BPA NEWS

Board on Physics and Astronomy • The National Academies • Washington, DC • 202-334-3520 • national-academies.org/bpa • December 2002

Neutrinos and Beyond: New Windows on Nature

Barry Barish, Caltech

THE Neutrino Facilities Assessment Committee, which I chaired, recently completed a report requested by John Marburger, Director of the Office of Science and Technology Policy. The letter of request, a list of the membership of the committee, our schedule, public submissions to the committee, a link to the full report, and other information may be found on the BPA Web site at <http://www.national-academies.org/bpa>. This article follows closely the executive summary of the report.

The charge to the committee, as we interpreted it, involved three elements:

- Identify the major science problems that could be addressed by cubic-kilometer-class neutrino observatories,
- Identify the major science problems that could be addressed with a deep underground science laboratory,
- Assess the scientific importance of the identified science and determine whether it could be addressed by other existing, soon-to-be-completed, or planned facilities.

Background

Discoveries involving neutrinos are reshaping the foundations of our understanding of nature. The detection of neutrinos coming from the Sun and from an exploding star and discoveries from underground experiments of the past decades were recognized by the 2002 Nobel Prize in physics. More recent underground neutrino experiments have excited the scientific community with definitive observations that neutrinos of different types transform into one another, implying that they have mass.

Indeed, neutrinos have moved onto center stage in astrophysics and in particle physics, and for good reason. The discovery that neutrinos have mass provides us with the first tangible evidence for physics beyond the very successful Standard Model of elementary particles. And, the neutrino mass indicated by these experiments leads to the conclusion that neutrinos account for about as much of the mass of the universe as do bright stars. Finally, the discovery that neutrinos have mass supports certain formulations of the long-sought theory that unifies the forces and particles.

These discoveries create a number of new fundamental questions and opportunities to further advance our understanding of the universe and the laws that govern it. They have spurred proposals for new initiatives, including both a project to develop a large neutrino detector under the ice at the South Pole (IceCube) and a proposal to develop a new deep underground laboratory that can house a broad range of important future experiments within the United States. The committee's report was commissioned to review and assess the scientific merit of these two proposals.

The committee assessed the science that requires instrumenting a very large volume of ice deep under Earth's surface with photodetectors. The goal of such

See "Neutrino Study" on page 4

In this issue:

The X–Games of Contemporary Science

Ron Davidson, Princeton University

THE Committee on High Energy Density Plasma Physics, which I chaired, recently released its report *Frontiers in High Energy Density Physics: The X–Games of Contemporary Science*. Full information on the committee, our schedule of meetings, and other information may be found on the BPA Web site at <http://national-academies.org/bpa>. This article follows closely the executive summary of the report.

The committee was established to identify scientific opportunities and develop a unifying theme for research on matter under extreme high energy density conditions. Specifically, the committee was charged with the following tasks: (a) to review recent advances in the field of high energy density plasma phenomena, on both the laboratory scale and the astrophysical scale; (b) to provide a scientific assessment of the field, identifying compelling research opportunities and intellectual challenges; (c) to develop a unifying framework for diverse aspects of the field; (d) to outline a strategy for extending the forefronts of the field through scientific experiments at various facilities where high energy density plasmas can be created; and (e) to discuss the roles of national laboratories, universities, and industry in achieving these objectives.

See "X–Games" on page 6

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, including the Keck Foundation.

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

ON November 5 and 6, 2002, the Board on Physics and Astronomy met in Irvine, California. After completing some NRC business, the Board turned its attention to the first speaker, Sidney Nagel of the University of Chicago. Dr. Nagel recently published an article entitled "Physics in Crisis," which discussed the increasing fractionation of the field into isolated subfields. In Dr. Nagel's view, this splintering is dangerous, for it leads to competition between different subfields and could harm the ability of physics as a field to attract faculty and support for research and new equipment in the future. To address this problem, Dr. Nagel has planned a plenary session for the upcoming March meeting of the American Physical Society (APS) to discuss the future of physics. One objective will be to encourage cross-fertilization among the subfields. The Board discussed the problem and pointed out that the APS plenary session was a start but that additional efforts will be needed to have a real impact. Some of the Board members also noted that the isolation of the subfields is less pronounced in industrial laboratories than it is in universities.

The Board's next topic was the need for direction and planning for the support of theory in physics. Kathy Levin and Boris Kayser addressed this topic, highlighting the historical interplay between theory and experiment and the way theory unifies disparate fields. Theoretical research, free from the need for large facilities or other big-ticket items, tends to be lost in the funding shuffle. Many theorists are significantly underfunded. Studies have already been conducted that conclude that the answer is not to reduce the number of theorists whose research is supported. On that basis, the next step would be to make the case for strengthening support for theorists. During the Board's discussion, it was pointed out that, in the astronomy community, the argument that theory and experiment work together synergistically is no longer effective. A new strategy must be found.

Next the Board turned its attention to the issue of women in physics. Frances Hellman proposed three possible actions:

1. Endorse a resolution made by the International Union of Pure and Applied Physics (IUPAP).
2. Address gender balance in determining the membership of the Board and the Committees.
3. Participate in a study being conducted by the Committee on Women in Science and Engineering.

An IUPAP study concluded that women are not appropriately represented in physics departments around the world. John Yochelson, an economist from the University of California at San Diego, led the Board through a number of statistics. In 2003 more women than men will receive higher education degrees below the Ph.D. level, and in 2010 their numbers should surpass those of men in Ph.D. programs as well. The sheer number of factors in this discussion, however, makes analysis difficult. There is no silver bullet that can, by itself, have a major impact on the number of women in the field.

After a break for lunch, the meeting resumed with a conversation with Anita Jones, discussing the National Science Board and its procedures and policies, in light of upcoming discussion about setting priorities for NSF major projects. The Major Research Equipment and Facilities Construction (MRE/FC) line has a substantial backlog of projects. Six approved projects have yet to begin construction. Priorities need to be set among projects approved by the National Science Board.

