as a focal point in the National Research Council for issues connected with these fields. The activities of the Board are supported by funds from the National Science Foundation, the Department of Energy, the Department of Defense, the National Aeronautics and Space Administration, the National Institute of Standards and Technology, and private and other sources.

1999 SSSC Forum (cont.)

credit permanent, streamlining regulations, and pursuing and developing effective partnerships.
3. Increase efforts in education at all levels—including preschool to graduate school, research on curricula and education, addressing issues of teacher training, recruitment, and retention, providing for a more diversified graduate experience, and increasing public outreach.
4. Strengthen the relationship between science and the society that supports it through improved communication among scientists, journalists, and the public and by engaging the scientific community in helping society make good decisions.

Session I: Materials and the Federal Role

The interdependence of different fields of research was emphasized by a number of representatives of federal agencies.

Office of Science and Technology Policy

Arthur Bienenstock, associate director for science in the Office of Science and Technology Policy, emphasized the Clinton administration's unequivocal commitment to maintaining leadership across the frontiers of scientific knowledge. Technology and the underlying science in many fields are responsible for more than 50% of the increases in productivity that we have enjoyed over the last 50 years. The various branches of science are truly interdependent — progress in one field depends on advances in many other areas. As an example, Bienenstock pointed to CAT scans, one of the mainstays of medical diagnostics, asking why it took so long after the discovery of x-rays for the technology to develop. Progress in many fields was needed to make the technology a reality — solid state physics and engineering to enable the computers that control the instrument and collect and analyze the data, materials science to provide the x-ray detectors, and mathematics and computer science for the algorithms to reconstruct the image from the raw data. CAT scans would not exist today if any of these were missing.

National Institutes of Health

Marvin Cassman, director, National Institute of General Medical Sciences, further developed the theme of interdependence by discussing the multidisciplinary nature of research at major facilities such as synchrotrons and neutron sources. In the United States, most such facilities are funded by agencies with major responsibilities for condensed-matter and materials research. Biological research, however, is finding an increasing need for these facilities and now accounts for a significant fraction of all work being carried out at these national sources. Appropriate cooperation among these communities and the agencies that fund them will be essential to the continued viability of these important and extremely costly facilities. An inter-agency working group has been formed under the auspices of OSTP to facilitate such cooperation.

Department of Energy

Martha Krebs, director of the Department of Energy Office of Science, presented the DOE perspective. The FY00 budget request for the Office of Science is $189M greater than the FY99 budget. This increase is largely for construction of the Spallation Neutron Source and for the Scientific Simulation Initiative (SSI), an interagency initiative that will bring teraflop-scale computing to bear on a number of problems, including global systems, combustion, and basic science (which may include materials). Krebs identified a number of future directions and opportunities in materials research, including neutron scattering, complex materials at high magnetic fields, sp^2 bonded materials, granular materials, complex materials, and high-temperature superconductors and other vortex matter.

Department of Defense

Hans Mark, director for Defense Research and Engineering in the Department of Defense, initiated his presentation by noting the basic axiom that pos-

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The Fractional Quantum Hall Effect

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I. Introduction

The various quantum Hall effects are arguably some of the most remarkable many-body phenomena discovered in the second half of the 20th century, comparable in intellectual import to superconductivity and superfluidity. They are an extremely rich set of phenomena with deep and truly fundamental theoretical implications. The fractional effect, for which the 1998 Nobel Prize in physics was awarded, has yielded fractional charge, spin, and statistics, as well as unprecedented order parameters. There are beautiful connections with a variety of different topological and conformal field theories studied as formal models in particle theory, each here made manifest by the twist of an experimental knob. Where else but in condensed-matter physics can an experimentalist change the number of flavors of relativistic chiral fermions, or set by hand the Chern-Simons coupling which controls the mixing angle for charge and flux in (2+1)-dimensional electrodynamics?

Because of recent tremendous technological advances in molecular beam epitaxy (MBE) and the fabrication of artificial structures, the field continues to advance with new discoveries even well into the second decade of its existence. Experiments in the field were limited for many years to simple transport measurements, which indirectly determine charge gaps. However, recent advances have led to many successful new optical, acoustic, microwave, specific heat, and NMR probes, which continue to advance our knowledge as well as raise intriguing new puzzles.

The quantum Hall effect takes place in a two-dimensional electron gas subjected to a high magnetic field. In essence it is a result of commensuration between the number of electrons, N, and the number of flux quanta, N_Φ, in the applied magnetic field. The electrons undergo a series of condensations into new states with highly non-trivial properties whenever the filling factor $\nu = N / N_\Phi$ takes on simple rational values. The original experimental manifestation of the effect was the observation of an energy gap yielding dissipationless transport (at zero temperature) much like in a superconductor. The Hall conductivity in this dissipationless state is universal, given by $\sigma_{xy} = \nu e^2 / h$ independent of microscopic details. As a result of this fact, it is possible to make a high-precision determination of the fine-structure constant and to realize a highly reproducible quantum-mechanical unit of electrical resistance, now used by standards laboratories around the world to maintain the ohm.

