BPA NEWS

Board on Physics and Astronomy • The National Academies • Washington, D.C. • 202-334-3520 • national-academies.org/bpa • Winter 2004

EPP 2010: An Assessment of and Outlook for Elementary Particle Physics

As the first project in the Board on Physics and Astronomy's decadal survey of physics, the Elementary Particle Physics 2010 Committee began its work in autumn 2004 with the ambitious task of preparing a 15-year plan for the future of elementary particle physics.

Fifty years of progress in understanding the physics of matter, energy, space, and time have led the field to a new frontier of unprecedented breadth. The frontier is defined by deep questions. Are there more than the four dimensions defined by Einstein in his general theory of relativity? Is there a unification of particles and forces? What is the nature of the dark matter and dark energy that seem to permeate the universe and account for most of its matter and energy? These questions are linked together in complex ways and they make contact with various other fields of research, including nuclear physics and astrophysics. Great progress has been made through new theoretical ideas that promise deeper understanding of experimental observations. Such ideas have helped to frame these questions and will play a key role in understanding the results of future experiments.

Space-borne and ground-based wide-field telescopes will be needed to map dark matter and study the acceleration of the expansion of the universe, which appears to be caused by a mysterious dark energy, the nature of which may be elucidated by elementary particle physics. Other questions can be addressed by observations that do not employ accelerators, including neutrino physics, proton decay, cosmic ray physics, the nature of dark matter particles, and various aspects of astrophysics. These experiments also require a new generation of observational apparatus and laboratories.

To directly attack the questions of the fundamental nature of space and time and the nature of the particles and forces that give rise to dark matter and energy will require a new generation of accelerator experiments. Some experiments are now slated to be carried out in international collaborations at the European laboratory CERN on the Large Hadron Collider (LHC), a facility currently under construction that will go into operation late in this decade. Beyond the LHC, the international community is discussing the possibility of constructing a very high energy electron-positron collider (the "Linear Collider") as a possible multinational project. Other accelerator-based experiments are under discussion that address scientific problems that cannot be addressed by the LHC or the Linear Collider. Long-baseline experiments to search for charge-parity (CP) violation in the neutrino sector may require accelerators with beam powers of megawatts. Studies of B-meson physics may require machines with luminosities of 10 to 100 times those now attainable.

See "EPP 2010" on page 8

In this issue:

Bose-Einstein Condensation of Excitons at High Magnetic Field

James P. Eisenstein, California Institute of Technology

Professor James P. Eisenstein is a returning member of the BPA's Solid State Sciences Committee. He prepared this article based on an invited lecture he gave at the fall 2004 meeting of the Board on Physics and Astronomy.

Elementary particles in nature are divided into two classes: fermions and bosons. Fermions are particles with spin angular momentum 1/2, 3/2, 5/2, etc., times Planck's constant h. Electrons, protons, and neutrons are all fermions. Fermions obey the Pauli exclusion principle: no more than one fermion can occupy a single quantum state. Bosons however, have integer spin: 0, 1, 2, etc. times $h/2\pi$. Any number of bosons can occupy the same state. Elementary bosons include photons, mesons, and gravitons. More importantly, bound objects made up of an even number of fermions can also often be regarded as bosons. The prototypical example of such a composite boson is a ^{4}He atom.

Bosons can undergo Bose-Einstein condensation (BEC), in which a macroscopic number of particles begin to occupy the lowest energy quantum state available as the temperature is reduced below a critical value. In the condensed state the many-particle quantum wavefunction of the system is coherent across macroscopic distances. At its root, BEC is a purely statistical mechanical phenomenon; no interactions between the bosons are required for the condensation to occur. The transition occurs when the thermal de Broglie wavelength of the particles becomes comparable to their separation.

See "Excitons" on page 12

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.

Highlights of the Fall Meeting of the Board on Physics and Astronomy

The Board on Physics and Astronomy met for its annual autumn meeting on November 6-7, 2004, at the Arnold and Mabel Beckman Center of the National Academies in Irvine, California. Chair Burton Richter brought the meeting to order and introduced the new members of the Board (Ron Davidson, Andrea Ghez, Marc Kastner, and Chris McKee). Dr. Richter briefly outlined the agenda for the meeting and thanked everyone for making the trip to southern California. Board director Don Shapero introduced David B. Lang, who joined the BPA in September 2004 as a research assistant.

Deborah Jin (JILA) presented a discussion of her recent groundbreaking observations of the condensation of fermionic atom pairs in the BCS-BEC crossover regime. With the use of a gas of potassium-40 atoms at low temperature, her research has explored the interactions of the fermionic atoms and the boson condensate simultaneously. Employing a 200-G magnetic field, the molecular dimers of potassium atoms can be formed such that the average molecular size is much larger than the average spacing between atoms. Making condensates with fermions is well understood in the Bardeen-Cooper-Schreiffer (BCS) theory of superconductivity, where fermions pair in momentum space. Tuning the magnetic field sets the energy scale of the pairing energy per molecular dimer, allowing access to a wide variety of regions on the overall phase diagram. In her now-celebrated experiment, Dr. Jin used a gas of 500,000 potassium atoms that was cooled to temperatures below 50 nK and then subject to a applied magnetic field. The field coaxed the fermionic atoms to match up into pairs, akin to the pairs of electrons that produce superconductivity, the phenomenon in which electricity flows with no resistance. The Jin group detected this pairing and the formation of a fermionic condensate for the first time on December 16, 2003.

Following Dr. Jin, James Eisenstein (Caltech) discussed his work with excitons to achieve Bose-Einstein condensates. He pointed out that a key element of the research program of modern condensed-matter and materials physics is to understand how and why "the whole is more than sum of its parts." The collective behavior of groups of interacting objectives, called emergent phenomena, is a crosscutting theme throughout much of physics, he said. Consider the neuron, he suggested: you put 10^{11} of them together and suddenly you have a brain that exhibits very sophisticated properties and behavior. And you cannot predict any of them! He described his research with doped bilayer semiconductors and magnetic fields to form novel excitons. (See Dr. Eisenstein's article elsewhere in this issue for more details.)

BPA staff member Timothy Meyer then presented a short report on activities related to the Board's discussion of opportunities at the intersection of the physical and life sciences at its meeting in autumn 2003. Dr. Meyer reported that there had been significant developments on the federal front, ranging from congressional report language to a joint NSF/NIH workshop exploring the possibilities for and challenges to "bridging the sciences." He also described a small meeting of experts planned for December 2004 that would evaluate the case for and scope of a potential NRC study in this area. (See article elsewhere in this issue for more details.) BPA members endorsed the concept and suggested that the full breadth of the physical sciences be included in the discussion, ranging from chemistry and physics to materials sciences and astrobiology.

Ronald Davidson (Princeton Plasma Physics Laboratory) presented a summary of the final report of the National High Energy Density Physics Task Force that he chaired for the OSTP Physics of the Universe interagency working group. The Task Force reviewed the scope of the high energy density physics area, building on the previous NRC report and some of the science identified in *Connecting Quarks with the Cosmos*. As a sidelight, Dr. Davidson noted that the interaction of the different participants led to the planning of a joint RHIC and plasma physics workshop later this year. The task force identified 15 different research thrust areas that fell into four broad categories: astrophysics systems, beam-induced plasmas, stockpile stewardship, and ultradense, ultrafast laser science. Dr. Davidson briefly described the different thrust areas and some of the science that each might cover. Although the Task Force did not prioritize amongst the thrust areas, the elucidation of a finite number of these research areas was an intrinsic prioritization of opportunities in the field. In closing, Dr. Davidson noted that the Task Force had explored a model for interagency coordinated investment, focusing on the potential role that medium-sized facilities and centers might play (the new COBRA center at Cornell being a prime example). For instance, he said, the task force imagined that NSF could fund research on the OMEGA laser at Rochester.

Marc Kastner presented an overview of the activities of the BPA's Solid State Sciences Committee (SSSC). He described the progress of the two studies in progress: the Committee on Opportunities in High Magnetic Field Science (led by Peter B. Moore of Yale University) and the Committee on Smaller Facilities (led by Robert Sinclair of Stanford). Both groups are drafting their final reports and hope to be in report review before the end of the year. [Peter Moore's committee released its final report on January 14, 2005; see article in this issue. –ed.] Dr. Kastner outlined opportunities for new business at the SSSC as well. A study on biomolecular materials and processes has been proposed; partial support from NSF has been approved, and discussions are under way with other agencies. In response to an informal request from NSF, the SSSC developed a proposal for a review of the past and future performance and impact of the materials research laboratories as embodied by the Materials Research Science and Engineering Center program. Clearly this study will offer a valuable prospective and retrospective review of this program, he said, but it will be important to find people with expertise and experience who are also free of conflicts of interest. Finally, the SSSC is also discussing the need for and scope of a study of materials discovery and crystal growth. At the autumn meeting of the SSSC, the committee discussed the issues; the ability to supply high-quality crystals within the United States is very limited, and so many researchers must team up with other groups offshore simply to get access to materials. Heterostructures constructed with advanced molecular-beam epitaxy techniques are another example where sample purity and availability have been a bottleneck in research pursuits. The SSSC resolved to prepare a study prospectus before the next meeting in April 2005.