The next agenda item addressed interagency cooperation, with the chairs of the three most recent survey studies (Michael Turner for the Committee on Physics of the Universe, Christopher McKee for the Astronomy and Astrophysics Survey Committee, and Barry Barish for the Neutrino Facilities Assessment Committee) leading the discussion. It was noted that NASA has effective approaches to identifying scientific directions and mounting programs to address the science. NSF, on the other hand, responds to initiatives from the scientific community. The discussion turned to the Large Synoptic Survey Telescope (LSST), a ground-based survey telescope recommended by the Astronomy and Astrophysics Survey and endorsed by the Solar System Exploration (SSE) Survey and the Committee on Physics of the Universe. The SSE Survey recommended that NASA share the cost of LSST with the NSF.

The discussion then turned to cooperation between the NSF and DOE in the area of high-energy physics (HEP). Eighty percent of HEP funding is in the DOE labs, but 80 percent of the scientists work at universities and are supported by the NSF. Despite this difference of roles, the interagency cooperative efforts seem to be going well. U.S. support for the Large Hadron Collider at CERN is a good example of NSF-DOE cooperation.

The final item on the first day's agenda was a discussion of the Neutrino Facilities Assessment Committee's draft report. The NFAC interpreted the charge to encompass more than neutrinos (to include, for example, proton-decay experiments) but not areas such as geophysics. The report recommends moving ahead with the construction of IceCube, an astrophysical neutrino detector at the South Pole, and a deep underground laboratory. (See page 1 of this issue for an article summarizing the results of the study.) After this discussion, the BPA adjourned for the evening.

The second day of the BPA meeting began with an overview of the activities of its standing committees. Items discussed included:

- The findings and recommendations of the High Energy Density Physics report,
- The progress being made by the Burning Plasma Assessment Committee and the need for the BPAC to address the issue of United States involvement in the ITER (See a summary of the Interim Report on page 9 of this issue.),
- A potential study on small facilities,
- A joint forum with the National Materials Advisory Board,
- The proposed study of high magnetic field research, and
- Possible interest in having the NRC conduct a periodic review of the nanotechnology initiative.

The first invited speaker of the day was James Griffin, from the Office of Science and Technology Policy. Dr. Griffin began by discussing the issues surrounding foreign students studying at American institutions. Each year there are 225,000 international students at the graduate level at American universities. One of the September 11 hijackers entered the nation on a student visa, drawing attention to this issue. The administration is concerned about tracking students who enter the nation, making sure they arrive at their university, seeing how long they stay, etc. It is creating a new automated system to provide more information about individuals with student visas.

Beyond the location of students, the government is also concerned that foreign students might be trained in the development of weapons of mass destruction. OSTP is committed to open science but sees the need for such an ideal to be balanced with the objective of ensuring homeland security. There is an interagency working group (including OSTP and the Department of Homeland Security) looking at the issue in response to a presidential directive. This working group has created a standing interagency panel on advanced science and security (IPASS). The technology alert list is now used to determine if an advanced screening mechanism should be used. The Board was very concerned about this issue and raised a number of points. Cornell University is choosing to eliminate all types of research on campus that would trigger this additional screening. Also mentioned was the fact that it is rarely possible to predict what field a graduate student will end up working in at the time of admission.

Griffin advised the Board that every major research university should develop a policy for how to respond to any students who seem to be getting involved in activities with security implications. IPASS review will be triggered by a large set of variables for incoming students (affiliations, country of origin, family members, funding, where they are going, what they might study, etc.). In some ways, physicists have been dealing with this problem for a long time (through the Cold War). The problem is a new one to biotech researchers. OSTP and OHS are working on an Executive Order to set up a framework for IPASS. State and Justice will

See "BPA Meeting" on page 11

Committees of the Board on Physics and Astronomy

Committee on Astronomy and Astrophysics
Wendy L. Freedman, Carnegie Observatories, and Roger D. Blandford, Caltech, *Co-chairs*

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

Plasma Science Committee
Thomas M. O'Neil, University of California at San Diego, *Chair*

Committee on Radio Frequencies
Donald Backer, University of California at Berkeley, *Chair*

Solid State Sciences Committee
Sol Gruner, Cornell University, *Chair*

Committee on Physics of the Universe
Michael Turner, University of Chicago, *Chair*

Committee on High-Energy-Density Plasma Physics
Ronald C. Davidson, Princeton University, *Chair*

Neutrino Facilities Assessment Committee
Barry Barish, Caltech, *Chair*

Burning Plasma Assessment Committee
John Ahearne, Sigma Xi, and Raymond Fonck, University of Wisconsin, *Co-chairs*

Committee on Smithsonian Scientific Research
Cornelius Pings, University of California at Los Angeles, *Chair*

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

Neutrino Study
(continued from page 1)

exploratory experiments is to open the neutrino window on the universe and to elucidate the origin and acceleration of nature's highest energy particles. High-energy neutrinos provide a unique probe into understanding the acceleration mechanisms from astrophysical objects such as active galactic nuclei and gamma ray bursts that could produce such particles. Detecting these neutrinos is particularly attractive because they reach Earth without absorption and can give insight into the production mechanisms at the source.

The second class of experiments we assess are those that might be placed in a new deep underground laboratory. In recent years, experiments performed below the surface of Earth have received more and more worldwide attention in nuclear physics, particle physics, cosmic ray physics, as well as astrophysics and cosmology. Such laboratories, shielded from cosmic rays, allow the study of rare phenomena and provide a window on unraveling some of the most compelling questions in physics and astrophysics today. The dramatic discoveries of neutrino oscillations (and mass) are a direct result of such experiments, and future deep underground experiments could be key to unraveling some of the most fundamental problems in physics and astronomy. Since we find that the scientific goals of an underground laboratory go well beyond neutrino experiments, we have assessed the scientific potential for such a facility in a broader context.