The integer quantum Hall effect (IQHE) owes its origin to an excitation gap associated with the discrete kinetic energy levels (Landau levels) in a magnetic field. The fractional quantum Hall effect (FQHE) has its origins in very different physics of strong Coulomb correlations, which produce a Mott-insulator-like excitation gap. In some ways, however, this gap is more like that in a superconductor since it is not tied to a periodic lattice potential. This situation permits uniform charge flow of the incompressible electron liquid and hence a quantized Hall conductivity.

The microscopic correlations leading to the excitation gap are captured in a revolutionary wave function, developed by R. B. Laughlin, which describes an incompressible quantum liquid. The charged quasiparticle excitations in this system are "anyons" carrying fractional statistics intermediate between bosons and fermions and carrying fractional charge. This sharp fractional charge, which despite its bizarre nature has always been on solid theoretical ground, has recently been directly observed two different ways. The first is an equilibrium thermodynamic measurement using an ultra-

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session of superior technology leads to victory in war. However, what has not been recognized is that fundamental scientific research is the link between superior technology and basic knowledge. He outlined four new science and technology topics that the Defense Science Board should be considering and invited the community to suggest others. The ones he suggested were:

1. "Strange" molecules, i.e., fullerenes, carbon nanotubes, or hyperbranched molecules;
2. Software development, especially new techniques for producing software such as genetic algorithm development and application and automation of software development;
3. High-power electrical devices; and
4. Predictive chaos theory/nonlinear dynamics and its applicability to national security.

He emphasized that it is essential for the U.S. military to receive the best possible scientific information and, to this end, the Department of Defense will continue to support basic research.

National Institute of Standards and Technology

Raymond Kammer, director of the National Institute of Standards and Technology, outlined the impact that NIST has had in materials science. He touched on the high quality of research performed in NIST laboratories, the provision of research facilities to the scientific community, and the role of the Advanced Technology Program with regard to the industrial sector of research in the United States. With the growth of industrial interest in soft materials, including biomaterials, the drive toward nanoscale structures, and the importance of magnetic materials, it is essential that NIST remain on the forefront of research in these fields. NIST will continue to develop, build, and operate the best possible research facilities to study topics where NIST can play a special role.

National Science Foundation

Robert Eisenstein, the assistant director for Mathematical and Physical Sciences of the National Science Foundation, surveyed the broad range of research that NSF currently supports, spanning length scales from the subatomic to the astronomic. While Mathematical and Physical Sciences supports a broad range of research, its budget has increased by only 60 percent over the past ten years. By comparison, the overall budget of the National Science Foundation has nearly doubled in the same period. MPS is not keeping pace, with greater budgetary increases going to Engineering, Biology, Education, and Computer Science. Can this situation be changed? Only if the direct impact of Mathematical and Physical Sciences research on these others fields and on society in general is demonstrated and argued convincingly. Quoting Neal Lane, "It is necessary to involve materials scientists in a new role, undoubtedly an awkward one for many, that might be called the 'civic scientist.' This role is one in which science shares in defining our future."

Session II: Materials R&D—The Next Decade

Materials R&D in Industry

Cherry Murray, director of research at Lucent Technologies, discussed materials R&D in the industrial sector in a lecture entitled "The Changing Role for Physical Science Research in Industry in the Information Age." The development of corporate research in the United States since the 1970s has evolved from "just in case" to "just in time" to "just indispensable." Without question, industrial research is becoming more tightly coupled to products, and the opportunities to conduct "blue sky" research (i.e., research completely disconnected from the bottom line) are very limited. However, the technological advances that have been witnessed during the past decade now place technology in the position of pushing fundamental limits. As a consequence, many companies are now increasing their support for long-term research. To maintain a competitive edge companies must maintain in-house competencies, stimulate innovation, fuel growth, and broaden their product portfolios. But why the need for research? Inventions, technological expertise, and strong intellectual property positioning are the answer. Murray concluded with the remark that ". . . physical sciences research is as essential as ever for leading-edge high-technology companies."

Condensed-Matter and Materials Physics

The focal point of the forum was to launch the report of the Committee on Condensed-Matter and Materials Physics. Venkatesh Narayanamurti, dean of Engineering and Applied Science, Harvard University, chaired this committee and gave an overview of the report.

Over the past decade CMMP has been marked by the unexpected. The Brinkman survey of physics (*Physics Through the 1990s*, National Academy Press, 1986) did not anticipate several of the most important developments. One need only look at the discoveries of fullerenes, giant magnetoresistance, the fractional quantum Hall effect, and atomic force microscopy, to name a few, to see the impact that unforeseen advances have had on science and society in general.

However, to ensure continuing intellectual vitality and the transfer of knowledge to practical applications, CMMP must face daunting challenges in the future. In general, science is becoming more multidisciplinary. Advances in different fields are sparked by the integration of the special knowledge of subfields. For the scientific effort to succeed, facilities infrastructure needs to be in place so that research can be done efficiently and effectively by a broad community. New modes of cooperation between the academic, industrial, and government communities must be established to ensure that CMMP addresses matters of concern to society and to preserve a climate of innovation. In addition, given the multidisciplinary nature of research, academic institutions need to evaluate and perhaps modify curricula to best educate students, who represent the future of science.