Continuing its interest in providing guidance to the volumes of *Physics 2010*, the Board organized a small roundtable discussion among the four currently active elements of the series: Jonathan Bagger for Elementary Particle Physics 2010 (EPP2010; see article in this newsletter); Pierre Meystre for Atomic, Molecular, and Optical Physics 2010 (AMO2010), Steve Cowley for Plasma Science 2010 (Plasma 2010), and Marc Kastner for Condensed-Matter and Materials Physics 2010 (CMMP2010). Of the four volumes under consideration, only EPP2010 and AMO2010 have been awarded funding; Plasma 2010 has not yet received the necessary increment of funding from DOE; CMMP2010 is still being developed by the SSSC. [Since the time of the BPA meeting, funding has been provided for the Plasma 2010 study and the committee nominaton process has started. —ed.] All four discussants agreed that determining the audience for their respective decadal surveys was the first and foremost challenge. Dr. Kastner described discussions at the recent meeting of the SSSC. Members of the community and representatives of several professional societies were invited to discuss the decadal survey with the SSSC. One key observation at that meeting was that the study would need to address three separate audiences—the funding agencies, the practitioners in the community, and the broader public. Another point of common agreement was the importance of articulating dreams for the future, but doing so in terms of the intellectual excitement. The selection of an appropriate and effective chair for each study was also discussed; Dr.

See "BPA Meeting" on page 9

Committees of the Board on Physics and Astronomy

Committee on Astronomy and Astrophysics
C. Megan Urry, Yale University, and Roger D. Blandford, California Institute of Technology, *Co-chairs*

Committee on Atomic, Molecular, and Optical Sciences
Pierre Meystre, University of Arizona, *Chair*

Plasma Science Committee
Cary B. Forest, University of Wisconsin at Madison, *Chair*

Committee on Radio Frequencies
Karen St. Germain, Naval Research Laboratory, *Chair*

Solid State Sciences Committee
Marc A. Kastner, Massachusetts Institute of Technology, *Chair,* and Peter F. Green, University of Texas at Austin, *Vice Chair*

Committee on Smaller Facilities
Robert Sinclair, Stanford University, *Chair*

Elementary Particle Physics 2010
Harold Shapiro, Princeton University University, *Chair,* and Sally Dawson, Brookhaven National Laboratory, *Vice Chair*

Committee on Review of Progress in Astronomy and Astrophysics Toward the Decadal Vision
C. Megan Urry, Yale University, *Chair*

More information on BPA committees may be found on the BPA Web site at <www.national-academies.org/bpa>.

Opportunities in High Magnetic Field Science

Peter B. Moore, Yale University

Peter Moore chaired the BPA's Committee on Opportunities in High Magnetic Field Science (COHMAG) with support from the National Science Foundation. Under his leadership, the committee met three times in seven months and released its final report in prepublication form in January 2005. Here, he writes about the committee's findings and recommendations.

Because of the scientific importance of high-field magnets and the possibility that new breakthroughs might develop, the Committee on Opportunities in High Magnetic Field Science was formed to assess the current state of, and future prospects for, high-field magnet science and technology in the United States, taking into account international trends and particularly promising multidisciplinary areas of research and development. The committee's task was to identify key scientific and technological challenges and opportunities, not to make specific programmatic recommendations. The committee met three times between September 2003 and April 2004 and its final report was released in prepublication form in mid-January 2005. In general, the committee found that high magnetic field science in the United States is healthy and broadly multidisciplinary. However, there are some important opportunities that will be missed unless attention is paid to them soon. In this article, I present a summary of the committee's findings and recommendations.

A magnet is "high field" if its field strength is high enough to test the limits of the mechanical and/or the electromagnetic properties of the materials from which it is built. High-field magnets have been—and continue to be—used for research in many scientific disciplines, including medicine, chemistry, and condensed-matter physics; they are also enabling for fields such as plasma science and high-energy physics. Research that could only have been done with such magnets has produced important insights in a host of areas ranging from brain function to high-temperature superconductivity. High magnetic fields are of great interest in areas such as astrophysics and magnetohydrodynamics, and high-field magnets also play an increasingly important role in industry.

High magnetic field science and technology are thriving in the United States today, and the prospects are bright for future gains from high-field research. Recent accomplishments include the development of functional magnetic resonance imaging, which is revolutionizing neuroscience; optically pumped magnetic resonance techniques, which allow visualization of new quantum phenomena in semiconductors; and ion cyclotron resonance mass spectroscopy, which is becoming an important tool for exploring the chemical composition of complex systems. High-field research has led to the discovery of new states of matter in low-dimensional systems. It has also provided the first indications of how high-temperature superconductors evolve into unconventional metallic alloys in the extreme quantum limit. Outstanding work continues to be done in the area of magnet engineering, the discipline on which all these activities depend. There is every reason to believe that new developments as interesting as those mentioned above will occur in the decades to come, especially if magnets are built that deliver higher fields than those available today. For instance, pulsed fields offer the opportunity to explore the highest magnetic fields in ways that can take research in new directions. Additionally, advances in high-speed electronics, instrumentation, and miniaturization also offer the potential to allow greater experimental access to higher fields.

The United States is a leader in many areas of high-field science and technology, but further investment will be required to make the United States competitive in some critical areas. There are many indicators of the strength of the U.S. effort in high magnetic field research. For example, condensed-matter physicists and materials researchers from other parts of the world routinely travel to the National High Magnetic Field Laboratory (NHMFL) to perform experiments that they are unable to do at home, but U.S. scientists seldom travel abroad for that reason. In addition, the superconducting magnets being installed in the Large Hadron Collider (LHC) at CERN, as well as those contemplated for the International Thermonuclear Experimental Reactor (ITER), depend on magnet technology developed in the United States (although the magnets are in fact being manufactured overseas), as do the magnets installed in several user facilities overseas. On the other hand, in the area of nuclear magnetic resonance (NMR), which is a major component of high-field science, the United States is competitive but not dominant. About half of the instrumentation used by NMR spectroscopists in the United States, and virtually all of the magnets in their spectrometers, were manufactured abroad. Further, many of the most important recent advances in NMR have been made overseas, and, in general, European and Japanese companies have been ahead of U.S. companies in commercializing magnet technology developments. Finally, Europe is far ahead of the United States in equipping its synchrotron light sources and neutron scattering centers with instruments for studying the X-ray and neutron scattering properties of materials in high magnetic fields. It also worth noting that several key facilities in Japan have made important contributions to the development of the technologies required for the generation of the highest steady-state and pulsed magnetic fields.

High-field magnet science is intrinsically multidisciplinary. The construction of high-field magnets has always been motivated by the science that could be done with them, and in recent decades, physics, chemistry, biology, and medicine have all benefited from advances in magnet technology. Even the technology of high-field magnets is cross-disciplinary. Materials science and engineering make dominant contributions, but several branches of physics contribute as well.

U.S. scientists will be unable to access a wealth of science opportunities if high magnetic field instrumentation is not provided at the Spallation Neutron Source and at the nation's third-generation light sources. The scientific opportunities available to those able to study the neutron and X-ray scattering properties of materials at high magnetic fields are attracting growing attention around the world. Certain aspects

See "High Magnetic Fields" on page 6

Instrumentation for a Better Tomorrow

A Symposium in Honor of Arnold O. Beckman

Caltech professor of chemistry John D. Roberts, Institute of Systems Biology president Leroy Hood, and Chemical Heritage Foundation president Arnold Thackray were among the distinguished scientists, engineers, and researchers who participated in a 1-day symposium on November 15, 2004, to honor famed inventor, entrepreneur, and philanthropist Arnold O. Beckman. The symposium focused on the role of instrumentation in scientific research and the important influence Arnold Beckman had on the development of laboratory instrumentation. Speakers discussed the evolution of instrumentation in several fields of research and how historical trends position us for the future.

The sophistication of instrumentation in research has grown immensely since Arnold Beckman, then a professor at the California Institute of Technology, marketed his first commercially successful instrument in 1935—an electronic meter designed originally to measure the acidity of lemon juice. Today, the conduct of most research is essentially inseparable from the development and use of reliable, high-performance, and integrated research tools. Indeed, instrumentation has become so important in research that instrument development has itself become the subject of research, creating a positive feedback loop that has accelerated the pace of scientific and technological progress.

The National Academies sponsored the symposium in honor of Arnold O. Beckman, the renowned inventor and philanthropist who died in 2004 at age 104. The symposium was entitled "Instrumentation for a Better Tomorrow," and over the course of the day the symposium participants were treated to a wide-ranging and inspiring overview of the role that research instrumentation has played—and will continue to play—in improving our lives. More than 60 people attended the symposium and were treated to special enhancements of the standing heritage exhibits (supported by the Arnold and Mabel Beckman Foundation) at the center. Beckman Coulter, Inc., set up a display featuring two modern laboratory instruments currently produced by the company that Dr. Beckman started. The Chemical Heritage Foundation provided an interactive multimedia display that chronicled several of Dr. Beckman's achievements and allowed visitors to tinker with a computer-simulated version of the Dr. Beckman's DU spectrophotometer.

