Issues in Physics & Astronomy at the BPA

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Inspired by Biology: From Molecules to Materials to Machines

Natalia Melcer, BPA Staff

Ed. Note: This article is largely inspired by the Executive Summary of the report.

The Board on Physics and Astronomy and the Board on Life Sciences jointly convened the Committee on Biomolecular Materials and Processes (BMAP) to assess current work and future promise at the intersection of biology and materials science. The charge for this study was developed in consultation with the study's sponsors at the Department of Energy and National Science Foundation. The Committee on BMAP was charged to identify the most compelling questions and the emerging scientific opportunities at the interface between biology and condensed matter and materials research, suggest strategies to best meet the identified opportunities, and consider connections to national priorities including healthcare, security, workforce, economic, and other societal needs.

The ability of biological systems to carry out extremely complex functions in a vast array of environments has long inspired scientists to create synthetic systems that function with similar precision and efficiency. A lack of understanding of how biological systems function has hampered the ability to make such materials and devices. Scientists are using an expanding toolbox of new ways to measure, manipulate, and compute properties of matter, living and nonliving. These efforts are beginning to uncover the principles that govern how biological systems work. Application of the principles uncovered by these investigations will allow scientists to create synthetic materials, processes, and devices that can carry out tasks with the precision of biological systems. Now is a very exciting time for research at the intersection of the biological and materials sciences.

Practical design of biologically inspired materials has the potential to improve the well-being of U.S. citizens and the nation's economic competitiveness by addressing some of the most urgent national challenges. Biomolecular materials and processes may improve medical therapeutics, allow the creation of reliable sensors to detect biological and chemical threats, and facilitate the path to energy independence. To realize these opportunities and fully harness the potential of biology to inform the development of materials and processes, further advances in fundamental physics, chemistry, and material science will be required. Three closely related strategies for the creation of new materials and systems may help realize the potential of biomolecular mate-

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In this issue:

Monde Trouvé: The Story of Graphene

Allan H. MacDonald, University of Texas at Austin

Ed. Note: This article and the BPA meeting science talk it partially represents are based on an article co-authored with Andre K. Geim of the University of Manchester which appeared in the August 2007 issue of Physics Today.

In condensed matter physics, every new material is its own world with its own set of rules. A research team at the University of Manchester led by Andre K. Geim has recently[1] managed to fabricate the first truly two-dimensional world, large area sheets of carbon atoms arranged in the planar honeycomb-lattice pattern illustrated below. Surprisingly, the quantum mechanics of an electron in one of these graphene sheets is like that of a relativistic particle with vanishing rest mass. Given a supply of graphene sheets, it is possible to study the properties of a degenerate system of ultra-relativistic fermions by performing table-top experiments. This new two-dimensional electron system possesses an elegant simplicity which appeals to physicists as they try to understand its mysteries, and also characteristics which make it exceptionally promising as a material for future electronic technology.

The electronic properties of graphene were first addressed[2] more than half a century ago by Phil Wallace who was interested in the electrical conductivity of graphite, apparently as part of the Canadian World War II Atomic Energy Project. Because graphite is a stack of weakly coupled graphene sheets, Wallace built his theory of graphite on a model for the electronic properties of graphene. His theory stands essentially unaltered today and is also used to describe nanotubes (graphene sheets rolled into a tube) and buckyballs (graphene sheets folded into a ball).

The chemistry of carbon is extremely simple and extremely versatile. Each carbon atom has one s and three p valence electrons which can organize into strong θ

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

Beth Masimore, Christine Mirzyan Science & Technology Policy Graduate Fellow

The Board on Physics and Astronomy held its annual fall meeting on November 3-4, 2007, at the Beckman Center of the National Academies in Irvine, California. Chair Anneila Sargent called the meeting to order, thanking everyone for being present and introducing the new board members. She noted this was the last meeting for staff member Tim Meyer and thanked him for his "service, dedication, and fun." In addition, she thanked board director Don Shapero for his leadership and direction and noted that he was recently elected a fellow of AAAS Physics Section. Vice chair Marc Kastner then described the main topics of this meeting: overviews of the Physics 2010 studies, updates on completed reports, progress reports of current studies, and proposals for future studies.

The first presentation was made by Matt Tirrell, UCSB, regarding the results of the study on Materials Research Science and Engineering Centers (MRSECs), which was recently released in its final form. While the committee found it difficult to uniquely attribute large impacts to the MRSEC program, they concluded that MRSECs mobilize efforts that would not have occurred otherwise.

The committee spent the rest of the morning hearing brief updates on the status of the Physics 2010 reports. Homer Neal led a discussion on the University Grants Program Subpanel of HEPAP. This subpanel was formed after the release of *Revealing the Hidden Nature of Space and Time: Charting the Course for Elementary Particle Physics* and was charged with completing a comprehensive review of the DOE and NSF high energy physics University Grants Program. Following extensive data collection, the subpanel concluded the university program must be strengthened to achieve the goals of the national high-energy physics program as articulated by EPP2010.

Steven Cowley spoke regarding Plasma 2010 which was released at the end of May. The co-chairs participated in two rounds of briefings, beginning with moderate level staff and following with top level staff at DOE, OSTP and appropriations committees. He felt that the briefings went well and urged future committee chairs to use the same structure for dissemination.