In addition to providing a scientific assessment of IceCube and a deep underground laboratory, we address their overlaps and complementarity, as well as how each initiative fits into plans internationally. Finally, we emphasize that this report is consistent with, and should be viewed within the context of, the broader planning for future projects in physics and astronomy. In particular, the NRC report *Connecting Quarks and the Cosmos: Eleven Science Questions for the New Century*, addresses a set of important questions at the interface of astronomy and physics, several of which would be addressed by these projects. By their nature, these two projects are interdisciplinary and overlap existing fields. Similarly, the recent DOE/NSF long-range plans for nuclear physics and particle physics endorse these projects. They find them important to those fields and address the importance of these projects within the context of the scientific goals and priorities of those fields.

IceCube

The IceCube experiment planned for the South Pole will instrument a cubic kilometer of deep ice. At this depth, the ice is sufficiently transparent to minimize light losses (although some scattering may still occur) and it provides a quiet environment in which to place a large phototube array. Deep underwater experiments with similar goals have also been proposed for the Mediterranean Sea, but they are not as developed as the IceCube concept at this time. Furthermore, the water and ice detectors potentially have complementary features, both technically and in their sky coverage.

An international collaboration has formed to build IceCube, which is a larger version of the pioneering AMANDA experiment that has provided initial results and a great deal of experience working with such techniques at the South Pole. AMANDA successfully demonstrated design implementation, data taking, and neutrino detection. IceCube has been successfully reviewed technically and is ready for construction. It includes some technical improvements over AMANDA that promise to provide a more robust and flexible detector system.

IceCube is an exploratory experiment at the forefront of a new area of science. Although it is not possible to predict the rates for such unknown physics, the best estimates from high-energy gamma-ray sources and cosmic-ray rates suggest that the sensitivity of the proposed km^3 scale of IceCube is sufficient to observe neutrinos from known astrophysical sources. In addition, we know from AMANDA and other experiments that there is a source of copious neutrinos resulting from cosmic ray interactions with our atmosphere at TeV energies and above whose study will be of significant interest for investigating neutrino interactions at these energies. (On the other hand, the absence of such a point-source neutrino signal in IceCube could still be significant as it restricts the broad class of models for cosmic acceleration.) The unique and important opportunity to observe the expected high–energy neutrinos makes the experiment very attractive and worth undertaking.

We find that there is evidence that the universe contains a variety of sources of very-high-energy neutrinos and that their detection would reveal much about how nature accelerates particles, as well as the inner workings of supermassive black holes and the mysterious gamma-ray bursts. The technology exists to build the enormous detectors necessary to detect neutrinos from across the universe, and the infrastructure exists at the South Pole. The time is right to open this new window on the Universe.

> ***The planned IceCube experiment can open a new window on the Universe by detecting very high energy neutrinos from objects across the Universe. The science is well motivated and exciting, the detection technique is proven, and the experiment appears ready for construction.***

IceCube has completed its R&D, prototyping, and conceptual design phases. With approval of funding, it would be ready to transition to the construction phase. Doing so will require putting into place appropriate project management, making final technical and design decisions, and ensuring that the collaboration is strong enough to support a project of this importance and magnitude.

A New Deep Underground Laboratory

The science of underground physics was pioneered in the United States by Raymond Davis, Jr., more than 35 years ago. He detected electron-type neutrinos coming from the Sun, confirming Hans Bethe's theory that a chain of thermonuclear reactions takes place in the solar core. He then made the profoundly significant observation that the actual number of detected solar neutrinos was much lower than predicted, giving the first hint of new physics.

Underground experiments at Japanese and Canadian mines have recently provided the explanation, with dramatic evidence that neutrinos oscillate from one type to another, implying that neutrinos have finite mass. With these discoveries and the emergence of this new field, it is now very timely to consider the possibility of building a new deep underground facility in the United States. This judgement recognizes both the large U.S. commitments being made to facilities abroad and the future science opportunities for such underground facilities. In fact, the development of a new underground laboratory with characteristics that are well matched to the needs of the future experiments could bring the United States back to a leadership position in this important area of science.

Laboratories deep underground are required for several reasons: they provide the possibility of studying rare forms of penetrating radiation (e.g., neutrinos and dark-matter particles) in a low background environment, and they also provide a low background environment to study rare processes (e.g., double beta decay and proton decay). To meet the unique challenges of the many possible experiments considered in this review, any future underground laboratory must have several key attributes. First, it must provide the ability to place experiments as deep as 4500 mwe (the equivalent of 4500 meters of water, or about 1500 meters of typical crustal rock), with the future possibility of siting experiments down to 6000 mwe. (Although 4500 mwe would likely satisfy the needs of many upcoming experiments, the potential for greater depth would result in a truly unique and longer-lived facility with even less risk of background processes.) Secondly, locating a facility at large distances—over 1000 kilometers—from accelerator facilities capable of producing intense neutrino beams will be essential for the next generation of neutrino oscillation experiments and would be another unique capability.

The proposals that are currently under consideration for a deep underground laboratory allow for the development of a flexible multipurpose infrastructure to support a full suite of experiments. The actual experiments will be proposed separately, peer reviewed and then funded to be done at the laboratory. Every effort should be made to closely integrate the actual development of a new laboratory with the experimental program that will be performed. A significant advantage of a central facility is in the sharing of common technical and equipment support among the various experiments. There are many other research uses for sufficiently shielded underground laboratory space, including various geophysics and geobiology projects, but the committee had neither the expertise nor sufficient time to make additional evaluations.

The committee found that to exploit fully the science opportunities underground, a new facility should meet certain special requirements. Its location must allow great depths for those experiments that require it, together with flexibility in siting experiments that need less overburden but more space. It must afford a long-term future for science at minimal cost. Siting the facility within the continental United States also offers important additional advantages in the presence of powerful existing accelerators with proven and expandable capabilities for neutrino-beam production and the potential for long-baseline experiments. The combination of these features would create a new deep underground laboratory that could fully exploit the science opportunities described in this report.