Narayanamurti then went on to describe several actions that need to be taken to maintain and enhance the productivity of CMMP. The different government funding agencies need to nurture the core research effort, modernize the

Materials in a New Era

The 1999 Solid State Sciences Committee Forum
National Academy of Sciences
Washington, D.C.
February 16-17, 1999

Tuesday, February 16, 1999

Opening Session

Welcome and Introduction – *Thomas Russell, SSSC Chair*
A National Perspective on R&D – *Laura Rodriguez, Office of Rep. Vernon Ehlers*

Session I: Materials and the Federal Role

Office of Science and Technology Policy – *Arthur Bienenstock, Associate Director for Science*
National Science Foundation – *Robert Eisenstein, Assistant Director for Mathematical and Physical Sciences*
National Institute of Standards and Technology – *Raymond Kammer, Director*
Department of Energy – *Martha Krebs, Director, Office of Science*
Department of Defense – *Hans Mark, Director for Defense Research and Engineering*
National Institutes of Health – *Marvin Cassman, Director, NIGMS, National Institutes of Health*
Panel Discussion – *Speakers and Congressional Staff*

Session II: Materials R&D—The Next Decade

Report of the Committee on Condensed-Matter and Materials Physics – *Venkatesh Narayanamurti, Harvard University*
Materials R&D in Industry – *Cherry Murray, Lucent Technologies*
Changing Roles for Research Universities – *David Litster, Massachusetts Institute of Technology*
Changing Roles for Government Laboratories – *John McTague, Ford Motor Company*
Panel Discussion of the Future of Materials R&D

Reception

Wednesday, February 17, 1999

Session III: Materials Education and Infrastructure

Materials Education for the 21st Century – *Robert Chang, Northwestern University*
The Spallation Neutron Source – *Thom Mason, Oak Ridge National Laboratory*
Synchrotrons and Next-Generation Light Sources – *David Moncton, Advanced Photon Source*
Smaller Facilities: Opportunities and Needs – *J. Murray Gibson, University of Illinois at Urbana-Champaign*

Session IV: Materials R&D—A Vision of the Scientific Frontier

The Science of Modern Technology – *Paul Peercy, SEMI/SEMATECH*
Novel Quantum Phenomena – *Steven Girvin, Indiana University*
Nonequilibrium Processes and the Mesoscale – *James S. Langer, University of California at Santa Barbara*
Soft Condensed-Matter and Macromolecular Science – *V. Adrian Parsegian, National Institutes of Health*
Tales from Flatland – *Horst Störmer, Columbia University*
Open Discussion: Issues and Opportunities in CMMP

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CMMP research infrastructure, and invest in state-of-the-art equipment.

Concerning larger facilities, the current gap between the United States and the rest of the world in neutron science needs to be closed by construction of the Spallation Neutron Source and by upgrading existing reactor- and spallation-based sources. Support for operating and upgrading existing synchrotron sources and investment in the next generation of synchrotron sources should be strengthened.

Incentives should be provided for partnerships among academic, industrial, and government laboratories. Universities need to enhance their students' understanding of the role of knowledge integration and transfer as well as knowledge creation.

Can we predict where advances will be made? Absolutely not. Nonetheless, it is abundantly clear that the successes achieved in CMMP have had an impact on many disciplines and have led to marked advances in completely unexpected areas.

Changing Roles for Research Universities

J. David Litster of the Massachusetts Institute of Technology described the current funding transition in which research universities are involved. Using his home institution as an example, Litster noted the enormous pressure that universities are facing in terms of recovering overhead costs with flat or declining budgets. The 1980s showed a significant decrease in the amount of federal financial aid to students, decreasing from 50% to 20%, with the universities being left to make up the difference. To meet these large financial burdens universities have turned to industrial support for research. However, a delicate balance must be struck, since industry is sensitive to intellectual property rights and ownership, whereas universities must be free to publish the results of research.

Changing Roles for Government Laboratories

John McTague, recently retired vice president of Ford Motor Company and co-chair of the Secretary of Energy's Laboratory Operations Board, addressed the challenges that face government laboratories. How can the national laboratories operate as a truly integrated system working more efficiently to address problems of national importance? McTague cited four specific examples: the Center for Excellence for Synthesis and Processing of Advanced Materials, the Partnership for a New Generation of Vehicles, the Spallation Neutron Source, and the Information Technology for the 21st Century initiative. Each of these collaborative efforts involves several national laboratories operating in a manner coordinated from the management level down to the laboratory bench level.

McTague concluded by noting that he was cautiously optimistic that the national laboratories will be able to meet the challenge of working together. Through cooperative projects, the laboratories may evolve beyond being simply a collection of isolated institutions toward becoming a unified system of national laboratory resources.

Panel Discussion

The first day concluded with a panel discussion including **Cherry Murray, Venkatesh Narayanamurti, Thomas Weber** of the National Science Foundation, **William Oosterhuis** of the Department of Energy, **Skip Stiles**, a member of the House Science Committee Minority Staff, and **Harlan Watson**, a member of the House Science Committee Majority Staff.