Phil Bucksbaum then discussed the release of the *Controlling the Quantum World: The Science of Atoms, Molecules, and Photons* report. A press release was held for the report. The physics community responded positively and several non-science publications featured stories on the report, including *The Economist*.

Condensed Matter and Materials Physics: The Science of the World Around Us was released this summer, and Tom Theis and Peter Green spoke to the committee about its major recommendations and the dissemination efforts underway. The recommendations that inspired the most discussion were those that focused on education and workforce issues and the shrinking role of industrial labs. The co-chairs have participated in two sessions of briefings in Washington, D.C. and briefed the executive board of the AIP governing board.

Jon Bagger led a discussion on the nature of the Gravitational Physics 2010 report that is currently in development. As the science falls naturally in the overlap between physics and astronomy, there was discussion about ways to incorporate this survey into both the Physics 2010 project and the upcoming Astronomy and Astrophysics 2010 project. This will continue to be discussed during the development of the astronomy survey.

Nuclear Physics 2010 is in development and Wick Haxton led a discussion about the project. The joint DOE/NSF Nuclear Science Advisory Committee recently published a long range plan, and the challenge for the future NRC NP2010 committee will be to find a way to add

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value to this plan. It was suggested that the international context of nuclear physics could be included since it is missing from the NSAC long-range plan.

Michael Turner and Chuck Shank were asked to lead a provocative discussion on a physics overview volume for the physics decadal survey. They proposed a study focused on defining physics in the 21st century. Discussion began to converge on the potential for a benchmarking study, similar to that recently undertaken by the NRC Board on Chemical Sciences and Technology.

Following a break for lunch and general discussion, Arup Chakraborty updated the board on the Biomolecular Materials and Processes study that is currently in review. He offered a few remarks on the study process and noted that it was extremely helpful to request assistance from scientists that were not on the committee. [The final report of the committee was released in February.]

Wick Haxton addressed the board again, this time about the Rare Isotope Science Assessment Committee. The report was released nearly a year ago and focused on the scientific opportunities possible with a rare isotope accelerator that would be smaller than an earlier proposed facility. Since report release, the Nuclear Science Advisory Committee formed a panel to assess the technical aspects of such a facility with a rare isotope beam, and the panel recommended that NSF and DOE proceed with the project.

During the rest of the afternoon, the Board heard presentations regarding studies that are currently in progress. Marshall Cohen began with a presentation on a study assessing the scientific uses of the radio spectrum. One challenge for the committee will be to articulate the need for protected radio bands when it is clear that band sharing is possible for some applications.

Jose Onuchic then updated the board on the committee to study research at the intersection of the physical and life sciences, which recently held its first meeting. The committee has decided to focus on both scientific opportunities and social impacts and is hosting a symposium to explore grand challenges at this scientific interface.

Next, Laura Greene updated the board on the materials synthesis and crystal growth study. The committee is examining the status of both the discovery of novel materials and the growth of single crystals of known materials in the U.S. They have been engaged in data collection and analysis to investigate the impact of waning industrial basic research and increasing international strength in these areas.

Ron Davidson addressed the committee regarding the status of the study to review and evaluate the plan for U.S. fusion community participation in the ITER program. [A committee has been formed to address this task and it has held a meeting in December 2007 and prepared its report].

Closing the day, Pat Colestock presented a new study to complete a scientific assessment of free electron laser technology for naval applications. One aspect of the study will be to identify the highest priority scientific and technical gaps along the development path from present-day capabilities through to a megawatt demonstration project.

The following morning, Anneila Sargent opened with a review of the first day. She noted that the Physics 2010 survey is progressing nicely and noted a repeated concern to address issues surrounding education.

Allan MacDonald gave a science talk on graphene, opening with a trailer from the animated film, *Flatland: The Movie*. A review of this exciting and emerging field of research is on page 1 of this newsletter.

The remainder of the morning was spent discussing possible new BPA projects. The first discussion centered on the upcoming astronomy and astrophysics decadal survey. BPA members Anneila Sargent, Meg Urry, and Jon Bagger led the discussion. A major challenge will be to conduct the study in a way that balances expert committee opinion with input from the broader community.

Edward (Joe) Redish, University of Maryland, then made a presentation proposing an additional volume of the Physics 2010 report series focusing on physics education. A study could include topics such as physics education research, physics teacher recruiting and training, college level course reform, and faculty development. He feels that the timing is ideal for such a report, given the

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Committees of the Board on Physics and Astronomy

Committee on Biomolecular Materials and Processes[1]
Arup Chakraborty, Massachusetts Institute of Technology, *Chair*

Committee on Radio Frequencies
Paul A. Vanden Bout, National Radio Astronomy Observatory, *Chair*
Jeffrey Piepmeier, NASA Goddard Space Flight Center, *Vice Chair*

Committee to Review U.S. ITER Science Participation Planning Process
Patrick L. Colestock, Los Alamos National Laboratory, *Chair*

Materials Synthesis and Crystal Growth Committee
Paul S. Peercy, University of Wisconsin at Madison, *Chair*

Plasma Science Committee
Riccardo Betti, University of Rochester, *Chair*

Research at the Interface of the Physical and Life Sciences Committee[1, 2]
Erik O'Shea, Harvard University, and Peter G. Wolynes, University of California at San Diego, *Co-chairs*

Scientific Assessment of Free-Electron Laser Technology for Naval Applications Committee[3]
Thomas Katsouleas, University of Southern California, *Chair*