After introductory remarks by Wm. A. Wulf, president of the National Academy of Engineering, and a welcome from Ralph Cicerone, chancellor of the University of California at Irvine and president-elect of the National Academy of Sciences, Dr. Beckman's daughter Pat Beckman shared some personal reflections about her father's philosophy. She described the enormity of his legacy, from instrumentation and research to philanthropy, education, and raising a family.

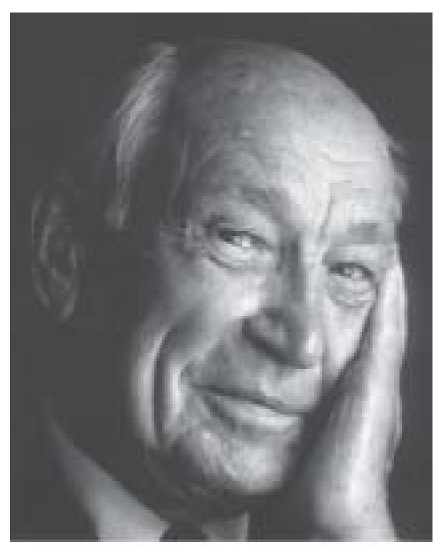
The morning keynote address was delivered by Arnold Thackray, president of the Chemical Heritage Foundation. He discussed Arnold Beckman's intuitive grasp of the "sweet spot of opportunity," and described Dr. Beckman's life and work in terms of his inventive recklessness, his contributions to chemists' tools and the new biology, and, finally, his role in the electronics revolution. Dr. Thackray closed by quoting from a printed advertisement promoting Beckman Instruments, Inc., in 1960: "Since the year one there has been no change in the scientific method. Only the tools are different. Our job—providing them...One day the present science of electronics will be supplemented or replaced. Still newer technologies will need even more advanced instruments to implement them. Our catalog for the future?—We're working on it now."

The program then shifted to a discussion of instrumentation in different fields of research in science, engineering, and medicine. John D. Roberts, Institute Professor of Chemistry, emeritus, at the California Institute of Technology, described the evolution of nuclear magnetic resonance (NMR) and its role in analytical chemistry. As a young faculty member at MIT, the first instrument he bought was a Beckman DU spectrometer. Then, just a few years later, NMR spectrometers were introduced. "Clearly, NMR had an enormous advantage," Roberts said, "except that infrared spectroscopy is easier to understand." Leroy Hood, president of the Institute for Systems Biology, then presented a discussion of the future of molecular and system biology, arguing that today's research problems require interdisciplinary teams and tools and that traditional organizational structures for research programs are often inadequate to meet these challenges. Gabrielle Long, an associate director of the Advanced Photon Source at Argonne National Laboratory, described the evolution of X-ray scattering instruments from the original benchtop tools to today's enormous national synchrotron user facilities.

A lunch keynote address was presented by Chad Mirkin, professor of chemistry at Northwestern University and a past recipient of the Young Investigator Award of the Arnold and Mabel Beckman Foundation. He detailed some of the dramatic frontiers of chemistry at the interface with nanoscale science and technology. He described how a new toolkit developed by his group at Northwestern, dip pen nanolithography, provided a new regime of control over the assembly of nano-structures with profound implications for medical research.

Michael L. Roukes, professor of physics, applied physics, and bioengineering at the California Institute of Technology, discussed the frontiers of nanotechnology and its intersection with chemistry, physics, and biology. "The underlying principle is that we can make devices so small and

See "Beckman Symposium" on page 13



High Magnetic Fields
(continued from page 4)

of magnetism and high-temperature superconductivity have already been elucidated overseas at scattering center laboratories that have high-field instrumentation. Nevertheless, the United States does not currently plan to increase the high magnetic field instrumentation at its national radiation laboratories. Unless steps are taken to rectify this situation, the nation is sure to lag behind in key areas of condensed-matter and materials physics.

There are important issues relevant to the advancement of magnet technology that could be more efficiently addressed if the interested constituencies interacted more strongly, communicated more fully, and coordinated their activities better. One striking characteristic of all the sciences that use high magnetic fields is how constrained they are by the limitations imposed by magnet technology. Nevertheless, despite a shared need to overcome the same set of fundamental problems, each constituency has historically tended to develop the magnets it needed without much reference to the others. The reasons are several and obvious. The various communities that use high-field magnets have different missions, and the magnets they need are specific to the mission of each. In addition, these communities are supported by different funding agencies, each of which has had its own perspective. A coordinated approach to magnet technology based on the pooling of resources and talent would be beneficial.

Based on these observations, the committee has several recommendations that it offers in the order of the most important first.

The United States should maintain a national laboratory that provides its scientific community access to magnets operating at the highest possible fields. A national high-field magnet facility is essential to the vitality of many important scientific disciplines. NHMFL has successfully fulfilled the need for high-field magnets for about a decade, and its activities have done much to foster the leadership position that the United States currently enjoys in many areas of magnetic science and technology. It is important to understand that at any high-field magnet laboratory, the capabilities of the devices available for controlling the environment in which a sample is tested and for measuring a sample's properties are almost as important as the field strengths of the magnets themselves. Thus it is vital that a national laboratory equip its magnets with the best possible supporting instrumentation and personnel. In addition, ways to maximize the return on capital invested in the national laboratory should be explored, such as longer hours of operation and flexible scheduling. The laboratory should undertake a cost-benefit analysis to identify the optimal balance between addressing user demand and the increased operating costs associated with longer hours of operation. For instance, the nation's synchrotron light sources and neutron scattering centers provide access 24 hours a day, 7 days a week when in full operation; this schedule allows visiting researchers to use their time at the facility to the best advantage. The trade-offs for expanding access to the NHMFL need to be identified and weighed carefully, especially in constrained budget situations.

New instruments for studying the neutron and x-ray scattering properties of materials in high magnetic fields should be developed in the United States. Nowhere in the domestic research program is the gap between the instrumentation available for experimentation at zero field and that available for high-field experimentation wider than in the areas of neutron and X-ray scattering. This gap in capability is unfortunate, because scattering experiments provide a powerful means for elucidating atomic and magnetic structure, as well as determining the nature of the spatial and dynamical correlations in materials. Development of new high-field capabilities at X-ray and neutron scattering centers in the United States could have an enormous scientific impact.

A consortium should be established to foster the development of magnet technology. Rather than supporting an all-out, brute-force effort to build higher-field magnets using current technology, it makes sense to find new approaches that will make it easier (and cheaper) to build the magnets needed for research. Essential to this enterprise will be the development of both resistive and superconducting materials with improved electrical, magnetic, and mechanical properties. Scientists and engineers from all the communities working today on magnet technology should be brought together: the magnet engineers at the NHMFL, academic researchers, the magnet designers in the high-energy physics and fusion communities, commercial vendors of superconducting magnets, including nuclear magnetic resonance and magnetic resonance imaging systems, and manufacturers of advanced materials, such as high-strength materials and superconducting wire. The sharing of information and resources within that larger community, which is now fragmented into components that communicate poorly, would accelerate the rate at which solutions are found to the fundamental problems they all confront. COHMAG proposes that the involved communities cooperate to establish a consortium whose objective would be the development of the technology necessary to pursue several aggressive goals that may have different timescales. Some groups might frame their goals in terms of application-specific requirements for magnet performance, such as the development of a 30-T superconducting high-resolution magnet for NMR, a 60-T DC hybrid magnet, or a 100-T long-pulse magnet. Others, such as the high-energy physics and fusion science communities, might focus explicitly on the materials problems intrinsic to enabling high-volume production of quality conductors for a variety of magnet systems.

Agencies supporting high-field magnetic resonance research should directly support the development of technology and instrumentation for magnetic resonance and magnetic resonance imaging. Without the concomitant development of ancillary technologies, the construction of higher-field magnets for magnetic resonance will not produce the scientific dividends it should. While federal funding for the application of existing technology and methods to specific scientific problems has generally been good, federal funding for the development of novel technology and methodology has been poor. Magnetic resonance and MRI instrument manufacturers have done a good job of advancing the supporting technologies relevant to these techniques when the commercial markets for their products justified their doing so. However, there are many areas where technological advances are sorely needed, but where the commercial market is not large enough to attract the attention of instrument manufacturers. Likewise, because higher fields result in significant changes in the relative strengths of the interactions that determine how nuclear magnetic moments evolve, improvements in pulse sequences and methodologies will be required if magnetic resonance research is to take full advantage of high-field magnet development. ■

Opportunities at the Intersection of the Physical and Life Sciences

David B. Lang, BPA Research Assistant

A compelling question of science has long been "How does life emerge from a network of chemical reactions?" In fact, the interagency guidance memo from the White House's Office of Science and Technology Policy and its Office of Management and Budget identified the molecular-level understanding of the basis of life as a priority area for federal research in 2004. The answer to this question lies beyond the traditional capabilities of the life sciences and begs for integrating the creativity of researchers in many fields of science beyond biology.