A deep underground laboratory can house a new generation of experiments that will advance our understanding of the fundamental properties of neutrinos and the forces that govern the elementary particles, as well as shed light on the nature of the dark matter that holds the universe together. Recent discoveries about neutrinos, new ideas and technologies, and the scientific leadership that exists in the United States make the time ripe to build such a unique facility.

It will require considerable strategic and technical guidance to construct a deep underground laboratory expeditiously and in synergy with the research program. Critical decisions that are beyond the scope of this report remain: choosing between several viable site options, defining the scope of the laboratory, defining the nature of the laboratory staff and the management organization, the site infrastructure, and the level of technical support that will be resident. Developing sound experimental proposals will require early access to deep underground facilities to perform necessary R&D. To initiate the experimental program in a timely fashion, it is important to complete the process of setting the scope and goals for the laboratory, soliciting and reviewing proposals, and building up the necessary infrastructure.

Redundancy and Complementarity

The exploratory physics of IceCube and the broad science program for a deep underground laboratory are truly distinct. IceCube concentrates on very high energy neutrinos from astrophysical sources that require a detector of much larger size than is possible in an underground laboratory, while an underground laboratory focuses on experiments, including neutrino experiments, that require the low backgrounds available deep underground. The committee finds essentially no overlap or redundancy in the primary science goals and capabilities of IceCube and that of a deep underground laboratory.

On the international scene of present and planned experiments, IceCube is unique in its technology and location (using ice at the South Pole) and is the most advanced project for gigaton-scale high-energy neutrino telescopes. Separately, the wealth of experimental opportunities available in an underground laboratory assures that an additional underground lab would contribute in a large way to the international science effort. While it is true that each particular experiment proposed for the underground lab could be individually sited elsewhere, there are likely to be scientific leadership, economic, and administrative advantages to a centralized national underground facility. ■

X–Games
(continued from page 1)

Background

Recent advances in extending the energy, power, and brightness of lasers, particle beams, and Z–pinch generators make it possible to create matter with extremely high energy density in the laboratory. The collective interaction of this matter with itself, particle beams, and radiation fields is a rich, expanding field of physics called high energy density (HED) physics. It is a field characterized by extreme states of matter previously unattainable in laboratory experiments. It is also a field rich in new physics phenomena and compelling applications, propelled by advances in high-performance computing and advanced measuring techniques. This report's working definition of "high energy density" refers to energy densities exceeding 10^{11} joules per cubic meter (J/m^3), or equivalently, pressures exceeding 1 megabar (Mbar). (For example, the energy density of a hydrogen molecule and the bulk moduli of solid materials are about 10^{11} J/m^3.)

The time is highly opportune for the nation's scientists to develop a fundamental understanding of the physics of high energy density plasmas. The space-based and ground-based instruments for measuring astrophysical processes under extreme conditions are unprecedented in their accuracy and detail, revealing a universe of colossal agitation and tempestuous change. In addition, there is a new generation of sophisticated laboratory systems ("drivers") existing or planned that create matter under extreme high energy density conditions, permitting the detailed exploration of physics phenomena under conditions not unlike those in astrophysical systems.

A consensus is emerging in the plasma physics and astrophysics communities that many opportunities exist for significant advances in understanding the physics of high energy density plasmas through an integrated approach to investigating the scientific issues in related subfields. Understanding the physics of high energy density plasmas will also lead to new applications and benefit other areas of science. Learning to control and manipulate these plasmas in the laboratory will benefit national programs such as inertial confinement fusion and the stockpile stewardship program, through the development of new ideas and the training of a new generation of scientists and engineers. Furthermore, advanced technologies in the areas of high-speed instrumentation, optics (including x-ray optics), high-power lasers, advanced pulse power, and microfabrication techniques can be expected to lead to important spin-offs.

High energy density experiments span a wide range of areas of physics, including plasma physics, laser and particle beam physics, materials science and condensed matter physics, nuclear physics, atomic and molecular physics, fluid dynamics and magnetohydrodynamics, intense radiation-matter interaction, and astrophysics. While a number of scientific areas are represented in high energy density physics, many high energy density research techniques have grown out of ongoing work in plasma science, astrophysics, beam physics, accelerator physics, magnetic fusion, inertial confinement fusion, and nuclear weapons research. The intellectual challenge of high energy density physics lies in the complexity and nonlinearity of the collective interaction processes that inform all of these subfields of physics.

It should be emphasized that while high energy density physics is a rapidly developing area of research abroad, particularly in Europe and Japan, the primary focus of this report is on assessing the present capabilities and compelling research opportunities in the United States.

To illustrate the energy scale of the high energy density regime, some of the systems that deliver the energy in high energy density laboratory experiments in the United States can be considered. Typical state-of-the-art short-pulse lasers and the electron beams generated at the Stanford Linear Accelerator Center can be focused to deliver 10^{20} watts per square centimeter (W/cm^2) on target. The present generation of lasers employed in inertial confinement fusion (on the NIKE facility at the Naval Research Laboratory, on OMEGA at the Laboratory for Laser Energetics at the University of Rochester, and at the TRIDENT laser laboratory at Los Alamos National Laboratory) deliver 1 to 40 kilojoules (kJ) to a few cubic millimeters volume in a few nanoseconds. In Z-pinch experiments on the Z-machine at Sandia National Laboratories, 1.8 megajoules (MJ) of soft x rays is delivered to a few cubic centimeters volume in about 5 to 15 nanoseconds (ns). With the planned upgrades of existing facilities and the completion of the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory in the early 2000s, the parameter range of high energy density physics phenomena that can be explored will expand significantly. Complementary technologies, such as gas guns, explosively driven experiments, and diamond anvils, can also generate physically interesting high energy density physics conditions in the laboratory. While the primary purpose of the major facilities sponsored by the Department of Energy's National Nuclear Security Administration (NNSA) is to investigate technical issues related to stockpile stewardship and inertial confinement fusion, increasing opportunities are also available at these facilities for exploring the basic aspects of high energy density physics. These state-of-the-art facilities allow repeatable experiments and controlled parameter variations to elucidate the important underlying physics.