Solid State Sciences Committee
Peter F. Green, University of Michigan, *Chair,* and Barbara Jones, IBM Almaden Research Center, *Vice Chair*

Spectrum Study Committee
Marshall H. Cohen, California Institute of Technology, and Albin J. Gasiewski, University of Colorado at Boulder, *Co-chairs*

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[1]Joint with Board on Life Sciences
[2]Joint with Board on Chemical Sciences and Technology
[3]In coordination with Naval Studies Board

Research at the Intersection of the Physical and Life Sciences

Natalia Melcer, BPA Staff

Under the auspices of the Board on Physics and Astronomy (BPA), the Board on Life Sciences (BLS), and the Board on Chemical Sciences and Technology (BCST), a new study committee has been formed to assess the status of Research at the Intersection of the Physical and Life Sciences (RIPLS) in the United States and to identify areas of opportunity for future research. The committee will develop a conceptual framework for this work, identify and prioritize the most compelling research opportunities and their potential benefits to society, and explore ways to enable and enhance effective interdisciplinary collaboration. The committee will explore key research areas in which the interaction of physical and life sciences is needed for scientific advancement. Specifically, the committee is charged with the following tasks:

1. Develop a conceptual framework for research at the intersection of the physical and life sciences and conduct an assessment of current work.
2. Identify high priority research opportunities at this intersection, articulate the potential benefits to society, and recommend strategies for realizing them.
3. Explore ways to enable and enhance effective interactions between the life and physical sciences to address the most compelling opportunities. Enabling mechanisms include facilitating collaboration, education, training, instrumentation, and infrastructure.

Across the government and across the research communities, interest has been building in the research opportunities at the intersection of the life and physical sciences. In preparations for fiscal year (FY) 2004, the annual interagency guidance memo from the White House's Office of Science and Technology Policy and Office of Management and Budget identified molecular-level understanding of the basis of life processes as a priority area. In Congressional reports concerning FY 2004 appropriations, the Nationals Science Foundation (NSF) and the National Institutes of Health (NIH) were directed to meet and discuss opportunities for collaboration between the life and physical sciences. In response, NSF and NIH organized a May 2004 workshop with broad participation across the federal agencies that examined collaborative efforts at this interface. In September 2004, the American Chemical Society hosted a workshop with support from NSF to identify the grand challenges at the interface of chemistry and biology. In October 2004, NSF organized a Molecular Basis for Life Processes workshop for young investigators. Following objectives outlined at the May meeting, NSF and NIH held a broadly advertised and open conference in early November 2004 on Research at the Interface of the Life and Physical Sciences: Bridging the Sciences that worked to identify the broad opportunities, challenges, and solutions for this type of research. Finally, in late November 2004, the National Academies released the final report of its Committee on Facilitating Interdisciplinary Research. The report concluded, in part, that the exploration of basic research problems at the intersections of disciplines was one of the drivers for interdisciplinary research; the intersection of the physical and life sciences was cited as a prime example.

The National Research Council (NRC) has considered its potential role in nurturing this research area as well. The current study is derived from the work of a program initiation meeting that the NRC convened on December 11-12, 2004, in Menlo Park, California. The group concluded that a multidisciplinary assessment undertaken by the NRC would be valuable. The BPA is also partnering with BLS on a subfield-specific assessment of the science opportunities at the interface of condensed-matter and materials physics and biology, focusing on biomolecular materials and processes (BMAP). The project is supported by NSF and the Department of Energy (DOE) and the expected outcomes include a set of priority areas and recommendations for addressing them. Thus, the BMAP project

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Research at the Intersection of the Physical and Life Sciences Committee

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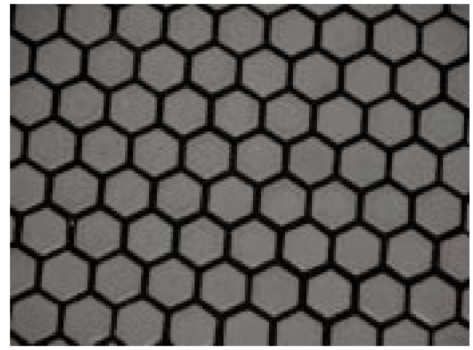
bonds between sp^2 hybridized orbitals. The sp^2 orbitals combine the s orbital and two of the p orbitals into three wave functions peaked in a common plane, along angles separated by 120 degrees. The honeycomb lattice structure, in which each carbon atom has three neighbors, is able to exploit this strong band. In a two-dimensional graphene crystal, the remaining out-of-plane π orbitals, one on each carbon atom, form a two-dimensional band structure. As students learn in elementary solid state physics courses, the honeycomb lattice is a non-Bravais lattice with two atoms per unit cell. It therefore has two π orbital bands, one of which is occupied in a neutral graphene sheet. (See image.)

In condensed-matter physics, most electronic properties depend directly only on states within a thermal energy k_BT of the Fermi energy. (The Fermi energy separates low-energy occupied states from high-energy empty states.) Because the thermal energy near room temperature and below is more than an order of magnitude smaller than typical chemical energy scales, only states very close to the Fermi energy directly influence physical properties. In graphene, the states near the Fermi energy are close to one of the two-independent Brillouin-zone corners (valleys) at which the valence and conduction π bands touch. When expanded to linear order around these points the π-band Hamiltonian is identical to the massless limit of a two-dimensional Dirac equation, with the role of quantum-spin in the Dirac equation assumed by the band-structure valley index. Graphene electrons are the first experimental realization of ultra-relativistic degenerate fermions.