The idea of pursuing interdisciplinary research at the interface between the physical and life sciences has long been brewing. Within the past few years, this vision has become more concrete: several workshops involving the National Academies, the American Chemical Society, the National Science Foundation, and the National Institutes of Health took place in 2004, bringing the excitement of this research area to a boil.

The Board on Physics and Astronomy and the Board on Life Sciences hosted a workshop on December 11–12, 2004, at the Stanford Linear Accelerator Center in Menlo Park, California, to discuss the spectrum of research problems that lie at the interface of life and physical science and to evaluate how the National Research Council might contribute. In response to the need to frame the discussion broadly, the Board on Chemical Sciences and Technology (BCST) and the Board on Mathematical Sciences and Their Applications (BMSA) were invited to participate in the workshop. The meeting, chaired by Kenneth Keller of the University of Minnesota, included experts in chemical engineering, science policy, biology, biophysics, physics, and biochemistry, as well as researchers who had crossed over from one discipline to another. This article discusses some of the discussions at the meeting and in subsequent activities.

Research is truly interdisciplinary when researchers operate and think outside traditional disciplinary boundaries, enabling a synthesis of ideas from many areas of science to form new ones. Interdisciplinary research is to be distinguished from multidisciplinary research; in the latter a group of researchers, each with their own expertise, come together to each tackle a part of a problem entangled with many different areas of science. This exposure to other fields often invites scientists to broaden their horizons and to integrate new science with their own disciplines.

One area identified at the meeting as having great potential is the understanding biomolecular machines. Molecular biology theory now requires creating models of how proteins move on a multitude of length and time scales. Creating such models would greatly improve understanding of how biomolecular structures self-assemble. To understand the machinery of cells demands the development of a new branch of statistical physics at the nanoscale. New synthetic materials are emerging to allow the design of new molecules and materials by using new technologies which are able to probe this length scale.

Similarly, the mechanics and spatial structure of the cell as an organized environment may become accessible with new tools of single-molecule physics and chemically driven cell structure and function redirection. The structure of a cell is an incredibly complex fabrication and is not only reliant on spontaneous self-assembly, but also on the history of the cell; the cell is far out of equilibrium, yet fantastically organized. Only recently has theoretical physics begun to examine systems far from equilibrium, and with the inclusion of this physics, it may be possible to physically intervene at a subcellular level. For astrobiology and molecular evolution, life's creation from a fortunate chemical amalgamation is of central interest. But, there are physical problems with organizing these chemicals into nonequilibrium structures. Understanding the origin of self-replicating systems would be a major step forward in putting the vision of nanotechnology to practical use.

Of course, what is opportunity without obstacles? The NRC workshop also recognized the barriers that must be overcome in order to see interdisciplinary research flourish. At the core of the problem lies a basic difference in the cultures of the life and physical science communities. Physical science benefits greatly from a rapid closed loop between theory and experiment, whereas many theories in life science lack general predictive power owing to the difficulty of conducting definitive experiments. Also, physical and life scientists tend to have different views about basic research tools such as instrumentation and facilities. Perhaps this difference also explains the difficulty in publishing across the disciplines.

One barrier to developing and promoting interdisciplinary research is the program processes involved. Budget strategies are often not tailored for research across fields, and so researchers at this crossroads often find themselves passed from program to program or from agency to agency. This situation is also due to the more speculative and innovative nature of the research. At most academic institutions, hiring, tenure, and promotion are controlled by individual departments aligned with traditional disciplines, which dissuades young researchers from working "outside the lines." This attitude results in a lack of overlap in professional training between physical and life sciences for students, tracing back to even before undergraduate education. The gap widens as researchers continue their education. The workshop participants also felt that the evolution from multidisciplinary research collaborations to interdisciplinary research will play an important role in characterizing this area. Pursuing this interface demands taking larger risks, so research centers with mixed programs that can balance more or less speculative research may play an important role. Also, instead of research proposal review heavily weighting potential outcomes, reviews should include other aspects, such as the past performance of the researcher. A better review process coupled with a redesigned, not retrofitted, funding engine will enable many young researchers to travel down this new avenue less encumbered.

The workshop concluded that an NRC study could add significant value to the development of research at the interface of the physical and life sciences. The NRC looks forward to examining the opportunities and barriers in this interdisciplinary research area and, with the guidance of both the life and physical science communities, hopes to help further this exciting vision. ■

EPP 2010 (continued from page 1)

A variety of experimental approaches will be required to answer the questions that define the field. Thus the time is ripe to define priorities among the science questions that could be addressed by new experiments. There is a recognized need for a realistic plan to implement these priorities that looks ahead 15 years.

In recognition of the current context, the National Science Foundation and the Department of Energy requested a National Research Council assessment of and plan for the field of elementary particle physics. As Robin Staffin, associate director of Office of High Energy Physics, said, "What we want to know is: What is the human significance of the current moment in particle physics?" In response to this request, the Board on Physics and Astronomy formed the Elementary Particle Physics 2010 Committee (EPP2010) in early autumn 2004 to address the following charge:

1. Identify, articulate, and prioritize the scientific questions and opportunities that define elementary particle physics.

2. Recommend a 15-year implementation plan with realistic, ordered priorities to realize these opportunities.

In developing plans for the project, the BPA was cognizant of the long history of planning documents developed by the elementary particle physics community. In part to bring in new perspectives on the important issues, the EPP2010 committee was convened with an unusual balance of membership. Rather than relying uniquely on the expertise of the practitioners, members with expertise outside particle physics were sought. Fully half of the committee has significant expertise outside traditional particle physics, in areas such as condensed-matter and materials physics, atomic, molecular, and optical physics, and observational astronomy. Three members are not even traditional physicists, bringing expertise from the aerospace industry, molecular genetics and biomedical research, and economics. The chair of the committee embodies the effort to bring new perspective and fresh energy to the task of articulating a vision for the future of the field and framing the best strategies for achieving it: Harold T. Shapiro, president emeritus of Princeton University and a famed economist and expert on bioethics. The simple fact that persons outside particle physics agreed to volunteer for this study says a lot about the broad appeal of particle physics.

The first meeting of the EPP2010 committee was held in Washington, D.C., November 30–December 1, 2004. At the beginning of the meeting, chair Harold Shapiro observed, "People here at the Academies and in the government believe that we need to do this [study], and they were insistent about the need to include people outside the field. We want to set priorities and set the agenda in a way that is exciting to many people in order to capture their attention—and commitment—for a program going forward." Vice chair Sally Dawson, a particle theorist from Brookhaven National Laboratory, agreed, adding, "I want to really encourage the non-particle physicists to really speak up if we lapse into jargon—or slogans! Together, we want to craft a better message."

Presentations at the first meeting focused on introducing the science of particle physics. The committee also discussed how to set scientific priorities in general. The meeting led off with a trio of physics talks by Joe Lykken and Chris Quigg of the Fermilab theory department and Persis Drell of SLAC. They described the "coming revolutions" in particle physics, with an emphasis on the pivotal nature of the questions now being studied in particle physics. Dr. Quigg started by stating that the greatest lesson of 20th century science was, perhaps, that the human scale of time and distance is not privileged—not even sufficient—for understanding the nature of the universe. He then articulated four "coming revolutions in particle physics": (1) understanding the everyday (Why are there atoms, chemisty, conditions for life?); (2) the meaning of identity (What makes things the way they are?); (3) unifying quarks and leptons (What do quarks and leptons have in common? Why are atoms neutral?); and (4) new conceptions of space-time (Are there more dimenions to space? How does gravity rejoin particle physics?). In his presentation, Dr. Lykken argued that "this is a special time in particle physics" by outlining provocative questions that have new urgency, describing the advent of new tools to investigate the frontiers, and—most important, he said—describing the emergence of connections between problems heretofore thought to be distinct and separately soluble. That is, the crosscutting nature of the apparent solutions is an indication that we are close to fundamental discoveries. Dr. Drell discussed experimental strategies for these discoveries, describing the role of both observatories (of all sorts) and accelerators. She then outlined three examples: dark matter, antimatter, and the mysteries of the vacuum.

The committee also heard from several representatives of the government, including Michael Turner from NSF, Robin Staffin from DOE, and J. Patrick Looney from the Office of Science and Technology Policy. Christopher McKee, co-chair of the most recent astronomy and astrophysics decadal survey, described the procedure that his community of scientists uses to identify compelling new directions and to develop a consensus-based priority list of the most important new initiatives. Abrahram Seiden, chair of the joint DOE-NSF Particle Physics Project Prioritization Panel, briefly described the panel's hoped-for function and role. He admitted that the panel's most significant project prioritization overview activity so far had been the high-energy physics contribution to DOE's Office of Science 20-year facilities outlook planning process. In a final formal address, Barry Barish, co-chair of the most recent HEPAP long-range planning subcommittee, outlined his views on what challenges lie before the committee and lessons learned from his experience. The first day of the meeting wrapped up with a public-comment session organized by representatives of the American Physical Society's Division of Particles and Fields. Twelve members of the community shared their excitement about the future of particle physics and offered short descriptions of their research.