Elucidating the physics of high energy density plasmas through experiment, theory, and numerical simulation presents exciting science opportunities for understanding physical phenomena in laboratory-generated high energy density plasmas and in astrophysical systems. Because the field is developing rapidly, a study of the compelling research opportunities and synergies in high energy density plasma physics and its related subfields is particularly pertinent at the present time.

Assessing the Field

In carrying out this assessment, the National Research Council's Committee on High Energy Density Plasma Physics found high energy density physics (pressure conditions exceeding 1 Mbar, say) to be a rapidly growing field of physics with exciting research opportunities of great intellectual challenge spanning a wide range of physics areas. Opportunities for exploring the compelling questions of the field have never been more numerous. The many excellent high energy density facilities—together with a new generation of sophisticated diagnostic instruments, existing or planned, that can measure properties of matter under extreme high energy density conditions—permit laboratory exploration of many aspects of high energy density physics phenomena in exquisite detail under conditions of considerable interest for the following: basic high energy density physics studies, materials research, understanding astrophysical processes, commercial applications (e.g., extreme ultraviolet lithography), inertial confinement fusion, and nuclear weapons research.

Furthermore, a revolution in computational capabilities has brought physical phenomena within the scope of numerical simulations that were out of reach only a few years ago. Numerical modeling is now possible for many aspects of the complex nonlinear dynamics and collective processes characteristic of high energy density laboratory plasmas and for the extreme hydrodynamic motions that exist under astrophysical conditions. The first phase of advanced computations at massively parallel facilities such as those developed in the Advanced Strategic Computing Initiative (ASCI) is reaching fruition with remarkable achievements, and a unique opportunity exists at this time to integrate theory, experimentation, and advanced computations to significantly advance the fundamental understanding of high energy density plasmas.

Exciting new discoveries in astrophysics have occurred along with dramatic improvements in measurements by ground-based and space-based instruments of astrophysical processes under extreme high energy density conditions. Using the new generation of laboratory high energy density facilities, macroscopic collections of matter can be created under astrophysically relevant conditions, providing critical data on hydrodynamic mixing, shock phenomena, radiation flow, complex opacities, high-Mach-number jets, equations of state, relativistic plasmas, and, possibly, quark-gluon plasmas characteristic of the early universe.

Supporting the Field

In reviewing the level of support for research on high energy density physics provided by federal program agencies, the committee found that the level of support by agencies such as the National Nuclear Security Administration, the nondefense directorates in the Department of Energy, the National Science Foundation, the Department of Defense, and the National Aeronautics and Space Administration has lagged behind the scientific imperatives and compelling research opportunities offered by this exciting field of physics. The NNSA's establishment of the Stewardship Science Academic Alliances program to fund research projects at universities in areas of fundamental high energy density science and technology relevant to stockpile stewardship is commendable and important, particularly because the nation's universities represent a vast resource for developing and testing innovative ideas in high energy density physics and for training graduate students and postdoctoral research associates.

A highly cost-effective way of significantly extending the frontiers of high energy density physics research is to upgrade and/or modify existing and planned experimental facilities to access new operating regimes. Such upgrades and modifications of experimental facilities will open up exciting research opportunities beyond those which are accessible with existing and planned laboratory systems. These opportunities range, for example, from the installation of ultra-high-intensity (petawatt) lasers on inertial confinement fusion facilities to create relativistic plasma conditions relevant to gamma-ray bursts and neutron star atmospheres, to the installation of dedicated beamlines on high energy physics accelerator facilities for carrying out basic high energy density physics studies, such as the development of ultrahigh-gradient acceleration concepts and of unique radiation sources stretching from the infrared to gamma ray regimes.

The committee is convinced that research opportunities in this crosscutting area of physics are of the highest intellectual caliber and that they are fully deserving of consideration for support by the leading funding agencies of the physical sciences. A broad federal support base for research in high energy density physics, including plasma science, and the encouragement of interagency research initiatives in this very interdisciplinary field would greatly strengthen the ability of the nation's universities to have a significant impact on this field.

The Key Questions

In developing a unifying framework for the diverse areas of high energy density physics and identifying research opportunities of high intellectual value, the committee found it useful to formulate key scientific questions ranging from the very basic physics questions to those at the frontier of the field. These are questions that, if answered, would have a profound effect on our fundamental physics understanding of matter under high energy density conditions. The following list of questions is not intended to be complete but rather to be illustrative of important questions of high intellectual value in high energy density physics:

- How does matter behave under conditions of extreme temperature, pressure, density, and electromagnetic fields?
- What are the opacities of stellar matter?
- What is the nature of matter at the beginning of the universe?
- How does matter interact with photons and neutrinos under extreme conditions?
- What is the origin of intermediate-mass and high-mass nuclei in the universe?
- Can nuclear flames (ignition and propagating burn) be created in the laboratory?
- Can high-yield ignition in the laboratory be used to study aspects of supernova physics, including the generation of high-Z elements?
- Can the mechanisms for formation of astrophysical jets be simulated in laboratory experiments?
- Can the transition to turbulence and

the turbulent state in high energy density systems be understood experimentally and theoretically?