But we are a bit ahead of ourselves. Graphene is amazing in the first place simply because it exists. Against all expectations and in defiance of the immensely expanded networking opportunities and entropy of the three-dimensional world, stable two-dimensional matter can be fabricated. How was this achieved? Not by standard chemical synthesis which has so far yielded only tiny platelets about 10 hexagons across. Not by conventional crystal growth techniques, since thermal fluctuations tend to kick flat nano-sized graphene crystallites (that could serve as precursors for further 2D growth) into the third dimension where they minimize their surface energy by morphing into one the rich variety of stable 3D structures that occur in soot. Instead, the University of Manchester[1, 3] group was able to isolate graphene sheets by cleverly examining the debris field of pencil traces in which individual atomic planes are mechanically separated from a 3D graphite crystal. Following the original discovery, further progress in the mechanical exfoliation of graphene sheets has been achieved by the Manchester[4] group, by a group led by Phillip Kim at Columbia University[5], and by others. Weak interactions with a substrate or with lithographically prepared graphene sheet support structures are then sufficient to maintain this non-equilibrium two-dimensional form of carbon. This *rub and hunt* method cannot be the basis for manufacturing graphene based devices, of course, but it does allow the physics of these materials to be explored. Future practical applications of graphite will likely require further development of epitaxial growth techniques, for example growth[6] by decomposition of SiC.

Because the graphene world is two-dimensional, its circumstances can be controlled by experimenters who operate in its three-dimensional environment. Experiments show that graphene sheets are rippled, for example, possibly due to interactions with the substrates on which they lie. Controlled charge densities on the surface of surrounding gate electrodes, unintended charges randomly distributed in the surrounding material, and thin films of water are all known to influence graphene properties.

By gating graphene it is possible to achieve a degenerate density of ultra-relativistic particles or anti-particles. Experiments have shown[3] that ultra-relativistic particles are amazingly robust conductors, maintaining a non-zero conductivity (against the expectations of theory) even in the limit of zero particle density. Because electrons in graphene move at a velocity of about 10^6 m/s (fast



Above Image: Graphene consists of carbon atoms at the vertices of hexagons which tile two-dimensional space. This image is a picture of the floor tiles at the downtown location of Jo's coffee shop in Austin. Photo courtesy Tami Pereg-Barnea.

enough to cross a graphene based device in 0.1 ps), its Hamiltonian is not Lorentz-invariant once electron-electron interactions are included. Interaction physics in graphene is described by a new kind of quantum electrodynamics (QED) in which ultra-relativistic particles and photons travel at different velocities. Much progress is now being achieved in understanding how electron-electron interactions, unintended disorder, and interactions with vibrations of the carbon lattice combine to determine the dependence on particle or anti-particle density and sheet environment of the electrical properties of graphene.

Magneto-transport measurements are a key probe of any two-dimensional electron system. They have a long history, for example, in the study of semiconductor heterojunction two-dimensional electron systems (2DESs), in which electrons near the Fermi energy are confined to planes 10 to 100 atomic layers thick. Because of the Lorentz force, two-dimensional electrons in a perpendicular magnetic field move in closed cyclotron orbits. In a quantum theory, the kinetic energy of cyclotron orbits is quantized, causing the continuous spectrum of a two-dimensional gas to collapse into macroscopically degenerate discrete levels known as Landau levels. Landau-level formation is manifested most dramatically in magneto-transport measurements, where it leads to the celebrated quantum Hall effect, recognized by two Nobel prizes. The

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strong political interest in science education and concerns of maintaining an educated workforce to maintain international competitiveness.

Phil Bucksbaum presented a possible study on quantum information science that would be a follow up to *Controlling the Quantum World*. While the science is very compelling, it may be difficult to generate interest for such a study at this time.

The morning session concluded with a presentation by Chuck Shank regarding a possible follow up to the 1997 report, *Harnessing Light: Optical Science and Engineering for the 21st Century*. The board felt that a follow-up study might be more appropriate for another board at the NRC with a stronger focus on engineering The discussion of the *Harnessing Light* report led to a discussion of advanced light sources. The U.S. is investing heavily in advancedlight sources and the science agenda for these new facilities is not well-developed. The Board plans to consider this topic in more detail.

After lunch, the committee heard a presentation by Charles Kennel, UCSD, regarding the results of the Beyond Einstein Program Assessment. A major challenge for the committee was to obtain robust cost estimates of the various programs under consideration. Lessons learned about engaging both scientists and engineers in this process will likely prove useful for the upcoming astronomy survey.

Leslie Theiss and Joe Patterson from the Bureau of Land Management presented an overview of the federal helium program to provide background for the upcoming study on the U.S. Helium Reserve to be conducted by the BPA (see *Emerging Projects* at the back of this newsletter). This study committee has yet to be formed but will likely include both experts from economics and natural resource management in addition to research scientists.