The committee met for a second half-day in executive session. Committee members discussed the broader context of their work, including comments about international perspectices and connections, a historical view of federal investment in basic research and in the field of elementary particle physics in particular. An aggressive

See "EPP2010" on page 14

BPA Meeting
(continued from page 3)

Bagger described the appointment of economist and Princeton president emeritus Harold Shapiro as chair of the EPP2010 committee because of the need for an impartial view and fresh perspective. Dr. Meystre echoed these sentiments and commented on the AMO 2010 plan of selecting two co-chairs, one from within the field and one from outside, as well as including several non-AMO scientists on the committee. Dr. Cowley agreed that involving leaders from outside the traditional community could add value; since the Plasma 2010 committee has not yet been formed, however, no specific plans have been proposed. Finally, Dr. Kastner explained that the SSSC was attracted to the idea of a well-qualified and prestigious outside chair but that some members worried that a lack of disciplinary expertise might undermine the authority of the chair with the community. That is, different disciplines face different needs, and if a community viewed itself as in need of an affirmation of identity and unity, an outside leader for a survey of the field might not be the appropriate.

The roundtable participants also commented on how they planned to respond to the Board's advice on setting scientific priorities. Although the temptation to prioritize large facilities was strong, they agreed that the objective was to identify compelling science themes and then describe the appropriate routes for pursuing them. Community outreach and buy-in to the process will be a critical component, however. The BPA encouraged each of the study planners to include town meetings and coordination with the professional societies in their plans. Each decadal survey should also take into account other recent reports that cover some similar issues; for instance, the CMMP 2010 study should examine the findings of the Committee on Smaller Facilities, and EPP2010 should consider the recent report *Quantum Universe*. The Board also discussed the challenge of setting convincing priorities while allowing flexibility to handle new developments and changes in the outlook for the future; teasing apart the scientific and project priorities was identified as a difficult but important task.

Megan Urry (Yale University) shared a report on the activities of the BPA's Committee on Astronomy and Astronomy (CAA) of which she is the co-chair. She briefly outlined several short letter reports that had been prepared under the CAA's auspices. At NASA's request, the CAA convened a committee to review the science goals of the current Terrestrial Planet Finder (TPF) project as well as NASA's plan for acquiring the necessary precursor knowledge to successfully meet those goals. The committee published its findings in a letter report on September 23, 2004. (See article elsewhere in this issue for details.) The CAA also oversaw a short scientific review of the AEOS telescope in Hawaii. Finally, the CAA has convened a special panel to address progress toward realizing the decadal vision of astronomy and astrophysics. The CAA has been considering the need for several research briefings that would make some of the latest science developments since the 2001 decadal survey more accessible to a broad audience. The Board speculated on some of the challenges in NASA's future as the exploration vision is implemented. The delay of elements of the Beyond Einstein program beyond the budget planning horizon was particularly troubling to some, especially in areas where NASA was cooperating with other agencies in support of a project. The Board also discussed potential new CAA business with Dr. Urry.

BPA members Gordon Baym, Christopher McKee, and Elihu Abrahams then reported briefly on a recent workshop at NSF sponsored by the Mathematical and Physical Sciences directorate that examined the state of theory. The workshop was tasked to give NSF advice on how to nurture advances in theory and how to strengthen all aspects of this part of the general research enterprise. The workshop was large, with over four dozen invited participants and almost as many observers, they said. The final report is still in preparation. Board members observed that the single largest concern for NSF is probably the lack of staff—while the grants programs have grown significantly over the past 20 years, the number of program managers and support staff have remained relatively constant. This situation needs to be addressed, everyone agreed.

In a final session, committee chair Donald Backer (University of California at Berkeley) discussed the plans of the BPA's standing Committee on Radio Frequencies (CORF). Prof. Backer described several of the recent filings before the Federal Communications Commission and the National Telecommunications and Information Administration. For instance, on the issue of licensing the transmission of broadband Internet services over electrical powerlines, CORF asked for protection of remote radio astronomy observatories. Similarly, it responded to a request for changing rules governing Channel 37 (a portion of the radio spectrum near 600 MHz) that is currently allocated for radio astronomy and other passive listening activities. CORF is engaged in an educational effort and plans to visit the FCC and NTIA after the administration teams settle into their second term. Because radio astronomy needs have changed radically over the years, CORF is interested in reanalyzing the system for spectrum management by scientists. The Board suggested trying to include international perspectives and interests in the project, as some important radio astronomy observatories are located in other countries. It was also suggested that OSTP be involved in some of the discussion because of its commitment to fostering cooperation and coordinations between agencies on scientific issues.

Turning its attention to the next meeting, the Board identified several topics for consideration. Hearing from OSTP about the interagency working group process was one priority item, as was a report from a BPA member about the NRC's newly formed Board on Science Education that he now chairs. With a warm thank you to everyone for participating, Dr. Richter adjourned the meeting in time for a light meal in the Beckman Center's spacious dining room. ■

Congressional Testimony on Astronomy and Astrophysics

Joseph H. Taylor, Princeton University

Professor Joseph H. Taylor is the James S. McDonnell Distinguished University Professor of Physics at Princeton University. He shared the 1993 Nobel prize in physics. He was a member of the NRC's Committee on Assessment of Options to Extend the Life of the Hubble Space Telescope; he is also a former member of the Board on Physics and Astronomy and was co-chair of the National Research Council's Astronomy and Astrophysics Survey Committee. On February 2, 2005, the Committee on Science of the U.S. House of Representatives held a hearing to explore options for the future of the Hubble Space Telescope. The hearing will help guide Congress' decisions regarding the telescope's fate. Dr. Taylor provided the following testimony as an expert witness.

Mr. Chairman, Ranking Minority Member, and members of the committee: thank you for inviting me here to testify today. My name is Joseph Taylor and I am the James S. McDonnell Distinguished University Professor of Physics and former Dean of the Faculty at Princeton University. I appear today in my capacity as co-chair of the Astronomy and Astrophysics Survey Committee.

As you know, the Astronomy community has a long history of creating, through the National Research Council (NRC), broad surveys of the field at ten-year intervals. These surveys lay out the community's research goals for the next decade, identify key questions that need to be answered, and propose new facilities with which to conduct this fundamental research. The most recent decadal survey, entitled *Astronomy and Astrophysics in the New Millennium*, was released in the year 2000.[1] I have been asked to answer the following questions from my perspective as the co-chair of the committee that produced that report:

1. To what extent, and in what ways, was the Decadal Survey premised on the Hubble Space Telescope having additional instruments that were to be added by a servicing mission? Would the loss of the Hubble cause you to entirely rethink your priorities? Would that change if the *Hubble Origins Probe* or a similar rehost mission is launched?

2. How important are the contributions that would be expected from extending the life of the Hubble Space Telescope when compared to advancements expected from other astronomical programs at NASA to be launched in the next decade, such as the James Webb Space Telescope?

3. Should either a Hubble servicing mission (whether by robot or by Shuttle) or a new telescope such as the Hubble Origins Probe be a higher priority for funding than other astronomical programs at NASA?

In the balance of my testimony I shall address all three questions.

Until recently, the NRC decadal survey was an activity unique to the discipline of astronomy and astrophysics. The most recent survey involved the direct participation of 124 astronomers; moreover, the direct participants received input from many hundreds more of their colleagues. Altogether, a substantial fraction of the nation's astronomers were in some way involved in the creation of the report. By gathering such broad community input, the survey process creates a document that reflects the consensus opinion of the researchers in the field. The value of this activity to NASA and the NSF has been demonstrated in many ways, and most recently by NASA's request for the NRC to conduct similar surveys for planetary science,[2] solar and space physics,[3] and earth science.[4]

The feature of the decadal Astronomy Survey that distinguishes it from summaries of other fields of science is the prioritized list of missions and facilities that are recommended for construction. This list is put together very carefully; many worthy projects do not make the list, while others are deferred to the next decade. I can assure you that the decision-making process is very thorough and sometimes leaves some "blood on the floor," metaphorically speaking. One of the factors that make the process possible is the remarkable success of the surveys. The National Science Foundation and NASA have used the survey reports as the basis of their planning processes, and the vast majority of recommended projects from previous surveys have been completed — even if they have sometimes stretched over the boundaries from decade to decade. The completed projects have much to do with the leadership position of our national enterprise in the astrophysical sciences.

The process of priority setting is based on a set of assumptions. For the purposes of this hearing, the most important of these is that priorities from previous decades should be completed. For example, the year 2000 Survey reaffirmed the importance of completing the Atacama Large Millimeter Array that had been recommended in the 1991 Survey.[5] Along the same lines, the most recent Survey was based on the expectation that a shuttle servicing mission would install in the Hubble Space Telescope new instruments called the Cosmic Origins Spectrograph and Wide Field Camera-3, and would refurbish the satellite in other ways so that Hubble would continue to operate until 2010 — about the time that the infrared James Webb Space Telescope (JWST) is planned to become available.[6] We were told that this mission, now referred to as SM-4, would cost $350 million, and it was one of the considerations that led to the final shape of the priority list.

There are a number of strong arguments for keeping the Hubble telescope operational until JWST is ready. The new instruments will expand Hubble's reach farther into the near-infrared region of the spectrum. This capability will enable the selection of potentially interesting targets that will form much of the basis of the initial JWST research program. The Hubble Space Telescope is still in the prime of its scientific life. Even with some temporarily reduced capacity, astronomers are using it to observe objects that were thought to be beyond any telescope's capability. Hubble is also important to the nation for reasons beyond its immediate scientific contributions. According to a recent NRC study, nearly one third of all federal support for astronomy research is tied to the Hubble telescope and its affiliated research programs.[7] NASA, in consultation with the community, plans to transfer these programs to the James Webb Space Telescope when it becomes operational; but the premature loss of Hubble would threaten the continuity and vitality of this research enterprise, and this source of highly trained technical personnel for the nation.

We all love Hubble. It is truly a remarkable instrument. That said, the object of my committee's decadal survey was to look ahead and identify the tools that would be needed to continue answering deep questions about the Universe and the most fundamental laws of Nature. In the Survey committee's judgment, in the present decade answers to these questions are more likely to be found in regions of the spectrum outside the Hubble telescope's capabilities. Top Survey priorities such as JWST and the Constellation X-Ray (Con-X) observatory will open large spectral windows on the universe that are simply not available to instruments on the ground. While we can never be sure where the next scientific breakthrough will arise, the future with these missions seems very bright. JWST will be able to observe and examine the very first galaxies that formed in our Universe, and to study the era when the first stars ignited. Con-X will be able to observe how matter and energy behave near black holes — an extreme environment in which the laws of physics have not yet been well tested.

The Survey does not neglect the optical region of the spectrum. Two of the Survey's top three recommendations for ground-based facilities are for new optical telescopes that will observe the universe in new and different ways.[8] While Hubble can do some things that are unmatched by telescopes on the ground, the choice to move space astrophysics into the infra-red and X-ray regions of the spectrum was one of the difficult decisions that the committee made. In this context, it is difficult to say that the premature loss of the Hubble telescope would significantly alter the Survey's priority list. It is possible that the committee would have given a stronger priority to the Space Ultraviolet Observatory (SUVO), which was omitted from the final priority list; but I do not believe that the rest of our list would have been very different.

Mr. Chairman, the scientific promise of JWST and other Survey priorities lies in the future, while your committee is grappling with decisions that need to be made very soon. Accounting methods and other changes that have taken place at NASA since the completion of the Survey now make it seem very unlikely that a Shuttle servicing mission would cost the science mission directorate as little as $350 million. However the Hubble telescope is serviced, present cost estimates seem to run to at least $1 billion—roughly equivalent to that of a second JWST. Such a cost, if borne by the science program, will likely delay a number of other missions that are under development, including those ranked highly in NRC decadal surveys across all of space science.

One option that I have not yet mentioned is to host the Hubble replacement instruments COS and WFC3 on a new satellite like the proposed Hubble Origins Probe (HOP). According to the team proposing HOP, the cost for such a mission would also be roughly $1 billion, and the telescope would be ready by 2010. The proposal also calls for an additional wide-field imaging camera. Such a satellite offers significant promise; however, to start work on it would in essence insert a new priority into the mission queue, without benefit of the kind of comparative review undertaken in the survey. From the point of view of the survey committee, I believe that neither a $1 billion servicing mission nor a $1 billion rehosting satellite should be a higher funding priority than the astronomical science priorities recommended by the survey committee.

Our nation's science enterprise has been well served by having open, broadly based mechanisms for setting priorities in astronomy, and by closely following the wise decisions made in that way. A project similar to the Hubble Origins Probe could easily be included in the next Astronomy Survey, and would likely be a strong contender then. As you know, I am also a member of the Committee on Assessment of Options to Extend the Life of the Hubble Space Telescope. I heartily endorse that committee's recommendation that NASA should pursue a Shuttle servicing mission to Hubble so as to accomplish the objectives of the planned SM-4 mission. However, I do *not* favor such a plan, much less the launch of a new satellite to host Hubble's replacement instruments, if it would require major delays or re-ordering of the Survey Committee's science priorities. With such a course of action, I believe that NASA would squander the excellent reputation for scientific judgment and leadership that it has so rightly earned over the years.

I should stress that these opinions are my own, informed by my work on the survey and other advisory committees and by conversations with many colleagues.

Thank you for your attention, and I would be pleased to answer questions.

Endnotes

[1] *Astronomy and Astrophysics in the New Millennium*, NRC, 2001.

[2] *New Frontiers in the Solar System*, NRC, 2003.

[3] *The Sun to the Earth – and Beyond*, NRC, 2003.

[4] Study underway - http://qp.nas.edu/decadalsurvey

[5] *The Decade of Discovery in Astronomy and Astrophysics*, NRC, 1991.

[6] The James Webb Space Telescope (then referred to as the Next Generation Space Telescope) was the highest priority recommendation of *Astronomy and Astrophysics in the New Millennium.*

[7] *Federal Funding of Astronomical Research*, NRC, 2000, pg 54.

[8] The Giant Segmented Mirror Telescope and the Large Survey Telescope.

Additional information about the hearing may be found at the House Science Committee's Website, http://www.house.gov/science/welcome.htm. ■

Excitons
(continued from page 1)

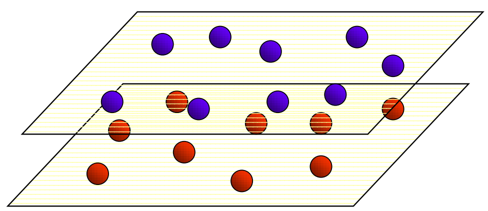
Superfluidity in liquid helium is the most dramatic phenomenon associated with Bose-Einstein condensation. Superfluidity, and its cousin superconductivity, refer to the dissipationless flow of the condensate around obstacles and imperfections in the system. Although not always appreciated, unlike BEC itself, superfluidity does require interactions among the particles in the system. In liquid ^{4}He these interactions are so strong that conventional BEC theory does not provide an adequate description of the system.

Superconductivity in metals arises from the condensation of pairs of electrons. These Cooper pairs may be regarded as composite bosons and the onset of superconductivity a type of Bose condensation. Interactions, however, are of paramount importance in superconductors, and the transition temperature of a superconductor is set not by bosonic statistical mechanics but by the details of the interaction between the constituent electrons. In fact, in a typical superconductor the size of a Cooper pair greatly exceeds the average distance between electrons in the material. Cooper pairs are thus far removed from the pointlike bosons one normally envisages as central to BEC. Recent experiments with ultracold gases of fermionic atoms have probed the crossover from conventional BEC (when two fermionic atoms bind to form a bosonic molecule) to the more tenuous Cooper pair condensate[1].

In analogy to superconductivity, physicists have long speculated that excitons in semiconductors could undergo a similar kind of BEC. An exciton consists of an electron bound to a hole. A hole is not an elementary particle but a vacancy, or unfilled orbital, in an otherwise nearly filled band of electrons. Usually but, as we shall see, not always, the hole is in the valence band of the semiconductor, while the electron is in the conduction band. Excitons are readily created by shining light on a semiconductor. The incoming photons promote an electron from the filled valence band into the conduction band. The electron is attracted to the hole it left behind and an exciton results. If a suitably dense collection of excitons cools down sufficiently following optical excitation, excitonic BEC should occur.

Optically generated excitons are unstable. In a bulk semiconductor like GaAs, excitons survive for only about 1 ns before the electron and hole recombine into a photon. This is a serious obstacle in the search for exciton BEC. Nowadays advanced crystal growth techniques, like molecular-beam epitaxy (MBE), have been used to create layered quantum well structures. Via appropriate optical excitation it is possible to create excitons in which the electron resides in one quantum well and the hole in another. Since the two quantum wells are spatially separated by a barrier layer, the recombination time of such *indirect* excitons is much longer than 1 ns. Several recent experiments have revealed intriguing collective behavior of cold indirect exciton gases[2]. BEC, however, has not yet been observed in such systems.

Double Layer 2D Electron Gas



A different type of cold exciton gas is provided by a system consisting of two parallel layers of electrons. Two identical quantum wells, separated by a thin barrier layer, are created by MBE. By suitable doping it is possible to produce sizeable, equivalent, and virtually disorder-free populations of electrons in the ground state of each quantum well. These two two-dimensional (2D) electron gases, which exist only in the conduction band, are stable and in thermodynamic equilibrium. (See the figure for a cartoon representation of such a system.)

It is a remarkable fact that such a bilayer electron gas can be rendered equivalent to a bilayer electron-hole system simply by applying a magnetic field perpendicular to the layers[3]. In such a field, electrons execute circular cyclotron motion. Since the electron motion is confined to 2D planes, quantization of this circular motion leads to a discrete energy spectrum, analogous to Bohr orbits in an atom. The individual orbitals, known as Landau levels, are highly degenerate and can accommodate many electrons. The degeneracy is proportional to the magnetic field and thus it is possible to adjust the field so that only the lowest Landau level is occupied at low temperatures. In what follows we shall assume that the lowest Landau levels in each layer are half filled with electrons.

If the two layers of electrons are far apart, they behave independently. The combination of confinement to a single Landau level and strong Coulomb repulsive forces between particles allows the electrons in each layer to avoid one another very effectively. In spite of this, at half filling of the lowest Landau level the electron gas remains compressible, i.e., it is possible to inject an additional electron at very little energy cost.

If the two layers are close together (i.e. the layer separation is comparable to the mean spacing between electrons in either layer), the situation changes dramatically. Now electrons must avoid not only their neighbors in the same layer but those in the opposite layer as well. This additional requirement suggests that an electron in one layer would like to position itself between electrons in the other layer and remain so positioned at all times. Such in-between positions exist in each layer because the lowest Landau level is only partially occupied. Furthermore, since each Landau level is half filled, the number of unoccupied states, or in-between positions, in one layer precisely equals the number of filled states in the other layer. As a result, every electron in the double-layer system can accommodate itself directly across from an empty state in the opposite layer. This commensurability heavily restricts the form of the many-body wavefunction and renders the electron system incompressible, i.e., a finite energy gap must be overcome in order to inject an additional electron.

The association of electrons in one

layer with empty states in the other brings excitons and exciton condensation to mind. A particle-hole transformation makes this connection rigorous. This transformation is the same as the one used to map empty valence band states into holes for understanding conventional optically generated excitons. Here, however, it is applied to one of the two electron layers to map empty conduction band Landau level states into holes. Since each layer contains a half-filled Landau level, the result of the transformation is a half-filled Landau level of holes in one layer and a half-filled Landau level of electrons in the other. If the two layers are close enough together, the negatively charged electrons in one layer bind onto the positively charged holes in the other to create interlayer excitons. These excitons are not independent; the strong Coulomb forces in the system engender a global quantum coherence of the many-body wavefunction. The situation is similar to superconductivity, only the Cooper pairs in this system are charge-neutral excitons. Since the average size of these excitons is roughly the same as the distance between them, this example of Bose condensation lies somewhere in the middle of the crossover between the condensation of pointlike bosons and that of highly overlapping fermion pairs.

What are the experimental signatures of this new state of matter and how well do they support the picture given above? Experiments in the early 1990s demonstrated clearly that a phase transition does occur when two 2D electrons layers, each at half filling of the lowest Landau level, are brought close together[4]. The signature of this transition was the onset of the quantum Hall effect (QHE). The ordinary Hall effect refers to the development of a voltage V_H perpendicular to the current I flowing through a material in a magnetic field. This voltage is due to the Lorentz force on a moving charge and is proportional to both the sign and magnitude of the charge. In the QHE, the Hall resistance $R_H = V_H/I$ exhibits a series of plateaus versus magnetic field which are given *exactly* by the quantum of resistance $h/e^2 \sim 25{,}813\ \Omega$ divided by certain rational numbers p/q. Each plateau signals the existence of a gap in the electronic energy spectrum and the number p/q indicates the total number of Landau levels that are occupied by electrons. For the case of interest here, $R_H = h/e^2$ and $p/q = 1$. This is the appropriate value since there are two layers of electrons each filling one-half of the lowest Landau level. This was an exciting observation because a single 2D electron layer at half-filling does not exhibit QHE. Despite this excitement, the QHE does not demonstrate that the system is equivalent to a Bose condensate of excitons.

The analogy between excitons and Cooper pairs suggests that some kind of superfluidity ought to exist in the double-layer electron gas at half-filling per layer. A uniform flow of excitons should result in little or no energy dissipation, in analogy with superconductivity. But unlike Cooper pairs, excitons are charge-neutral. Their flow carries no net electrical current. Generating and detecting such a flow presents experimental difficulties not faced in experiments with superconductors.

In the QHE experiments mentioned above, equal electrical currents were driven in the same direction through both layers of electrons. If excitons are present in the system, they could not contribute to such currents because they carry no net charge. However, if currents of equal magnitude but opposite direction could be set up in the two layers, excitons could take part. Establishing such a counter-flow configuration requires the ability to make separate electrical connections to the individual 2D layers, in spite of the fact that they are typically only a few hundred angstroms apart. Fortunately, such separate contacts can in fact be made, using a novel technique whereby one or the other layer is completely depleted of electrons just in the vicinity of the contact[5]. In the bulk of the sample electrons occupy both layers with equal (and yet controllable) densities.

Recent experiments with oppositely directed currents in the two layers have pro-

See "Excitons" on page 14

Beckman Symposium (continued from page 5)

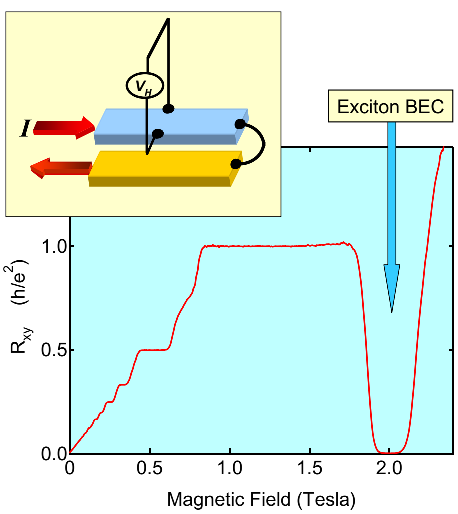
sensitive that we can resolve individual binding events," said Dr. Roukes. "We can follow the stochastic chemistry in real time." Forensic science and technology was identified by Robert Gaensslen, head of the forensic science program at the University of Illinois at Chicago, as one of the emerging societal impacts of analytical chemical instrumentation. He described the challenges in forensics and how modern scientific tools such as the gas chromatograph and mass spectrometer are helping to address them. "Instrumental analysis is deeply interwoven with the analysis of chemical, trace, and biological evidence" in forensic science, he said. T. Vincent Shankey, a clinical scientist at Beckman Coulter's Advanced Technology Center, discussed the technique of flow cytometry and its impact on diagnosing, monitoring, and understanding disease. In describing the development of flow ctyometry, he said, the first step is to define what the goals of an instrument are. The users of an instrument "need to talk to people who are building an instrument and say, 'This is what we need. Build us an instrument that will answer those questions.' " Otherwise, said Dr. Shankey, "companies frequently build machines to answer questions that you don't have."

The symposium wrapped up with a panel discussion that included the symposium speakers and William Ballhaus, Sr., former president of Beckman Instruments, Inc. The panelists discussed the future of instrumentation, highlighting themes such as education, the twilight of major industrial research labs, and the importance of interdisciplinary research to foster innovation and creativity. In general, instrumentation and research have a symbiotic relationship. Scientific and technological advances lead to new instruments, while important scientific and technological problems stimulate the development of new instruments. Instruments developed for one area of research often find application in other areas, both in the research enterprise and in the broader society.

A man of charity, wit, humility, and curiosity, Arnold O. Beckman was also a man of great strength and vision. At this symposium, participants celebrated his many legacies and the promise they hold for the future. ■

Excitons
(continued from page 13)

vided compelling evidence for exciton condensation[6,7]. The most dramatic effect is also the simplest: the Hall voltage in the two layers (measured separately) *vanishes* at low temperatures when the layers are brought close together and the magnetic field is adjusted to produce the half-filling per layer condition. This is expected if the counterflowing electrical currents are carried by excitons. The Lorentz forces on the electron and hole within each exciton cancel exactly. To fully appreciate the significance of this result, consider what is expected if the two layers are far apart or the magnetic field is not at the magic half-filling value. In that case there will be large Hall voltages in each layer. The signs of these voltages will be opposite simply because the current is flowing in opposite directions in the two layers. Indeed, in actual experiments this is precisely what is observed at magnetic fields away from the half-filling condition and at all fields when the layers are too far apart. But when the field is adjusted to the proper value and the layers are close, the Hall voltage in both layers drops precipitously, vanishing as the temperature heads toward absolute zero. (The figure schematically illustrates the experimental setup and the basic observation.)