- What are the dynamics of the interaction of strong shocks with turbulent and inhomogeneous media?
- Will measurements of the equation of state and opacity of materials at high temperatures and pressures change models of stellar and planetary structure?
- Can electron-positron plasmas relevant to gamma-ray bursts be created in the laboratory?
- Can focused lasers "boil the vacuum" to produce electron-positron pairs?
- Can macroscopic amounts of relativistic matter be created in the laboratory and will such matter exhibit fundamentally new collective behavior?
- Can we predict the nonlinear optics of unstable multiple and interacting beamlets of intense light or matter as they filament, braid, and scatter?
- Can the ultraintense field of a plasma wake be used to make an ultrahigh-gradient accelerator with the luminosity and beam quality needed for applications in high-energy and nuclear physics?
- Can high energy density beam–plasma interactions lead to novel radiation sources?

These questions cut across the boundaries of this field, and answering them will require new approaches to building a comprehensive strategy for realizing the exciting research opportunities. With this in mind the committee makes several recommendations.

Recommendations

1. Recommendation on external user experiments at major facilities

It is recommended that the National Nuclear Security Administration continue to strengthen its support for external user experiments on its major high energy density facilities, with a goal of about 15 percent of facility operating time dedicated to basic physics studies. This effort should include the implementation of mechanisms for providing experimental run time to users, as well as providing adequate resources for operating these experiments, including target fabrication, diagnostics, and so on. A major limitation of present mechanisms is the difficulty of obtaining complex targets for user experiments.

2. Recommendation on the Stewardship Science Academic Alliances Program

It is recommended that the National Nuclear Security Administration continue and expand its Stewardship Science Academic Alliances program to fund research projects at universities in areas of fundamental high energy density science and technology. Universities develop innovative concepts and train the graduate students who will become the lifeblood of the nation's research in high energy density physics. A significant effort should also be made by the federal government and the university community to expand the involvement of other funding agencies, such as the National Science Foundation, the National Aeronautics and Space Administration, the Department of Defense, and the nondefense directorates in the Department of Energy, in supporting research of high intellectual value in high energy density physics.

3. Recommendation on maximizing the capabilities of facilities

A significant investment is recommended in advanced infrastructure at major high energy density facilities for the express purpose of exploring research opportunities for new high energy density physics. This effort is intended to include upgrades, modifications, and additional diagnostics that enable new physics discoveries outside the mission for which the facility was built. Joint support for such initiatives is encouraged from agencies with an interest in funding users of the facility as well as from the primary program agency responsible for the facility.

4. Recommendation on the support of university research

It is recommended that significant federal resources be devoted to supporting high energy density physics research at university-scale facilities, both experimental and computational. Imaginative research and diagnostic development at university-scale facilities can lead to new concepts and instrumentation techniques that significantly advance our understanding of high energy density physics phenomena and in turn are implemented at state-of-the-art facilities.

5. Recommendation on a coordinated program of computational-experimental integration

It is recommended that a focused national effort be implemented in support of an iterative computational-experimental integration procedure for investigating high energy density physics phenomena.

6. Recommendation on university and national laboratory collaboration

It is recommended that the Department of Energy's National Nuclear Security Administration (NNSA) continue to develop mechanisms for allowing open scientific collaborations between academic scientists and the NNSA laboratories and facilities, to the maximum extent possible, given national security priorities.

7. Recommendation on interagency cooperation

It is recommended that federal interagency collaborations be strengthened in fostering high energy density basic science. Such program collaborations are important for fostering the basic science base, without the constraints imposed by the mission orientation of many of the Department of Energy's high energy density programs.

To summarize, the committee believes that now is a very opportune time for major advances in the physics understanding of matter under extreme high energy density conditions. A sustained commitment by the federal government, the national laboratories, and the university community to answer the important questions of high intellectual value identified by the committee and to implement the recommendations of this report will contribute significantly to the timely realization of these exciting research opportunities and the advancement of this important field of physics. ■

Burning Plasma Assessment Committee Interim Report: Rejoining ITER

Michael Moloney, BPA Staff

THE Burning Plasma Assessment Committee (BPAC) held its first meeting in Washington, D.C., on September 17, 2002. Co-chaired by John Ahearne of Sigma Xi and Duke University and Raymond Fonck of the University of Wisconsin, Madison, the committee was appointed to carry out an assessment of a U.S. burning plasma experimental program and its role in magnetic fusion research. (A fusion plasma is said to be burning when more than half of the plasma heating comes from the fusion reaction. All fusion reactors require a burning plasma, and the key challenge is to confine a sufficiently hot and dense plasma while it burns.) The committee's diverse membership includes not only fusion experts but members drawn from the plasma science, high-energy physics, condensed matter, astrophysics, and policy fields.

The study has three components: (1) an assessment of the importance of a burning-plasma experimental program to fusion energy sciences and technology and the development of fusion as an energy source, plasma physics, and science in general; (2) an assessment of scientific and technical readiness to undertake a burning plasma experimental program; and (3) an independent review and assessment of the plan for the U.S. magnetic fusion burning plasma experimental program as developed by the Department of Energy through the FESAC (Fusion Energy Sciences Advisory Committee) and Snowmass processes. The committee has been asked to make recommendations on the program strategy aimed at maximizing the yield of scientific and technical understanding as the foundation for the future development of fusion as an energy source.

At its first meeting the committee was addressed by the Director of the Department of Energy's Office of Science, Raymond Orbach, who, in the course of his presentation, asked BPAC to address, in its planned interim report, not only selected elements of the committee's charge but also the question of whether the United States should reenter the negotiations on the International Thermonuclear Experimental Reactor (ITER)—an international burning plasma experiment that is at an advanced stage of planning and from which the United States withdrew in 1998. In his remarks to the committee, Dr. Orbach stressed the importance of fusion energy in setting future global energy policy, reminding the committee of recent statements by the President on fusion and recounting his discussions with policy makers from other countries. The committee undertook to respond to Dr. Orbach's request by issuing an early interim report in December 2002.