To conclude the meeting, BPA staff presented the status and plans of the standing committees. David Lang gave an overview of the Committee on Radio Frequencies. In addition to completing three FCC filings in 2007, CORF released the Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses. Tim Meyer then gave an overview of the Committee on Atomic, Molecular, and Optical Science (CAMOS) and the Plasma Science Committee (PLSC). CAMOS was deactivated during the AMO2010 study, but there is interest in reinstating the committee. PLSC is overseeing the dissemination of the Plasma 2010 report in addition to preparing a proposal for a study on laboratory astrophysics. Natalia Melcer updated the board on the activities of the Solid State Sciences Committee (SSSC). SSSC is working on a proposal for a study to assess the role and opportunity for materials to contribute to meeting global energy challenges, focusing on long-term basic research priorities. The last presentation was made by Brian Dewhurst, regarding the Committee on Astronomy and Astrophysics. The committee, though dormant, is interested in obtaining information about the demographics of the astronomy community and is exploring ways to obtain this information prior to beginning the decadal survey. ■

RIPLS
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will serve as a helpful case study, but will not address the overall framework and structural issues that this study will include. Additionally, BCST recently completed a study titled *Visualizing Chemistry: The Progress and Promise of Advanced Chemical Imaging* that pointed to promising future developments and their applications, and suggested a research agenda to enable breakthrough improvements in our capacity to image molecular processes simultaneously in multiple physical dimensions as well as time. BLS has also addressed interdisciplinary education directly in its 2003 report, *Bio2010: Transforming Undergraduate Education for Future Research Biologists*. That report identified the need for incorporating examples and modules from the physical sciences into undergraduate biology curricula and biological content into physical science courses.

To date, the RIPLS committee has held two meetings and a symposium. At the first meeting on September 14-15, 2007, the committee heard from its sponsors: DOE, NIH, and NSF. The committee also heard from other stakeholders including Dr. John Marburger, Director of the Office of Science and Technology Policy; Dr. James Gentile, President of Research Corporation; and Dr. Ken Dill, Chair of the Bridging the Sciences Coalition. The committee discussed its work plan and also began preparing for a research symposium.

The committee's research symposium was held on December 19, 2007 in Washington, DC and explored ways that physical and life scientists, working together, can promote transformative advances in scientific understanding. The symposium was organized around a series of questions and potential applications including biomedicine, the origin of life and evolution, cognition and learning, energy security, climate change and environment, safety and national security, biologically-inspired materials, research from molecules to organisms and from organisms to ecosystems, and the tools necessary to conduct such research. Nine prominent speakers, chosen for their area of expertise and who work at the intersection of the physical and life sciences, were invited to attend. The agenda included short presentations by each speaker and ample time for discussion after each talk. For more information on the symposium, please visit: http://www7.nationalacademies.org/bpa/RIPLS_Symposium.html.

The symposium was followed by a one-day committee meeting at which the committee heard from Dr. Nancy Sung of the Burroughs Wellcome Fund, a new sponsor of the study. This discussion was followed by committee reflection on the symposium and subgroup reporting. The committee developed a report outline and organized working groups to begin drafting the report. The third committee meeting is scheduled for April 29-30, 2008, in Washington, DC. At this meeting, the committee expects to review an initial draft of the report and discuss findings and recommendations. A fourth and final meeting is being planned for July 30-31, 2008. ■

Review of the Plan for U.S. Participation in ITER

David B. Lang, BPA Staff

There has long been great interest in developing the capability to harness fusion energy for the generation of power. In the decades leading up to the 21st century, great advances were made in the scientific and technological understanding necessary if this vision were ever to come to fruition. The United States, in 1985, joined the Soviet Union, European Union, and Japan in designing a next-generation tokamak reactor which would explore the magnetic confinement concept. The U.S. dropped out of the project in 1998 even while momentum grew overseas.

In 2002, the DOE's Fusion Energy Sciences Advisory Committee (FESAC) and the U.S. National Research Council's Burning Plasma Assessment Committee recommended that the United States rejoin international ITER negotiations or risk missing a critical opportunity. In response to growing domestic enthusiasm for the project and increasing worries about energy security, on January 30, 2003, President George W. Bush issued a Presidential Initiative announcing that the U.S. would rejoin the ITER collaboration, which then consisted of Russia, the U.S., the EU, Japan, the People's Republic of China, and the Republic of Korea. India became the seventh member of the project in December 2005.

Following the Initiative, the Energy Policy Act of 2005 (EPAct 2005), Section 972, authorized U.S. participation in ITER and directed DOE, in consultation with FESAC, to develop a plan for the participation of U.S. scientists in ITER. DOE then asked the U.S. Burning Plasma Organization (BPO) to develop the plan in response to this mandate, which it completed in June 2006. DOE then submitted this plan, with FESAC approval, to Congress in August 2006. Section 972 (c)(4)(B) of the Act directs the DOE to then request a review of this plan by the National Academy of Sciences. The National Research Council (NRC) is now presented with the following charge:

The committee will prepare a short report addressing the following tasks:

1. Review the document "Planning for U.S. Fusion Community Participation in the ITER Program." Determine whether the plan provides a good initial outline for effective participation of U.S. plasma scientists in research at ITER.
2. Evaluate the following required elements of the plan: (a) an agenda for U.S. research at ITER, (b) methodologies to evaluate ITER's contribution to progress toward a power source, (c) description of the anticipated relationship between the U.S. ITER research program and the overall U.S. fusion program.
3. The committee will recommend next steps in the development of the plan, including: (a) appropriate elements and/or goals for the plan; (b) procedures to facilitate further development of the plan; and (c) metrics for measuring progress in establishing robust U.S. participation in the ITER research program.

To respond to this charge, the NRC constituted a committee of experts in plasma science, fusion technology, fusion engineering, and the organization and development of large international projects. The membership of the committee, dubbed the Committee to Review U.S. ITER Science Participation Planning Process (CRISPPP), is given in this newsletter.

CRISPPP met at the Keck Center in Washington, DC on December 14-15, 2007. After being familiarized with the National Academies study process, the committee heard testimony from DOE's Office of Fusion Energy Sciences on the current status of U.S. ITER preparations and plans for the future. The Office of Science and Technology Policy then provided a policy perspective on the committee's task. The committee also invited several foreign colleagues who are central to the ITER project's organization and development. David Campbell of the ITER Organization delivered a presentation on the evolution of the ITER project, its organization, and the developing scientific agenda for the project. Jerome Pamela, European Fusion Development Agreement, presented a talk on the organization of fusion R&D in Europe, the EU strategy toward a DEMO reactor, and the EU's research program. Shinzaburo Matsuda of the Japan Atomic Energy Agency discussed Japanese participation in ITER and its research plans.

The committee also invited Ned Sauthoff, Director of the U.S. ITER Project Office at Oak Ridge National Laboratory (ORNL), to speak about plans for U.S. engagement in ITER. James Van Dam, University of Texas at Austin and Director of the BPO, then discussed the role of the BPO in organizing the knowledge base for U.S. participation. Earl Marmar, Massachusetts Institute of Technology, followed by describing the BPO subpanel which has been constituted to follow-up the DOE plan. Stanley Milora of ORNL, then discussed the research mission of the Virtual Laboratory for Technology and how it will contribute to U.S. ITER efforts.

The report of the CRISPPP committee will take on the difficult task of assessing the evolving status of U.S. planning for involvement in ITER, and will make recommendations for the future development of the DOE plan. The committee plans to complete its report in spring 2008. ■

Committee to Review U.S. ITER Science Participation Planning Process

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Scientific Assessment of Free Electron Laser Technology for Naval Applications

Caryn J. Knutsen, BPA Staff

Weapons that use very high power beams to disable or destroy targets, known as directed-energy weapons, have been researched by the U.S. military for decades The Air Force has sponsored research using chemically powered lasers; the Army, the use of solid-state laser technologies; and the Navy's Office of Naval Research (ONR) has developed free-electron lasers (FELs). These testbeds typically use a single optical system to both track a target and to focus the beam on the target.

A free-electron laser (FEL) is an accelerator-based device that causes stimulated emission of radiation to occur from an electron beam. It generates tunable, coherent, highly-collimated, high power radiation, currently ranging in wavelength from microwaves to the visible spectrum. While an FEL laser beam shares to some degree the same optical properties as optically or chemically pumped lasers (such as coherence), the operation of an FEL is quite different. Unlike gas or diode lasers which rely on transitions between bound atomic or molecular states, FELs use a relativistic electron beam as the lasing medium, hence the term free-electron. Free-electron lasers can be used to generate terahertz radiation. Today, a free-electron laser requires the use of an electron accelerator with its associated shielding. These accelerators are typically powered by microwave klystrons, which require a high-voltage power supply. Usually, the electron beam must be maintained in a vacuum which requires the use of numerous pumps along the beam path. Free-electron lasers can achieve extremely high peak powers.

The Navy has chosen to pursue the free-electron laser route to a directed-energy weapon, in part because of a perceived advantage that the wave-length-tuneability would allow in maritime environments. Its relatively efficient conversion of "wall-plug power" to "beam power" (perhaps 25%) could make it an attractive system to be used on a mobile platform such as a ship. FEL designs for shipboard (or wide-body aircraft) applications generally assume the use of high beam currents. The stability of such beams, at beam currents required for megawatt-class laser outputs has not been demonstrated. Thus there are still physics problems that need to be resolved. If a low-current design is chosen, the beam must be recirculated many times to achieve the necessary acceleration. This in turn leads to significant energy losses.

Researchers at the U.S. Department of Energy's Thomas Jefferson National Accelerator Facility (J-Lab) in Newport News, Virginia, delivered first light from their FEL on June 17, 1998. Only 2 years after ground was broken for the FEL, infrared light of more than 150 watts was delivered—fifteen times the power of existing free-electron lasers. By the end of 2006, J-Lab had achieved powers greater than 14kW. Finally, recent advances in accelerator science and technology using superconducting radio-frequency cavities in an energy-recovering linear accelerator suggest that the device could be contained within a 20-m long structure.

ONR's FEL research program is currently classified as an applied-research program (budget category 6.2), and ONR is considering an expansion of the research effort in the form of an advanced-technology development program (budget category 6.3). In order to ultimately design and build a ship-based directed-energy weapon, the next step might be to develop a larger-scale dedicated FEL prototype that would push the performance parameters of existing free-electron laser technology. It is estimated that such a transition would require approximately an order of magnitude more funding (currently $20M).

Early in 2007, the chief of ONR, at the suggestion of the Assistant Secretary of the Navy for Research, Development, and Acquisition, requested an independent assessment of the readiness of the FEL science and technology from the National Academies. Under the auspices of the Board on Physics and Astronomy, a new study committee has been formed to carry out this scientific assessment of free-electron laser technology for naval applications. This NRC study will be completed in two phases, producing up to two reports, and is specifically charged with the following tasks:

1. Review the current state-of-the-art and anticipated advances for high-average-power free-electron lasers (FELs). Using performance characteristics defined by the Navy for directed-energy applications, analyze the capabilities, constraints, and tradeoffs for FELs.
2. Evaluate the scientific and technical development path from current demonstrated capabilities toward the eventual goal of achieving megawatts of radiated power at wavelengths suited to naval applications; consider the realistic constraints of ship-board installation.
3. Identify the highest priority scientific and technical gaps along the development path from present-day capabilities through a 100 kW test facility to a megawatt demonstration project. Recommend a phased approach for this development path using staged milestones with explicit performance and success criteria at each stage.
4. Assess the capabilities and constraints related to beam steering and atmospheric propagation at wavelengths suited to naval applications for an FEL-based system.

The committee will not make budgetary recommendations or address the generic issues connected with directed-energy weapons but will rather explore the feasibility of FEL-based countermeasures in terms of the realizability of specifications defined by ONR.

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Free Electron Laser Study Committee

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Graphene
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quantum Hall effect is a macroscopic quantum effect in which the Hall resistance (the voltage drop perpendicular to the direction of current flow) is constant over broad ranges of particle density. It occurs only in samples with relatively weak disorder, so its discovery[4, 5] in graphene demonstrated the high quality of the material which experimenters were able to prepare. More specifically it verified in an essential way the relativistic character of graphene electrons. From our understanding of the quantum Hall effect, we know that Hall resistance plateau values measure the electron densities at which Landau levels are full. Experiments in graphene sheets demonstrated that a Landau level occurs exactly where the π-orbital conduction and valence bands meet, and that its states are drawn in equal measure from each band. This observation has been refereed to as the *half-quantized Hall effect* in the graphene literature, and corresponds precisely to Paul Dirac's discovery that his relativistic wave equation was able to account in a very simple way for the anomalous value of the electron g-factor, g=2.

The growing band of researchers interested in graphene has high hopes that future research will bring unexpected discoveries, or useful technology, or—even better—both. Partly because of the relativistic character of its electrons, current graphene samples have better electrical conductivity per carrier than silicon, and researchers hope that much further progress is possible. A key challenge to developing graphene as a replacement for or a supplement to silicon is finding an effective way to turn the electrical current off. One possibility is opened up by the properties of graphene bilayers, which turn out to differ quite dramatically from those of a single-layer system. The wave equation which describes low-energy electrons in this case turns out to be one which has not arisen previously in physics; energy depends quadratically on momentum as in a non-relativistic system but the eigenstates have unusual chiral properties. Most importantly, an electric field perpendicular to a bilayer opens up an energy gap which could make it easier to fabricate MOSFET circuits with reasonable leakage currents. Graphene bilayers appear also to offer more opportunities for the discovery of collective broken-symmetry states which could give rise to new and potentially useful phenomena not directly related to the underlying π-bands. Several theoretical suggestions have been made in this direction, none yet verified. The history of condensed matter physics suggests, however, that new worlds bring new surprises. ■

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Free Electron Laser
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The committee of 16 members, chaired by Thomas Katsouleas, University of Southern California, will complete the first phase of the study over a 12-month period. The committee held its first meeting January 17-18, 2007 at the Keck Center in Washington, DC. Recent results from leading researchers in the FEL field were presented and briefings from the Navy specified their background and needs for this study. Speakers included Dr. Dinh Nguyen, LANL, Dr. George Neil, J-Lab, Dr. Phillip Sprangle, NRL, and Rear Admiral William Landay, the Chief of Naval Research. Two additional committee meetings will be held on April 4-5, 2008 and May 4-6, 2008. In Phase I, this committee will prepare a report addressing item one of the statement of task in summer 2008. The second phase plan, still in development, will address the remaining items in the statement of task. ■

BMAP
(continued from page 1)

rials and processes:

Biomimicry. This strategy relies on first learning the mechanistic principle used by a living system to achieve a particular function. Then one attempts to copy the same scheme to achieve similar function in a synthetic material. One example is the design of materials where the building blocks themselves encode information during their synthesis. One can also try to create materials that mimic whole cells in responding to external stimuli. Such materials could be used in devices for detecting hazardous biological and chemical agents.

Bioinspiration. Merely knowing that a task can be achieved by a living system can inspire scientists to develop a synthetic system that performs the same function, even if the synthetic system uses a scheme quite different from that employed by the biological system. Nature provides examples of functional systems with exceptional materials properties and performance that would be useful to replicate for technological applications. Examples include the adhesive gecko's foot, self-cleaning lotus leaf, and fracture-resistant mollusk shell, which have fueled recent interest in "smart" biological materials. Yet attempts to create synthetic analogs have largely been unsuccessful, in part because the fundamental understanding of the biological systems is often limited.

Bioderivation. This strategy involves using an existing biomaterial in concert with artificial materials to create a hybrid. A prominent example is the incorporation of biologically derived proteins into polymeric assemblies for targeted drug delivery.

Progress in these areas will be facilitated by a number of actions and investment by research agencies, the scientific community, and other stakeholders. In particular, the following steps will help confront the scientific challenges associated with these strategies and to translate the resulting knowledge into societal and economic value.

The synergistic application of approaches traditionally confined to distinct disciplines will be imperative. While such concerted efforts are already emerging in individual circumstances, substantial interagency cooperation in support of such interdisciplinary research and development efforts will be needed.

Recommendation 1: DOE, NIH, NSF, and other relevant agencies should develop jointly sponsored multidisciplinary programs of innovative research at the crossroads of disciplines. New initiatives of this type will provide incentives for universities to break down and work across traditional departmental boundaries. OSTP should take the lead in coordinating this effort.

Fundamental physical, chemical, and biological scientists need to work together with engineers to create new biomaterials and technologies. Education of scientists and engineers that can work at the intersection of these fields is crucial.

Recommendation 2: University physics, chemistry, biology, materials science, mathematics, and engineering departments and medical schools should cooperatively examine their curricula to identify ways to prepare scientists and engineers for research at the intersection of the physical sciences, engineering, and the life sciences. These educational programs should also be evaluated, incorporating a wide range of viewpoints, including input from leaders in industry and national laboratories.

Communication between scientists and engineers from different disciplines is hampered by difficulties in understanding methods, concepts, and jargon. Mechanisms for facilitating communication across and between disciplines are essential.

Recommendation 3: DOE, NIH, NSF, and other relevant agencies should support the development of one- or two-week summer courses to train physical scientists and engineers in the tools and concepts of biology and medicine and conversely to train biologists in the tools and concepts of the physical sciences. Special attention should be given to developing ways of communicating fundamental physico-chemical concepts to biologists while using mathematical knowledge common to that community. Summer courses focused on these areas would help bridge the physical and life sciences communities to exploit research opportunities at the intersection of the fields.

Fundamental research is necessary to realize the applications envisaged in this report and could lead to yet-unimagined technological applications, but translation of new discoveries into useful products is also crucial. Thus, both fundamental and translational research should be emphasized.

Recommendation 4: DOE, NIH, NSF, and other relevant agencies should collaborate to build bridges from the most fundamental research to commercial applications. While it is imperative to recognize and exploit the connections between fundamental advances and opportunities to translate the advances into practice, curiosity-driven fundamental research on outstanding unsolved questions should be encouraged as it could lead to currently unforeseen technological advances.

It is difficult for a single laboratory to house the diverse instrumentation and expertise required for interdisciplinary research in biomolecular materials and processes. Standard equipment in biology laboratories, for example, is usually not found in engineering laboratories and vice versa. Further, many researchers do not have access to shared or private facilities containing such equipment and instrumentation. National facilities that house clusters of small to mid-range instrumentation and associated expertise are important for fostering interdisciplinary research in biomolecular materials and processes.

Recommendation 5: DOE should evaluate the effectiveness of recently created facilities to provide access to mid-range instrumentation and computational facilities for the advancement of interdisciplinary research in nanoscience and technology. Analogous, but distinct, centers could be created to facilitate research in biomolecular materials and processes.

The committee's final report, *Inspired by Biology: From Molecules to Materials to Machines*, was released on Friday, February 15, 2008, in unedited, prepublication form. The chair briefed interested parties in the federal agencies, Administration, and Congress. For further information on the report and other dissemination activities, please see the Board on Physics and Astronomy website (www.nas.edu/bpa). ■

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, 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 about 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

- *Astronomy and Astrophysics 2010.* The BPA, in conjunction with the Space Studies Board, is preparing for the next decadal survey of astronomy and astrophysics, labeled Astronomy and Astrophysics 2010. The two Boards have developed a proposal for the study which is under consideration by the NSF Astronomy Division, the NASA Astrophysics Division, and the DOE Office of High-Energy Physics. In addition, the Board continues to solicit input from the astronomy and astrophysics community on a number of issues regarding the next survey. For further details please refer to the activity's website at http://www7.nationalacademies.org/bpa/Astro2010.html.
- *The impact of selling the U.S. Federal Helium Reserve.* In a follow-up to a report published in 2000, this study would assess the impact of having sold the Federal Helium Reserve on U.S. scientific, technical, biomedical, and national security users of helium over the past 5 years. To provide a meaningful context for this effort, the study will examine the helium market and the helium supply chain. Measures that would enable the Federal Helium Program to respond to future changes in the dynamics of the helium market will be identified.
- *Nuclear Physics 2010.* A committee will be formed to prepare an assessment and outlook for nuclear physics research in the United States. The study will develop a clear and compelling articulation of the scientific rationale and objectives of nuclear physics, taking into account the most recent Nuclear Science Advisory Committee Long-Range Plan. The study will present very-long-term priorities for the field in an international context and a strategy that can serve as a framework for the field through 2020. This activity is expected to begin in 2009.

BPA Update: Meetings in 2008

March 2008	
3/29-30	Spectrum Study Meeting, Boulder, Colorado.
April 2008	
4/4-5	FEL Meeting, Washington, D.C.
4/11-12	SSSC Meeting, Washington, D.C.
4/25-26	BPA Meeting, Washington, D.C.
4/29-30	RIPLS Meeting, Washington, D.C.
May 2007	
5/4-6	FEL Meeting, Newport News, Virginia.
5/20-21	CORF Meeting, Washington, D.C.

BPA Newsletter for:

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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:

Inspired by Biology: From Molecules to Materials to Machines
NASA's Beyond Einstein Program: An Architecture for Implementation

Coming Soon:

Final Report of the U.S. ITER Science Participation Planning Process Review Committee
Final report of the New Materials Synthesis and Crystal Growth Committee
Final report of the Research at the Intersection of the Physical and Life Sciences Committee
Final Report of the Spectrum Study Committee