While the members of the panel fully agreed that CMMP has a compelling case for support, that the impact of CMMP in society has been significant, and that the importance of CMMP in industry has been and will continue to be great, these facts are not sufficient to ensure the health and prosperity of the field. Specifically, scientists need to continually "beat the stump" with local and national politicians, educating them about how CMMP has had a significant impact on their constituents and making clear why future funding is essential. Although these arguments have been made in the past, the message has not been transmitted effectively. Even with convincing arguments for support, the reality is that funding for science will be capped over the next two years and that no new money will materialize unless these caps are lifted. The S.1305 authorization bill is a good organizational tool but will not produce more funding, and it does not bind future Congresses.

Session III: Materials Education and Infrastructure

Materials Education for the 21st Century

Robert Chang of Northwestern University presented several sobering facts concerning the current state of education in the United States. He emphasized the need for prompt educational reform in materials science if the field is to remain vibrant. From the number of American students attending college and advancing on to higher degrees to the overall poor performance of American schoolchildren in international testing and the dearth of teachers trained in materials science, the outlook for the future of materials science must be of concern to every materials scientist. Materials science, essential in our everyday lives and vital to our future, still has a very low profile in secondary education.

Because materials science is an ever changing discipline with new areas continually emerging, it is necessary for academic institutions to be able to adapt in a commensurate time frame. Such flexibility is very hard to realize, given the slow rate at which academic institutions can change. Consequently, existing resources, such as the Materials Research Science and Engineering Centers and Science and Technology Centers funded by the National Science Foundation, must be used to best advantage. Outreach programs of these centers that address K-12 education needs, although effective, are simply not enough. Chang's studies indicate that middle school and high school are a particularly crucial phase in the educational development of children. At this age many students lose interest in science, and we must ask why this occurs and how the gap between high school and college can be bridged.

Chang concluded that all materials science initiatives must undertake to foster greater awareness of the importance of materials science education; to introduce materials science at the high school level; to enhance mathematics and science education; and to get teachers involved in materials science education.

The Spallation Neutron Source

Thom Mason, science coordinator for the Spallation Neutron Source, outlined the status of this $1.3B project that involves an integrated effort from the five national laboratories. The history of neutron sources has been marked by several key threshold points.

In particular, for neutron scattering, the development of the graphite reactor at Oak Ridge, the National Research Universal (NRU) reactor at Chalk River Laboratories in Canada, and the development of neutron waveguides marked significant breakthroughs in the use of neutrons for materials research.

We stand now on another threshold with the planned construction of the Spallation Neutron Source at Oak Ridge National Laboratory. This will be the world's most powerful neutron source. It will enable qualitatively new and different science in disciplines ranging from materials science to biological sciences. The Spallation Neutron Source will offer nearly an order-of-magnitude enhancement in the neutron flux on the sample. This enhancement, coupled with time-of-flight detection, will open areas of materials science that are currently only dreams.

Is the pathway straightforward and without obstacles? Any effort that involves five different national laboratories and that requires each component constructed at the different laboratories to operate perfectly and to mesh with exceptional precision will not be straightforward. The construction of the Spallation Neutron Source is technically difficult. And the coordination of five different laboratories operating under severe budget constraints poses a significant managerial challenge. Nonetheless, the future of materials science based on neutrons rests on the Spallation Neutron Source. It is absolutely imperative for the scientific well-being of the nation that the Spallation Neutron Source be successfully completed on time and within budget.

Synchrotrons and Next-Generation Light Sources

David Moncton, (then) director of the Advanced Photon Source, described the tremendous advances that have been made in the x-ray flux with the developments in synchrotron radiation sources and the science that these sources have enabled. The development of these sources has been driven by the urgent and compelling needs of science. In turn, however, the massive increases in flux have also opened unexpected areas of science.

In comparison with current sources, fourth-generation sources offer spectacular gains in flux and brilliance; large quantitative improvements in beam coherence, timing, and dynamics; and large qualitative improvements in photon degeneracy. Such sources promise tremendous opportunities in atomic and molecular physics, biology, chemical physics, materials science, high-field physics, and soft-matter physics.

Smaller Facilities

J. Murray Gibson of the University of Illinois addressed an often overlooked component of materials science research, namely the smaller facilities. Among these are facilities for electron microscopy, ion-beam studies, and mass-spectrometry research. These facilities are too expensive for any single investigator and yet are too small to capture national attention. However, these facilities play a vital role in materials science research. They provide capabilities far beyond that afforded by the laboratory of an individual researcher.

Operating costs upwards of $1M with replacement costs of over $2M annually are not uncommon. Yet the number of mechanisms that such facilities have for obtaining the necessary funding is limited. Many are situated at NSF-supported Materials Research Science and Engineering Centers, Science and Technology Centers, and Engineering Research Centers or DOE-supported Materials Research Laboratories. Because such facilities have proven to be important, opening different avenues for their support and maintenance is critical.

Session IV: Materials R&D—A Vision of the Scientific Frontier

The Science of Modern Technology

Paul Peercy of SEMI/SEMATECH discussed the science underlying modern technology. While the scientific discoveries over the past decade have been both unexpected and impressive, equally impressive have been the technological advances based on our increased understanding of the physics, chemistry, and processing of materials. These insights have enabled modern computing and telecommunications technology to keep pace with, if not exceed, the expectations set by Moore's law. Scientific understanding has not only demonstrated the feasibility of advances in technology but has also led the way to high-volume, low-cost production of devices.