The vanishing of the Hall resistance in counterflow demonstrates that excitons are present. But it is not obvious from this that the excitons are behaving coherently, like the Cooper pairs do in a superconductor. Additional experiments have, however, established that such coherence exists, at least to a limited extent. The first such indication came from studies of the rate at which electrons quantum mechanically tunnel from one layer to the other[8]. The tunneling rate was observed to increase explosively at the onset of exciton condensation. Although quantitative theoretical analysis of this effect has proven difficult[9], the experiments strongly suggest that coherence over a spatial extent encompassing roughly 100 excitons exists. A more obvious sign of coherence, and the superfluidity that it suggests, has been provided by additional counterflow transport experiments. These experiments have clearly shown that in addition to the Hall voltage, the ordinary resistive voltage parallel to the current in either layer vanishes as the temperature goes to zero in the exciton condensed state. This result demonstrates that energy dissipation accompanying exciton flow becomes extremely small at low temperatures. While the microscopic processes that prevent truly infinite conductivity of the excitons at finite temperature are far from understood, there is now compelling evidence that a closely spaced bilayer 2D electron gas at an appropriate high magnetic field provides a concrete example of the long-sought Bose-Einstein condensate of excitons. ■

References

[1] C.A. Regal, M. Greiner, and D. Jin, *Phys. Rev. Lett.* **92**, 040403 (2004).

[2] D. Snoke, *Science* **298**, 1368-1372 (2002).

[3] See J.P. Eisenstein and A.H. MacDonald, *Nature*, in press, and the references cited therein.

[4] S.Q. Murphy et al., *Phys. Rev. Lett.* **72**, 728 (1994).

[5] J.P. Eisenstein, L.N. Pfeiffer, and K.W. West, *Appl. Phys. Lett.* **57**, 2324 (1990).

[6] M. Kellogg, J.P. Eisenstein, L.N. Pfeiffer, and K.W. West, *Phys. Rev. Lett.* **93**, 036801 (2004).

[7] E. Tutuc, M. Shayegan, and D.A. Huse, *Phys. Rev. Lett.* **93**, 036802 (2004).

[8] I.B. Spielman, J.P. Eisenstein, L.N. Pfeiffer, and K.W. West, *Phys. Rev. Lett.* **84**, 5808 (2000) and *Phys. Rev. Lett.* **87**, 036803 (2001).

[9] L. Balents and L. Radzihovsky, *Phys. Rev. Lett.* **86**, 1825 (2001); A. Stern, S.M. Girvin, A.H. MacDonald, and N. Ma, *Phys. Rev. Lett.* **86**, 1829 (2001); and M. Fogler and F. Wilczek, *Phys. Rev. Lett.* **86**, 1833 (2001).

EPP2010
(continued from page 8)

work plan for the committee was developed that includes three more meetings (each with its own public-comment session), several informal particle physics tutorial sessions between members of the committee, and presentations at future meetings of the joint DOE-NSF High Energy Physics Advisory Panel and the American Physical Society.

The second meeting of the EPP2010 committee, held at the Stanford Linear Accelerator Center in Menlo Park, California, on January 31 and February 1, 2005, focused on a survey of the broad research areas in elementary particle physics. The committee heard presentations from Ian Hinchliffe, Hitoshi Murayama, and JoAnne Hewett on the science motivation for exploring TeV-scale physics and the science capabilities of the Large Hadron Collider and a linear collider. Robert Cahn presented an overview of research studying the B meson with precision experiments. Boris Kayser discussed studies of neutrino physics with the committee and outlined several key points from the recent American Physical Society multidivisional study of this area. Steve Kahn described the emerging connections to cosmology, astronomy, and astrophysics, underlining the need for particle physics to understand and include particle astrophysics in thinking about the future. In the final plenary session, SLAC director Jonathan Dorfan shared a vision for the future of SLAC. Capping off the day was a town meeting session organized by the American Physical Society's Division of Particle and Fields. Participants presented brief comments on their own work and on how the EPP2010 committee should think about the breadth of the field. The committee met in executive session for the second day and reviewed the presentations of the day before. They also began discussing a framework for the final report and agreed on plans to address the need for international perspectives on the future of the field.

The committee's third meeting , scheduled for May 16–17, 2005, will be held at the Fermi National Accelerator Laboratory in Batavia, Illinois. Please visit the committee's public Website for more information, including copies of presentations made to the committee. ■

BPA Mission

The Board on Physics and Astronomy (BPA) was created in 1983 as the successor to the National Academy of Sciences Office of Physical Sciences. Several standing committees were assigned at that time to the BPA, including the Committee on Atomic, Molecular, and Optical Sciences, the Solid State Sciences Committee, and the Committee on Radio Frequencies. Later, the Committee on Astronomy and Astrophysics and the Plasma Science Committee were created in response to requests from the scientific community. Since its inception, the BPA has published more than 40 reports, workshops, and collaborative activities, including two surveys of physics and two surveys of astronomy.

The important questions in physics and astronomy change as we learn more about nature, and that rate of change has been increasing. The BPA seeks to inform the government and the public regarding important scientific opportunities and issues as well as the changing nature of science. It builds bridges between the evolving subdisciplines of physics and astronomy and with other areas of science. The BPA is successful if it helps the science community and society understand what is needed to advance physics and astronomy and why doing so is important.

Every activity of the BPA is aimed at accomplishing one or more of the following goals:

- Monitor the health of physics and astronomy.
- Identify trends in research and new developments at the scientific forefronts.
- Foster interactions with other fields and cooperation among academic disciplines.
- Strengthen connections to technology.
- Facilitate effective service to the nation.
- Improve public understanding of science.
- Encourage cooperation among federal agencies, government laboratories, and universities involved in research in physics and astronomy.

Approaches for achieving these objectives include the following:

- Periodic assessments of major fields. By setting priorities, these surveys provide programmatic guidance to agencies.
- Response to particular needs and requests from federal agencies, both those that have programs of research and those that play an administrative role.
- Continuing surveillance of scientific progress and identification of issues and problems in various fields. Several standing committees are focused on this task.
- Cross-disciplinary studies of special areas that lie at the intersection of several disciplines.
- Many scientific assessments address the benefits that accrue to society through technology development that follows from the pursuit of science.

BPA Update: Emerging Projects

• *Plasma 2010: An Assessment of and Outlook for Plasma Science.** Since publication of the previous decadal study of this area in 1995, the field has undergone rapid advances and significant changes. A committee of about 15 members with broad expertise in plasma science will be convened to address the following tasks in a report that will communicate well to policymakers and scientists in other fields: (1) Assess the recent progress and achievements of plasma science; (2) Identify the new opportunities and the compelling science questions for plasma science, frame the outlook for the future, and place the field in the context of physics as a whole; (3) Evaluate the opportunities and challenges for the applications of plasma science to fusion and other fields; and (4) Offer guidance to the government research programs and the scientific communities aimed at addressing these challenges and realizing these opportunities.

• *Review of the Science Requirements for the Atacama Large Millimeter Array (ALMA).* In response to a request from the National Science Foundation, a committee of about 10 experts will be formed to review the technical requirements for the Atacama Large Millimeter Array (ALMA) and prepare a report analyzing the impact on its performance and scientific merit of a reduction in the number of elements in the array.

• *The Future of Materials Research Laboratories.* A committee of about 15 members will be formed to assess the Materials Research Science and Engineering Center (MRSEC) program at NSF's Division of Materials Research. The assessment will evaluate the program's performance and impact and frame an outlook for its future. Factors to be considered will include the role of the MRSECs in enabling multidisciplinary research, supporting instrumentation development, providing research and education infrastructure, and facilitating collaboration and cooperation between researchers and industry. The committee will complete its work over the course of 18 months.

• *Biomolecular Materials and Processes.* The goal of this study is to review current achievements, assess the compelling science at the interface between biology and materials, and recommend actions to realize the identified opportunities. In particular, the study will identify the most compelling questions and the emerging scientific opportunities at the interfaces between biology and condensed matter and materials research and suggest strategies to best address the identified opportunities.

*Elements of *Physics 2010*

BPA Update: Upcoming Meetings in 2005

April 2005	
4/1-2	PLSC meeting, Washington, D.C.
4/7-8	SSSC meeting, Washington, D.C.
4/27-28	CORF meeting, Washington, D.C.
4/29-30	BPA meeting, Washington, D.C.
May 2005	
5/16-17	EPP2010 meeting, Batavia, Illinois
August 2005	
8/2-3	EPP2010 meeting, Ithaca, New York.
Sept 2005	
9/24-25	PLSC meeting, Irvine, California
Oct 2005	
10/20-21	SSSC meeting, Irvine, California
Nov 2005	
11/6-7	BPA meeting, Irvine, California

THE BPA Web site at **www.national-academies.org/bpa** provides news on recently released reports and other developments as well as a link to this newsletter in PDF format. Reports may be ordered at **www.nap.edu.**

Recent Reports:

Opportunities in High Magnetic Field Science

Letter Report of the Committee on Review of Progress in Astronomy and Astrophysics Toward the Decadal Vision

Coming Soon:

Final Report of the Committee on Smaller Facilities

Proceedings of "Instrumentation for a Better Tomorrow: A Symposium in Honor of Arnold O. Beckman"

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