At its second meeting, in November, the committee heard from the Director of the Office of Science and Technology Policy (OSTP), John Marburger. He told the committee that the United States had three decisions to make: Do we enter the ITER negotiations? What terms are acceptable for U.S. participation? What changes should be made in the Fusion Energy Sciences Program if we to decide to move in the direction of a burning plasma experiment? He said, in addition, the United States needs to understand how a burning plasma program will potentially shift the focus and direction of the Fusion Energy Sciences Program and what aspects of the program will need to change.

In response to Dr. Orbach's request, BPAC issued an interim report on December 20, 2002. The committee is in an early stage of its study, so this report addresses only aspects of its first two charges—namely, the importance of a burning plasma experiment for fusion energy and the readiness to undertake a burning plasma experiment—and offers advice on entering ITER negotiations. The report notes that the issues discussed in the letter will be amplified in the course of this study, and that the committee's final report, due in mid 2003, will address the wider elements of the burning plasma issue and its relation to the fusion energy science program.

Overview

BPAC's interim report opens by recalling the conclusion of the BPA's 2001 FUSAC study, *An Assessment of the Department of Energy's Office of Fusion Energy Sciences Program,* which found that "experimental investigation of a burning plasma remains a grand challenge for plasma physics and a necessary step in the development of fusion energy." Reflecting the FUSAC findings, the BPAC report states that during the last decade, by focusing its reduced resources on plasma science, the U.S. fusion community has achieved notable advances in understanding and predicting plasma performance—particularly in the field of plasma theory and experimental work on small and intermediate physics experiments. These advances are documented in detail in the FUSAC report, which noted the "remarkable strides" in fusion science research. Of particular note is progress in fundamental understanding of the complex, turbulent processes that govern the confinement of hot plasmas in magnetic fields. This progress has involved the successful development of large-scale computer simulations, new diagnostic techniques, and quantitative comparisons between theory and experiment. BPAC notes in its report that applications of these models give added confidence to projections for the operation of a burning plasma experiment. There also has been progress in the understanding and control of a new class of large-scale magnetohydrodynamic (MHD) plasma instabilities (known as the neoclassical tearing mode), which have been a significant concern for the burning plasma regime. Progress in predicting, controlling, and mitigating fast plasma terminations has significantly reduced concerns about unacceptable electromechanical stresses in the proposed experiment. The report comments that experiments, both current and planned, and theory are bringing attractive advanced tokamak regimes, with high pressure and self-driven currents, closer to reality and that these may open possible paths to a more economically attractive fusion reactor concept.

Commenting on the readiness to undertake a burning plasma experiment, the committee writes:

> The progress made in fusion science and fusion technology increases confidence in readiness to proceed with the burning

> plasma step. A modest reduction in mission, and incorporation of advanced design elements from the fusion science community have resulted in a more attractive proposal ITER. These changes have reduced the estimated cost of such an experiment and allowed development of advanced tokamak features in the burning plasma regime. The proposed design requires less extrapolation from present experiments, and the operating regime resides safely below established limits in plasma density, pressure, and current, making operational projections much more reliable. However, an additional and important goal of the burning plasma experiment is to explore operational regimes that are not so predictable, where instabilities are expected to arise in the self-heated burning plasma.

The committee also notes that experience with prototype components built as part of the design preparations for the ITER and IGNITOR experiments has increased confidence in the ability to build, assemble, and operate a burning plasma experiment.

In coming to its findings, the committee noted two points of caution. First the fusion community is aging and has long-range demographic problems. New people are required if the nation is to expand its efforts and make the program endure. The committee comments that attracting graduate students and postdocs into the program requires a strong university-based component of the program. Second, the report says "a technology program without a strong science base, or a science program without a strong technology base, will leave the United States in a position where it cannot build effectively on the developments coming from more advanced programs abroad."

The report continues "The United States was arguably the world leader in fusion science and technology two decades ago"—a position recognized by the 1995 fusion report from the President's Committee of Advisors on Science and Technology (PCAST) and the FUSAC report. However, the committee warns that "owing to the subcritical utilization of domestic facilities, the near-elimination of the technology program, and the inability to mount major new experiments building on improved scientific understanding, the U.S. fusion community could be at risk of dropping out of even the 'among the world leaders' group." The report states that the largest and most capable facilities are now outside the United States and many of the critical confidence-building steps that must precede the construction and operation of a burning plasma experiment, particularly the technology steps, have taken place in other countries, including those that are members of the ITER team, albeit with U.S. participation prior to its withdrawal from the program.

In summary, the panel agreed with the conclusions of the recent FESAC and Snowmass studies that the scientific and technical basis to proceed with a burning plasma experiment has been established. Recent theoretical and experimental progress in understanding and controlling tokamak plasmas and progress in developing burning-plasma-relevant technology provide added confidence in proceeding now with such a burning plasma experiment.

Recommendations

The Need for a Burning Plasma Experiment

Having found that there has been significant progress in the readiness to undertake a burning plasma experiment and having discussed in some detail in the report the important scientific questions that are ripe for answering in a such a project, the committee made two recommendations.

The committee noted in the report that there appears to be a clear consensus among those members of the fusion community who participated in the 2002 Snowmass meeting and the subsequent FESAC panel and FESAC committee that the United States "should now seek to join the ITER negotiations." The committee was convinced by presentations at its first two meetings and by consideration of the Snowmass and FESAC reports that it should recommend reentering ITER negotiations. Furthermore, independently of how a future fusion energy development path is envisioned, the report notes that the fusion community has concluded, and the committee agrees, that a burning plasma experiment is necessary and is the next immediate step.

The committee has recommended, therefore, that the United States reenter the ITER process and pursue "an appropriate level of involvement which, at a minimum, would guarantee access to all data from ITER, the right to propose and carry out experiments, and a role in the producing the high-technology components of the facility, consistent with the size of the U.S. contribution to the program."