Today's technological revolution would not be possible without basic scientific understanding. This fact holds true for industries across the board, ranging from semiconductors to communications to commodity polymers. To maintain progress, research in the optical, electrical, and magnetic properties of materials must continue. As size scales shrink, nanostructured materials, artificially structured materials, self-assembled systems, and biologically based systems will become increasingly important for future advances.

Novel Quantum Phenomena

Steven Girvin from Indiana University presented a lecture focused on novel quantum phenomena. He dispelled the notion that there are few surprises or intellectual challenges left when considering the physics of well-known objects, such as atoms, that interact via well-defined and well-understood electromagnetic forces. Superconductivity, superfluidity, and the fractional quantum Hall effect are three recent examples of suprises lurking in familiar systems. These phenomena underscore the fact that the quantum mechanics of large collections of objects can be unusual and unexpected. Emergent phenomena, such as phase transitions and broken symmetries, often appear in large collections of objects. These phenomena pose significant theoretical and experimental challenges to condensed-matter and materials physicists, since materials constructed from a large collection of atoms routinely have completely unexpected properties. [A full-length article on these phenomena by Girvin appeared in the last issue (December) of *BPA News*. Another full-length article by Girvin on the theory of the fractional quantum Hall effect appears in this issue.]

Nonequilibrium Processes

James Langer of the University of California at Santa Barbara treated the subject of nonequilibrium physics—the physics of materials not in mechanical or thermal equilibrium with their surroundings. Although the importance of nonequilibrium behavior was recognized in the Brinkman report (*Physics Through the 1990s*, National Academy Press, 1986), its critical role in areas ranging from friction and fracture to granular materials to weather to ductility was completely overlooked.

One goal of nonequilibrium physics is to quantify the relationship between precision and predictability. Nonequilibrium phenomena continually come to the fore as key to understanding a material's response to an applied external field or its ultimate properties. With increasing interactions between different disciplines, it is evident that nonequilibrium phenomena will increase in importance.

Biology and Physics: Soft Condensed Matter

Adrian Parsegian of the National Institutes of Health underscored the importance of condensed-matter and materials physics to the biological community and the general importance of cross-disciplinary research. Advances made with high-powered synchrotron and neutron sources have had a significant impact on other fields. For example, as discussed previously by Cassman in his talk in Session I, the number of protein structures that are being determined has increased tremendously through advances developed by the synchrotron community.

However, it is not sufficient simply to offer sophisticated instrumentation. At present physicists are simply off the radar screen of most biologists, where the former are considered as being insular and parochial. It is necessary to establish a dialogue between the different communities. Doing so, however, will require that both physicists and biologists be educated in ways that will increase each community's awareness of the other and, thereby, stimulate interactions.

The Fractional Quantum Hall Effect—Tales from Flatland

Horst Störmer of Columbia University, who recently shared the 1998 Nobel Prize in physics with D. C. Tsui for their discovery of the fractional quantum Hall effect, addressed the forum with his "Tales from Flatland," where electrons can move along a two-dimensional surface, being confined in the third dimension, and carry a fractional charge. Fractional charges arise when a two-dimensional gas of electrons becomes highly correlated. In an animated presentation, Störmer took the forum attendees through the initial discovery of the quantum Hall effect and then to experiments performed under very high magnetic fields where fractionally charged excitations are observed. [A full-length article on FQHE by Steven Girvin appears in this issue of *BPA News*.]

Conclusion

The tone of the 1999 forum was considerably more upbeat than that of the 1996 forum. Federal funding for scientific research has stabilized and improved. Awareness of the value of sustained investment in research has grown, and industrial support for physical science has stabilized. With such relatively good news, it is tempting for the community to become complacent about being recognized as an invaluable contributor to the U.S. and world economy. However, we, as a community, cannot afford to be complacent but must work proactively to bring condensed-matter and materials physics to a more broadly based audience, including politicians and the lay person not versed in science. Doing so will require active participation by scientists in educating students on all levels and getting young students interested in materials physics.

In addition, scientific research is becoming much more interdisciplinary. Key advances are occurring at the interfaces between different disciplines. It is imperative that active communication be established among different communities so that the knowledge and advances made in materials physics can be brought to bear on other disciplines. ■

Fractional Quantum Hall Effect (continued from Page 3)

sensitive electrometer built from quantum dots. The second is a dynamical measurement using exquisitely sensitive detection of the shot noise for quasiparticles tunneling across a quantum Hall device.

Quantum mechanics allows for the possibility of fractional average charge in both a trivial way and a highly non-trivial way. As an example of the former, consider a system of three protons forming an equilateral triangle and one electron tunneling among the 1S atomic bound states on the different protons. The electronic ground state is a symmetric linear superposition of quantum amplitudes to be in each of the three different 1S orbitals. In this trivial case, the mean electron number for a given orbital is 1/3. This situation, however, is a result of statistical fluctuations because a measurement will yield electron number 0 two-thirds of the time and electron number 1 one-third of the time. These fluctuations occur on a very slow time scale and are associated with the fact that the electronic spectrum consists of three very nearly degenerate states corresponding to the different orthogonal combinations of the three atomic orbitals.

The $\nu = 1/3$ quantum Hall effect has charge 1/3 quasiparticles but is profoundly different from the trivial scenario just described. An electron added to a $\nu = 1/3$ system breaks up into three charge 1/3 quasiparticles. If the locations of the quasiparticles are pinned by (say) an impurity potential, the excitation gap still remains robust and *the resulting ground state is non-degenerate*. This means that a quasiparticle is not a place (like the proton above) where an extra electron spends one-third of its time. The lack of degeneracy implies that the location of the quasiparticle completely specifies the state of the system, that is, implies that these are fundamental elementary particles with charge 1/3. Because there is a finite gap, this charge is a sharp quantum observable that does not fluctuate (for frequencies below the gap scale).

The message here is that the charge of the quasiparticles is sharp to the observers as long as the gap energy scale is considered large. If the gap were 10 GeV instead of 10 Kelvin, we (living at room temperature) would have no trouble accepting the concept of fractional charge.

II. Magnetic Order of Spins and Pseudospins

At certain filling factors ($\nu = 1$ in particular) quantum Hall systems exhibit spontaneous magnetic order. For reasons peculiar to the band structure of the GaAs host semiconductor, the external magnetic field couples exceptionally strongly to the orbital motion (giving a large Landau-level splitting) and exceptionally weakly to the spin degrees of freedom (giving a very small Zeeman gap). The resulting low energy spin degrees of freedom of this ferromagnet have some rather novel properties, which have recently begun to be probed by NMR, specific heat, and other measurements.

Since the lowest spin state of the lowest Landau is completely filled at $\nu = 1$, the only way to add charge is with reversed spin. However, because the exchange energy is large and prefers locally parallel spins (and because the Zeeman energy is small), it is cheaper to partially turn over several spins forming a smooth topological spin "texture." Because this is an itinerant magnet with a quantized Hall conductivity, it turns out that this texture (called a skyrmion by analogy with the corresponding object in the Skyrme model of nuclear physics) accommodates precisely 1 extra unit of charge. NMR Knight shift measurements have confirmed the prediction that each charge added (or removed) from the $\nu = 1$ state flips over several (~ 4–30 depending on the pressure) spins. In the presence of skyrmions, the ferromagnetic order is no longer collinear, leading to the possibility of additional low energy spin wave modes, which remain gapless even in the presence of the Zeeman field (somewhat analogous to an antiferromagnet). These low frequency spin fluctuations have been indirectly observed through a dramatic enhancement of the nuclear spin relaxation rate $1/T_1$. In fact, under some conditions, T_1 becomes so short that the nuclei come into thermal equilibrium with the lattice via interactions with the inversion layer electrons. This effect has recently been observed experimentally through an enormous enhancement of the specific heat by more than 5 orders of magnitude.

Spin is not the only internal degree of freedom that can spontaneously order. There has been considerable recent progress experimentally in overcoming technical difficulties in the MBE fabrication of high-quality multiple-well systems. It is now possible, for example, to make a pair of identical electron gases in quantum wells separated by a distance (~ 100 Å) comparable to the electron spacing within a single quantum well. Under these conditions strong interlayer correlations can be expected. One of the peculiarities of quantum mechanics is that, even in the absence of tunneling between the layers, it is possible for the electrons to be in a coherent state in which their layer index is uncertain. To understand the implications of this situation, we can define a pseudospin that is up if the electron is in the first layer and down if it is in the second. Spontaneous interlayer coherence corresponds to spontaneous pseudospin magnetization lying in the XY plane (corresponding to a coherent mixture of pseudospin up and down). If the total filling factor for the two layers is $\nu = 1$, then the Coulomb exchange energy will strongly favor this magnetic order just as it does for real spins as discussed above. This long-range transverse order has been observed experimentally through the strong response of the system to a weak magnetic field applied in the plane of the electron gases in the presence of weak tunneling between the layers.

Another interesting aspect of two-layer systems is that, despite their extreme proximity, it is possible to make separate electrical contact to each layer and perform drag experiments in which current in one layer induces a voltage in the other due to Coulomb or phonon-mediated interactions.

Stacking together many quantum wells gives an artificial three-dimensional structure analogous to that of certain organic Bechgaard salts in which the quantum Hall effect has been observed. There is recent growing interest in the bulk and edge ("surface") states of such three-dimensional systems and in the nature of possible Anderson localization transitions.

These phenomena, and numerous others that cannot be mentioned because of space limitations, have provided a wonderful testing ground for our understanding of strongly correlated quantum ground states that do not fit into the old framework of Landau's fermi liquid picture. As such they are providing valuable hints on how to think about other strongly correlated systems such as heavy-fermion materials and high-temperature superconductors. ■

BPA Meeting (continued from Page 1)

report on federal funding of astronomical research that will support the work of the Policy and Education Panel of the Astronomy and Astrophysics Survey.

Joseph Taylor and Christopher McKee, co-chairs of the Astronomy and Astrophysics Survey Committee, reported on the progress of that study. The AASC met recently to hear progress reports on the work of the various panels that have been set up to develop priorities for the subfields of astronomy. The panels outlined a menu of future possibilities for initiatives in astronomy on all scales that could only be described as breathtaking in its scope. A panel of astronomers from Europe and Japan gave an international perspective on major initiatives in the field. The next meeting of the AASC will take place in July. The "shootout" at which the top initiatives recommended by each panel will be put in priority order is scheduled to take place in October.

The Board also heard from Paul Steffes of the Georgia Institute of Technology, chair of the Committee on Radio Frequencies. CORF's mandate is to monitor developments in radio spectrum use that could threaten passive uses of the spectrum, including radio astronomy and remote sensing, and to alert the Federal Communications Commission to these concerns. CORF is now writing a new position paper in preparation for the upcoming World Radio Communication Conference.

CORF recently filed Comments with the FCC on a proposed amendment to the FCC's rules concerning communications-satellite downlinks. CORF explained that it would be difficult for satellite downlinks in the 10.7-12.7 GHz band to avoid causing harmful interference to radio astronomy observations in a neighboring band that is reserved for radio astronomy. CORF argued that radio astronomy must be protected from satellite downlinks at the level required under international radio regulations. In addition, CORF recommended that the FCC modify its rules to provide for a filtering requirement to ensure that these levels are met.

Perspectives from Federal Agencies and Professional Societies

Guenter Riegler of NASA's Office of Space Science briefed the Board on the strategic planning process for new initiatives in space-based astronomy and described its relationship to the work of the AASC. Outyear budgets for the Office of Space Science in the 2000 budget request are looking much better than in the recent past, so there is a spirit of optimism in the program. Today's expectations for 2000-2005 have a number of encouraging elements. The explorer program has a firm program with 8 missions (in 3 size categories) every two years. A new technology verification program is firmly established with 5 major missions for the 2000-2005 period. There is a clear emphasis on data accessibility, education and public outreach, and technology development for new instruments. OSS has a mission plan that follows from extensive work on strategy development with participation of the scientific community. The number of simultaneously operating missions grows steadily to 2005.

Joseph Dehmer, who recently took up the directorship of the Physics Division at NSF, described a new framework for the physics program.

Michael Lubell of the Office of Public Affairs at the American Physical Society described the APS's increasingly active role in making Congress aware of the concerns of the membership and the importance of physics to the nation's economic and military security.

The Science Talk: Wavelets

For each of its meetings, the Board schedules a talk on a science topic. Ingrid Daubechies of Princeton University and Wim Sweldens of Lucent Technologies described the principles whereby waveforms can be represented by an expansion in terms of "wavelets," which are wave packets rather than waves. Over the last decade, wavelets have emerged as a synthesis from many scientific disciplines. The list includes pure mathematics (harmonic analysis), electrical engineering (filters), quantum physics (coherent states), geophysics (time-frequency analysis), numerical analysis (multigrid methods), and computer-aided design (subdivision).

In essence, a wavelet transform decomposes complex objects (functions, signals, images) into linear combinations of simple, elementary building blocks. The main characteristic is that the building blocks or "wavelets" are well localized in both time (or space) and frequency (or scale). Each wavelet represents a certain location and frequency. This approach is in contrast with classical methods such as sampling (which is local in time but not in frequency) and Fourier analysis, which is only local in frequency (and not in time).

In addition, wavelets go hand in hand with multiresolution analysis. The coarse-scale or low-frequency wavelets typically give a broad-brush approximation of the object. Fine-scale detail can be added locally using higher-frequency wavelets. The finer the scale, the more precise the localization of these extra details becomes.

Traditionally, wavelets have been constructed using the regular spacing of a lattice, and the different scales are generated by dilations by powers of 2. This procedure has allowed the construction of very fast (linear in time) wavelet transform algorithms. Such wavelet transforms are suited for regularly sampled signals defined on Euclidean geometries like a line (sound), plane (images) and 3-space (video). One of the major applications has been image and video compression. Wavelets form the basis for the new JPEG2000 standard.

More recently, so-called second-generation wavelets were built to handle data defined on more complex geometries. Typical examples are wavelets on spheres or arbitrary triangulated meshes. While such wavelets no longer can use the translation and dilation structure, they still lead to fast transform algorithms.

BPA Studies in Progress

The second day of the Board meeting was devoted to progress reports on various studies.

Fusion Science

Charles Kennel, recently appointed to chair an assessment of the science component of the program of DOE's Office of Fusion Energy Sciences, outlined the purpose and structure of the study. The assessment was requested by Martha Krebs, director, Office of Science, Department of Energy, who asked for an assessment of the science in OFES. She suggested criteria including excellence, impact, and role in education. Subsequently, with the enthusiastic support of the director of OFES, Anne Davies, the charge was elaborated to include formulation of a program strategy for the future.

The BPA's involvement in fusion science goes back to the second volume of the physics survey *Physics in a New Era*. That volume, entitled *Plasma Science: From Fundamental Research to Technological Applications*, stressed the importance of strengthening the science underpinnings of the program. It was published in 1995. Subsequently, the Congress directed a reorientation of the fusion program from one aimed primarily at development of fusion as an energy technology to a program focused more on research. The fusion science assessment's objective, then, is to assess progress in this reorientation of the program and to develop a road map for the future.

Among the specific technical issues to be addressed are the following:

•Simulation and modeling of turbulence, transport, and stability based on:
  –theoretical understanding,
  –experimental results,
  –large-scale computational modeling;
•Interaction of energetic particles and plasmas;
•Plasma boundary conditions;
•Physics of burning plasmas;
•Scientific basis for innovative confinement concepts; and
•Physics of materials under extreme thermal and radiation conditions.

Working groups have been formed to address theory, experiment, and program structure. A steering group will oversee the study and promulgate its results. One of the criteria for developing the membership of the committee was to involve researchers working in closely allied and related fields but whose principal work is not supported by or included in the OFES program. Most of the members of the committee do not receive support from OFES. But at least one member of each panel has recent direct experience with the program to ensure access to relevant background information and expertise.

The members of the steering group are Charles Kennel, chair (Director, Scripps Institution of Oceanography, U.C. San Diego), France Cordova (U.C. Santa Barbara), Robert Frosh (Kennedy School of Government), Al Narath (retired VP, Lockheed Martin), and Robert Socolow (Princeton University).

The experiment working group, headed by Claudio Pellegrini of UCLA, includes George Gloeckler (U. Md.), Patrick L. Colestock (Fermilab), and Raymond Fonck (U. Wisconsin). This group will review experimental work on all scales ranging from small university work to larger machines such as those at Princeton Plasma Physics Laboratory.

The theory and computation working group, headed by Robert Rosner of the University of Chicago, includes James W. Van Dam (U. Texas), Nathaniel J. Fisch (Princeton Plasma Physics Laboratory), Zoran Mikic (SAIC), and Jonathan Wurtele (U.C. Berkeley). This group will assess efforts to understand the basic theoretical issues in plasma science and to model and simulate plasma processes.

The initial task of these two working groups will be to form a preliminary assessment of the experimental and theoretical science efforts within OFES. On that basis, an interim report will be prepared for submission to the Department of Energy in September.

A working group on program architecture headed by James F. Drake of the University of Maryland will look at the strategy and structure of the program. This group will form a judgment about the degree to which the program has been successful in reorienting itself more in the direction of basic research that underlies fusion. The present program strategy will be reviewed and suggestions will be formulated aimed at building the most robust possible science base for the future development of fusion. Other members of this working group include Stewart C. Prager (U. Wisconsin), Andrew M. Sessler (Lawrence Berkeley Laboratory), Lennard Fisk (U. Michigan), and Linda Capuano (AlliedSignal Inc.).

The first meeting was held on May 16-19 at U.C. San Diego. At this meeting, the theory and experiment groups convened for the first time and began their work in assessing the program. A second meeting is scheduled for July 21-23 in conjunction with the Snowmass Fusion Conference that will have taken place over the previous two weeks. The interim report will be assembled at that meeting and the program architecture working group, on that basis, will begin its work on the program strategy.

Physics Survey Overview

Thomas Appelquist (Yale U.), chair of the Physics Survey Overview Committee, described his approach to a framework for consideration of physics as a whole.

Education

Jack Wilson briefed the Board on the education component of the physics survey overview and also described the most recent evolution of the Board's proposal for a study of physics education.

The Helium Reserve

John Reppy and Ray Beebe, co-chairs of the helium reserve study, shared their committee's conclusions with the Board in closed session. The study should be released this summer.

Solid State Sciences Committee

Thomas Russell, chair of the Solid State Sciences Committee, described the committee's plans for the future now that the condensed-matter and materials physics volume of the physics survey, which the SSSC oversaw, is complete. The SSSC is developing a plan for a brochure, aimed at a wide audience, entitled "The Physics of Life." The proceedings of the 1999 SSSC Forum (summarized in this issue of *BPA News*) will soon be published.

Committee on Atomic, Molecular, and Optical Sciences

Kumar Patel, who recently agreed to lead an update of the atomic physics volume of the physics survey (the first volume in the series *Physics in a New Era*), described his plans for a short report that will explain recent developments, such as Bose-Einstein condensation of atoms, that have taken place since the publication in 1994 of *Atomic, Molecular, and Optical Science: An Investment in the Future.*

Conclusion

Board chair Robert Dynes (U.C. San Diego) closed the meeting with a discussion of the BPA strategy in light of a recently concluded review of the BPA program. Expanding the objectives of the Board to include education issues is under consideration. ■

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THE BPA Web site at **www.national-academies.org/bpa** provides news on recently released reports and other developments. Reports may be ordered at **www.nap.edu**.

New Reports:

•*Nuclear Physics: The Core of Matter, the Fuel of Stars* ISBN 0-309-06276-4

•*Condensed-Matter and Materials Physics: Basic Research for Tomorrow's Technology* ISBN 0-309-06349-3

Coming Soon:

•*Gravitational Physics: Exploring the Structure of Space and Time*

•*Materials in a New Era: Proceedings of the 1999 Solid-State Sciences Committee Forum*

•*The Impact of Selling the Helium Reserve*