Programmatic Impact of Engaging in a Burning Plasma Experiment

The BPAC interim report noted Snowmass conclusion No. 6: "A strong base science and technology program is needed to advance essential fusion science and technology and to participate effectively in, and benefit from, the burning plasma effort" (see <http://web.gat.com/snowmass/exec-summary.pdf>) and the FESAC recommendation: "A strong core science and technology program is essential to the success of the burning plasma effort, as well as the overall development of fusion energy" (see <http://www.ofes.fusion.doe.gov/More_HTML/FESAC/Austinfinal.pdf>). Further, the report notes that the 2001 FUSAC report stated: "A fusion research program must investigate a range of confinement approaches" and "…it is the combined progress made in science and engineering that will determine the pace of advancement toward the energy goal."

BPAC has concluded that if the United States joins ITER it will be essential to maintain a strong base-science program. The report says:

> The theoretical understanding of the conditions required for a burning plasma will evolve as new data come in from existing tokamaks and advanced-concept machines and from large scale computer simulations. New, advanced diagnostics will be developed. All of these will be needed to optimize the scientific value of participation in a burning plasma experiment. In addition to supporting the burning plasma experiment, the U.S. fusion program must continue a parallel effort focused on developing the scientific base for attractive fusion reactor concepts. This effort will need to include fundamental plasma science, exploration of innovative confinement concepts, and theory and computation development. The relationship between the core program and the proposed burning plasma program will be addressed in more detail in the committee's final report.

The committee acknowledges in the report that, while there has not been time to examine in detail the estimates it heard for the cost of being an ITER partner, it recognizes that a strategically balanced fusion program must "contain two indispensable components, a strong domestic fusion science program and meaningful U.S. participation in ITER." The committee's report stresses that maintaining such a program will necessitate "a very large increase in the total funding level of the order presented to the committee [by the Office of Science Director]." An expanded fusion program, the committee notes, "would be needed to participate in ITER, maintain the necessary activities in the domestic program, and position the United States to reap the maximum benefits from the scientific and technological progress that will come from both the ITER program and the DOE's Office of Fusion Energy Science's core program."

While the impact of joining ITER has not been considered in detail, the committee reports that it heard that the estimated additional sums are "a significant fraction of the existing fusion energy science program support." The committee notes that to go beyond an ITER-scale machine toward some sort of demonstration project would require additional facilities and that while the committee has not addressed the total DOE burning plasma program and related elements, it will do so in its final report.

In this context, the committee has recommended that "a strategically balanced fusion program, including meaningful U.S. participation in ITER and a strong domestic fusion science program, must be maintained, recognizing that this will eventually require a substantial augmentation in fusion program funding in addition to the direct financial commitment to ITER construction."

Summary

In summary, the Burning Plasma Assessment Committee recommended in its interim report that the United States enter ITER negotiations and that a strategically balanced fusion program, including meaningful U.S. participation in ITER and a strong domestic fusion science program, be maintained.

Furthermore, the committee recommends that in entering the ITER negotiations, the Department of Energy should take several actions:

1. Develop an estimated total cost of full participation in the ITER program, using standard U.S. costing analysis methods and considering the potential full scope. (The committee was pleased to learn that a preliminary review of the construction costs has been delivered to the Department of Energy and believes this is an important first step in understanding the potential costs of the ITER program for the United States.)
2. Analyze several scenarios for U.S. involvement.
3. Assess the impacts of U.S. participation in ITER on the core fusion science program, including opportunities to increase international leverage in the core program as well.
4. Develop other options for a burning plasma experiment in case ITER construction is not approved by the negotiating parties.
5. Establish an independent group of experts to support the U.S. ITER negotiating team on scientific and technical matters.

The letter report was delivered to Dr. Orbach on December 20, 2002, and a decision on whether the United States should enter ITER negotiations is expected from the government soon. Meanwhile, the Burning Plasma Assessment Committee continues its work with a meeting in January, when it will begin to consider the production of its final report, due later in 2003.

For more information on BPAC and its progress, access the BPAC Web site through the BPA Web site at <http://www.national-academies.org/bpa> or send email to burningplasma@nas.edu. ■

BPA Meeting
(continued from page 3)

co-chair it. IPASS will move to DHS once the new department is established. OSTP has been in conversation with NAS, trade associations, universities, etc., to develop the plans, and will retain some oversight role.

At this point the Board asked Dr. Griffin about obtaining visas for visiting scholars or scientific meetings. Dr. Griffin responded by admitting that the system is overworked. It is hoped that the IPASS will streamline the admittance process. Tom O'Neill then suggested that the problem is not to track the students, but to isolate the site of research. The solution might be to establish sites just off campuses.

Following Dr. Griffin's presentation, Shana Dale, OSTP's Chief of Staff, gave a rundown on the "sensitive but not classified" category of information. The emphasis of this category is on threats and vulnerabilities. The administration wants to be able to provide information to nongovernment entities but still have it be protected; that is why it developed the "sensitive" designation. The main area of concern is biological research. The new designation is not intended to affect federal grants.

During the discussion, Burt Richter pointed out that there are two different regimes: classifying existing information and the development of new information. The location of pipelines at a chemical plant is sensitive information, but new research is more problematic. Universities need to get involved, too, and once again the best strategy may be to isolate problematic research in off-campus labs or other secure facilities. Self-policing by the universities, within the new framework set up by OSTP, is necessary. Shana Dale then pointed out that if the universities make mistakes with security, there could be consequences. What the biologists do has a much shorter time-to-market than what physical scientists do. The security problem could develop into a major one for the biology community but will probably be less serious for the physical sciences community. ■

These notes were contributed by BPA staff member Brian Dewhurst.

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**.

New Reports:

Frontiers in High Energy Density Physics: The X-Games of Contemporary Science

Neutrinos and Beyond: New Windows on Nature

Burning Plasma Assessment Committee Letter Report

Board on Physics and Astronomy
The National Academies, 5-922
500 Fifth Street, N.W.
Washington, DC 20001

BPA Newsletter for: