BPA NEWS

Board on Physics and Astronomy • National Research Council • Washington, DC • 202-334-3520 • bpa@nas.edu • June 1998

Elementary-Particle Physics: Revealing the Secrets of Energy and Matter

by Bruce Winstein, Chair, Committee on Elementary-Particle Physics

The Committee on Elementary-Particle Physics was convened by the National Research Council's Board on Physics and Astronomy to assess the field of elementary-particle physics as part of the survey series *Physics in a New Era*. The committee was charged to make recommendations about the role that the United States should play in research in this field in the next two decades. The members of the committee, all active researchers in the field, brought a diversity of perspectives to bear on this study.

In preparing its report, the committee had two main objectives: to describe the current status of elementary-particle physics and the most important research issues within this domain, and to identify the elements of a research program for the next two decades that, given limited resources, represents a wise approach to addressing these issues and maintaining the United States as a leader in the field.

This article is a highly condensed version of the Executive Summary contained in the full report *Elementary-Particle Physics: Revealing the Secrets of Energy and Matter.*

In this issue:

Elementary-Particle Physics: Explaining the Physical World

The remarkable state of our understanding of elementary particles, embodied in the present theory called the "Standard Model," has taken shape over the last 30 years. The Standard Model provides an organizing framework for the known elementary particles. These consist of "matter particles," which are grouped into "families," and "force particles." The first family includes the electron, two kinds of quarks (called "up" and "down"), and a neutrino, a particle released when atomic nuclei undergo radioactive decay. There are two more families consisting of progressively heavier pairs of quarks and a corresponding lepton and neutrino. All normal, tangible matter is made up only of particles from the first family, since the others live for very short times. Why are there three families? This question is one of the great unsolved mysteries of elementary-particle physics.

The matter particles exert forces on one another that are understood as resulting from the exchange of the force-carrying particles. Electric and magnetic forces arise when particles exchange photons (the familiar repulsion or attraction of two magnets results from one of them emitting photons that the other receives). The strong force that holds quarks together to form protons and neutrons comes from the exchange of gluons. The weak forces that cause radioactive decay are created by massive *W* and *Z* particles (the photon and gluon have no mass). These three forces have been successfully described by quantum theories that have remarkably similar structures.

Yet crucial questions remain unanswered by the Standard Model. For

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Harnessing Light: Optical Science and Engineering for the 21st Century

Report of the Committee on Optical Science and Engineering Released at CLEO Conference

Report Predicts Optics Revolution

SAN FRANCISCO, CALIF. — A new report by a committee of the National Research Council has predicted that harnessing the properties of light will lead to a technology revolution having a pervasive impact on life in the next century.

This dramatic vision, and recommendations to help the nation's research community maximize the potential of optical science and engineering, was to be previewed here today (May 6) by Charles V. Shank, director of the Department of Energy's Lawrence Berkeley National Laboratory, at the Conference on Lasers and Electro-Optics and the International Quantum Electronics Conference (CLEO/IQEC).

Shank was chair of the Research Council's Committee on Optical Science and Engineering, a distinguished group of academic and industry leaders which spent three years undertaking a comprehensive assessment of the field of optics—its progress over the last decade, its vision of the future, and its technological opportunities. The result, *Harnessing Light: Optical Science and Engineering for the 21st Century*, will be available (in a full-color summary) from National Academy Press in mid-May; the complete report will be available in June.

Shank, in summarizing the report's conclusions, described optics as a critical enabler for technology that promises to revolutionize the fields of communications, medicine, energy efficiency, defense,

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

Elementary-Particle Physics (cont.)

example, the masses of elementary particles can be established by measurement, but they appear to be arbitrary. There is not a set of rules that allows these masses to be calculated or that explains why the up quark is a bit lighter than the down quark. However, the consequences of these values are profound. Were it the other way around, creation of the heavier elements in the interior of stars—elements essential for the existence of planets and life—would have been dramatically different, leading to a far duller universe.

Key Research Opportunities

Recent advances in technology, experimental techniques, and theoretical understanding mean that over the next two decades, it will be possible to investigate some of the most compelling issues in particle physics. Questions that once seemed beyond the scope of science now lie within the reach of experiment, and it will be possible to achieve a deeper understanding, not only of elementary particles, but also of the earliest moments in the history of the universe.

Determining What Gives Elementary Particles Their Mass

One especially important opportunity is to understand what determines the observed—and very disparate—masses of both the force particles and the matter particles. The Standard Model of particle physics invokes a very special kind of particle, called the Higgs (after the theorist who suggested it). Higgs particles (there may be one or more kinds) are unlike any other particles. Their effects are ever present, even in the vacuum; they give all matter particles their mass and account for the large mass of the carriers of the weak force and the masslessness of the carrier of the closely related electromagnetic force. (Physicists refer to this important asymmetry as electroweak symmetry breaking.) Other possible explanations involve new, very strong forces.

Only experiments at higher energies than those to which experimenters now have access will conclusively determine which, if any, of these theories is actually realized in nature. One thing is certain: The creation of mass involves some completely new physics that must show up in experiments at sufficiently high energy. There are very compelling theoretical arguments guaranteeing that this physics will be uncovered by the next generation of experiments.

Supersymmetry and Strings

A long-standing goal of science has been to find the simplicity underlying the wide diversity in nature. Two examples of such achievements in basic physics were the realization that sound and heat could be understood in terms of the motion of atoms, and Maxwell's synthesis of electricity, magnetism, and light, in terms of the electromagnetic field. These unifications of seemingly disparate phenomena resulted in a far deeper, far more useful understanding.

Theories have recently been developed that link elementary particles, the very smallest known structures, with one of the grandest questions of all: How did the universe begin? These theories suggest that many of the complexities manifest at lower energies would be greatly simplified under conditions of extremely high energy. For example, under such conditions the different forces between the particles would be seen as unified, different manifestations of a single underlying force. There is nothing artificial about these energies—they are understood to have prevailed at the time of the "big bang" that initiated the expansion of the universe. If these theories are correct, the simplicity long sought by particle physicists is a fact of cosmic history.

Although recreating these energies lies beyond the reach of existing and planned accelerators, experiments at these accelerators could nonetheless reveal evidence for what is called supersymmetry. Supersymmetry, which is really a very profound statement about the structure of space and time, predicts that for every fundamental particle there should exist another related and as yet undiscovered new particle; conclusive evidence for these additional particles is eagerly sought because supersymmetry shows how the electroweak and strong interactions could be unified.

In addition, evidence of supersymmetry would support another even more comprehensive theory, called string theory. Traditionally, elementary particles have been modeled as points that take up no space at all. This approach leads to some theoretical problems because two particles could (in principle) get extremely close and exert arbitrarily large forces on each other. String theory solves this problem by picturing particles as extremely tiny vibrating loops, with the details of their vibrations determining their properties and interactions. This simple idea, with the aid of recent theoretical developments, leads to a theory that is able to encompass *all* of the forces of nature in a unified and self-consistent manner, including—for the first time—gravity.

Role of Antimatter in the Universe

Deep mysteries are connected with the way particles from different families transform into one another. For example, a tiny but startling asymmetry in the behavior of matter and antimatter has been found in certain particle interactions. These particle decays violate what is called CP or time-reversal symmetry. This curious phenomenon is crucial to knowing how matter came to predominate in the universe because without it, there would be no stable chunks of matter in the form of stars, planets, and ultimately, human beings to wonder at it all. However, there is as yet no fundamental understanding of this important asymmetry. Experiments in the coming decade are poised to increase greatly our knowledge in this area.

Of course, new understanding does not always proceed along a direct path from prediction to discovery. The history of particle physics is full of unexpected experimental results, which have lighted the way to more useful and complete models. Historically, such important surprises have been most probable when experiments are conducted at previously inaccessible energies.

Recommendations for U.S. Elementary-Particle Physics

The committee has developed its recommendations with two goals: (1) to exploit the great opportunities for discovery that lie ahead and (2) to maintain U.S. leadership in the field of elementary-particle physics. These goals require a diverse but focused program.

We are poised on the threshold of a new energy frontier, where discoveries are certain to be made and new phenomena are likely to be revealed. This is the TeV mass scale, where both well-established theory and revolutionary ideas predict new physics. First, the remarkable success of the Standard Model ensures that the secret of electroweak symmetry breaking will be revealed at this scale. Second, the exciting idea of supersymmetry, which offers the hope of great insights into unification of all the forces of nature, predicts that a rich array of new particles can be produced. Finally, we will obtain the first glimpse of physics well above the typical mass scale of the Standard Model. In the past, when such a large step has been taken, dramatic experimental surprises have occurred. One might expect that similar revolutionary discoveries will be made at the TeV mass scale.

The committee therefore believes that the highest priority is full involvement in TeV mass scale physics at large facilities uniquely suited to this purpose. This involvement includes exploiting the Fermilab Collider (presently the highest-energy facility extant); strong participation in construction of and research at the Large Hadron Collider (LHC) being built in Europe; and taking a leadership role in a future forefront international facility, possibly to be built in the United States. This path has historically provided the most fruitful avenue for uncovering new phenomena.

Other problems of great importance to the understanding of elementary particles do not require the highest energies for elucidation. One is understanding rare quark and lepton transitions. Another is the nature of CP violation—a phenomenon that bears on the apparent dominance of matter over antimatter in the universe. There are additional astrophysical questions of great importance that can likely be explained by particle physics dynamics, the most important being the nature of dark matter. A number of the most important

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Elementary-Particle Physics (cont.)

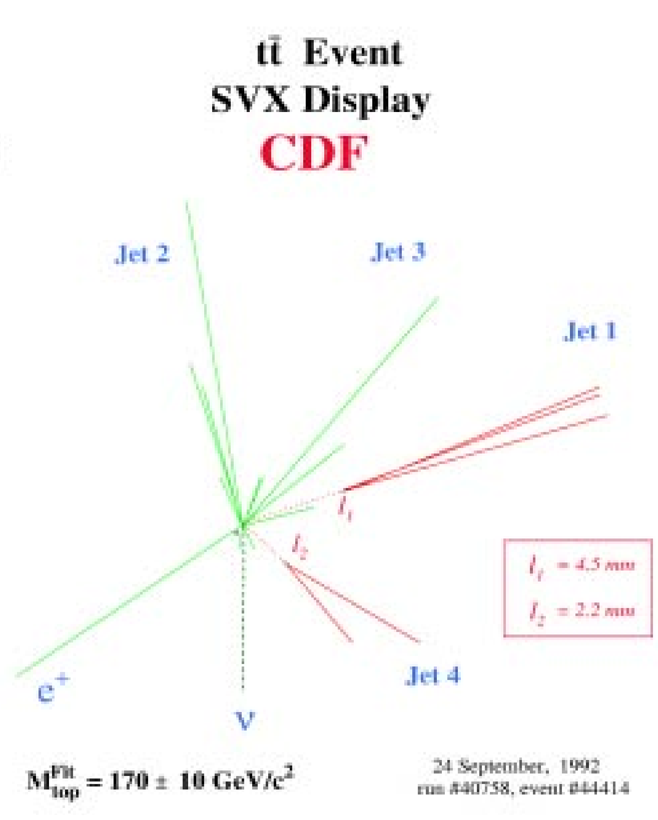
findings in the field in the past two decades have been made by experiments studying problems such as these, and facilities presently being upgraded or under construction will allow such studies to continue. The committee believes it is crucial to support a well-targeted program in these areas. Given the limited resources that will be available, however, maintaining a proper balance between such efforts and those at the energy frontier will require difficult choices and keen foresight.

The committee's recommendations are therefore grouped into two classes: first, those relevant to the energy frontier, and second, one concerning important studies that are best done elsewhere. Both are essential to a balanced program.

Before presenting its recommendations concerning experimental initiatives, the committee comments on two subdisciplines of the field that are critical elements of a forefront program: non-facility-specific advanced accelerator R&D, which can lead to extension of the energy frontier, and theoretical physics, which provides the framework that organizes our observations.

Advances in elementary-particle physics have historically been tied to advances in accelerator technology. Accelerator research and development is of two general types—efforts targeted at the design and construction of specific facilities and more generic (and forward-looking) R&D targeting completely new methods of acceleration that will be required to support energy frontier facilities decades from now, should the physics demand it. This report contains specific recommendations with regard to the former. It is necessary to maintain an appropriate level of investigation in the latter area to secure the longer-term future of the field.

Theoretical work in elementary-particle physics provides the intellectual foundation that motivates and interconnects much of experimental research. The more formal areas of theoretical physics, especially string theory, hold the promise of providing a picture of the universe that accounts for an extremely broad range of observations and phenomena. The committee believes that a healthy level of activity both in formal areas and in the more phenomenological investigations that touch directly on experiments now and in the coming decade should be maintained.



Top quark event from the CDF experiment operating at the Tevatron collider. (Courtesy of the CDF collaboration at Fermilab.)

1. Recommendations Concerning the High-Energy Frontier

At the present time, the Tevatron at Fermilab and the Large Electron-Positron collider (LEP II) in Geneva are the only machines operating at the energy frontier. In two years, LEP II will be dismantled, leaving the Tevatron alone at this frontier until completion of the LHC in the middle of the next decade. The LHC will dramatically extend the energy reach, pushing beyond the TeV scale, where we know that the physics of electroweak symmetry breaking must appear. However, this report concludes that in the future, another collider will be required to complement or extend the range of the LHC and to explore fully the physics of the TeV scale. These considerations motivate a chronological structure for the committee's recommendations concerning the high-energy frontier.

1.a. The United States should capitalize on the potential of the Fermilab Collider Facility while it has unique capabilities for investigations of high mass scale physics.

1.b. The committee enthusiastically endorses U.S. participation in the Large Hadron Collider project as a vital and essential component of the U.S. experimental particle physics program.

1.c. The Next Generation of Accelerators

As this report emphasizes, the committee anticipates that major discoveries will be made at the LHC. These will almost certainly point toward new phenomena that physicists will want to explore using an appropriate new collider.

Three types of machines have been discussed by the physics community: electron-positron linear colliders, muon colliders, and very large hadron colliders. Each has its unique capabilities and challenges, and each is at a different stage of development. Only the linear collider is far enough along to proceed to a conceptual design, with the engineering details and cost and schedule information appropriate to this stage. The other two options are sufficiently promising that increased research efforts are called for to make more realistic preliminary designs. These steps will put the community in the position to make a decision in the future about starting a new collider construction project with the best information possible.

A collider that complements or extends the reach of the LHC will require multiyear and multinational cooperation because of the magnitude of the resources needed. If the United States is to maintain a leadership role in this enterprise, it must participate both in accelerator technology development and in international decisions on the choice of technology and the location of the next facility. Although it is highly desirable to have a forefront facility located within the United States, it is crucial that the United States maintain a technological base sufficient to allow full participation in all aspects of the design, construction, and operation of such a facility, independent of its ultimate location.

Recognizing that it is too soon to endorse construction of any new machines, the committee makes recommendations concerning the development of each.

1.c.1. Recommendation on Electron Colliders

The committee recommends support of an international effort leading toward a complete design and cost estimate of an electron linear collider that would be able ultimately to reach a center-of-mass energy of 1.5 TeV and a luminosity of 10^{34} cm^{-2} s^{-1}.

1.c.2. Recommendation on Muon and Hadron Colliders

R&D targeted at developing the technologies for muon and very large hadron colliders should be vigorously pursued.

2. Recommendation for Addressing Important Fundamental Physics Problems Below the TeV Mass Scale

The committee recommends strong support for a well-targeted program to study the fundamental particle physics that can best be explored with experiments below the TeV scale.

In its first recommendation, the committee has emphasized the range of important physics questions that are addressed at the TeV scale. It is important to recognize, however, that a number of outstanding fundamental questions can best be studied using other techniques. Foremost among these are the understanding of quark and lepton flavor mixing and of particle-antiparticle asymmetry (CP violation). There are also astrophysical questions of importance to particle physics, such as the nature of dark matter.

Conclusion

The recommendations above, if adopted, should maintain U.S. leadership in the field of elementary-particle physics well into the next century. They will allow our scientists to participate in what are likely to be profound and exciting discoveries, discoveries of a nature not seen before.

The report, *Elementary-Particle Physics: Revealing the Secrets of Energy and Matter,* is available from the National Academy Press, 800-624-6242. The report may be accessed on the web from the "Reports" section of the BPA website at www.nas.edu/bpa. ■

Harnessing Light (from Page 1)

manufacturing, and the frontiers of science into the next century. Since the development of the first laser in 1960, optics has impacted the global economy in countless ways, in fiber-optic communications, manufacturing, and imaging.

"There are about 5,000 optics-related companies with a financial impact of more than $50 billion annually," he said. "But that number is insignificant compared to what optics has spawned as an enabler. An investment of a few hundred million dollars in optical-fiber technology has leveraged a trillion-dollar worldwide communications revolution."

And that is only the beginning. The report envisions major advances in telecommunications, in disease diagnosis and therapy, in electric lighting efficiency, in semiconductor manufacturing, and in defense surveillance and guidance systems, to name a few.

These developments will change the world in ways that are hard to imagine, Shank said, but to realize the vision will take a reordering of research priorities, more coordination among agencies and industries engaged in optical science, and federal leadership in focusing efforts of the research community.

"Optics is an extraordinarily strong and dynamic field," Shank said. "In a few important areas, however, action is needed to overcome barriers that might slow the present pace of rapid progress—to break down the barriers to individual home access to high-speed fiber-optic communications, for example, or to take full advantage of the potential of non-invasive optical methods for medical monitoring and diagnosis."

Some of the key areas identified by the COSE report for particular focus of optics research in the coming years are:

• **Information technology and telecommunications:** Around the world, optical fiber is being installed at a rate of 1,000 meters every second, comparable to the speed of a Mach 2 aircraft. By the year 2005, about 600,000 kilometers of fiber optic cable will cross the oceans, enough to encircle the Earth 15 times. It will eventually be feasible to extend these networks all the way to the end-user in individual homes, resulting in high-speed data and video transmission more ubiquitous than the telephone. But many research and manufacturing capabilities will have to advance a hundred-fold to achieve this vision.

The report recommends that Congress "challenge industry and the federal regulatory agencies to ensure the rapid development and deployment of a broadband fiber-to-the-home information infrastructure."

• **Health care and the life sciences:** Building on present capabilities for laser surgery and noninvasive diagnostic methods, optics can help realize the potential for laboratory and clinical health care methodologies. In the future, for example, people could have personal health monitors that can evaluate the optical properties of their blood and tissue. But, according to the report, fundamental science that would lead to such innovations is presently incomplete, and the disease-oriented structure of the National Institutes of Health (NIH) "does not encourage the growth of biomedical optical technology programs."

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BPA Washington Meeting Highlights Facilities

The Board on Physics and Astronomy held its Spring meeting in Washington, D.C., on April 24 and 25.

Facilities

Facilities were the focus of the first day of discussions. In keeping with BPA tradition, the subject was addressed from two perspectives—policy and science. Speakers on policy issues included Ernie Moniz of the Department of Energy, Artie Bienenstock of the Office of Science and Technology Policy, Z.X. Shen of Stanford, and Robert Eisenstein of the National Science Foundation. David Moncton of the Advanced Photon Source (APS) spoke on the new science capabilities of the APS. This article covers primarily the science discussion.

Moniz was recently appointed Under Secretary of Energy with responsibilities in the areas of energy research, defense programs, environmental management, and civilian radioactive waste management. He discussed the Presidential Investment funds and their potential impact on research. Bienenstock addressed general facilities policy issues. Shen reviewed the results of the Birgeneau panel that was commissioned by DOE's Basic Energy Sciences Advisory Committee to evaluate the various DOE synchrotron facilities. Bob Eisenstein discussed the increasing involvement of the National Science Foundation in facilities both for materials research and astronomy and gravitational physics.

Moncton began his talk by reviewing progress in developing accelerators with sufficient stability to be effective sources of synchrotron light. The success of the APS is based on 25 years of experience in progressive development of more powerful sources of synchrotron radiation. One of the early sources was the Stanford Synchrotron Radiation Laboratory (SSRL), which began its operation in a parasitic mode dependent on sharing a storage ring with the Stanford Linear Accelerator Center. SSRL pioneered both the concept of facilities oriented to outside users and the development of insertion devices called "wigglers," which use strong magnetic fields to wiggle the particle beam, generating more powerful synchrotron radiation with a wider overall spectrum.

The National Synchrotron Light Source was the first national x-ray facility constructed specifically as a dedicated source of synchrotron radiation and the first to use the Chasman-Green storage-ring magnet lattice that produces a stable, low-emittance beam, yielding a very bright source.

The APS has built on these technical developments and has pursued a policy of making the facility as user-friendly as possible to researchers with little familiarity with accelerators and their operation. The APS was particularly designed to use insertion devices known as undulators to generate x rays. Undulator magnets have about 100 poles in them, and they generate kilowatt beams of x rays with very high spectral brilliance exceeding that of simple bending magnets by 4 or 5 orders of magnitude. The magnet gaps are adjustable, which allows tuning of the output spectrum. Even the very high harmonics produce useful intensities, so that x rays up to several hundred kilovolts can be obtained. The monochromaticity of undulators is an advantage, avoiding generation of radiation that is not used, as most experiments require a narrow spectrum.

There will be 70 beam lines at the APS, access to which is assigned (in pairs) by a peer-review process. User groups must make a case for their unique need for very-high-brilliance undulator radiation. At the APS users are organized into "Collaborative Access Teams" (CATs). CATs can consist of any group or collaboration. There are presently 14 such groups, representing 150 institutions and around 1000 investigators. CATs have invested $150 million to build 40 beam lines. Studies under way span physics, biology, polymer chemistry, geoscience, and other fields. APS has made an investment in beam-line front ends of another $50 million, which includes the cost of undulators. The total investment in beam lines is thus $200 million. Because of the heavy investment in beam lines, nearly 60 percent of the facility was occupied by users at the beginning of operations. This large, early user presence has also enabled much individual access because 25 percent of each CAT's beam time is provided to independent investigators.

Convincing biologists to use undulators in their experiments has been a major challenge. In what is called a multiwavelength anomalous dispersion experiment, which is now the preferred method for establishing protein crystal structure, it is necessary to scan the x-ray energy across the selenium edge. To do that, it is necessary to change the gap of the undulator, and the beam has to remain stable while the gap is changed. Ordinarily, biologists have preferred wigglers because of their smooth spectrum. It was a challenge to be able to made tunable undulators (with their highly peaked spectrum) with enough stability to meet the needs of biologists.

Among the 150 institutions involved in CATs are about 30 industries, including a consortium of 12 major pharmaceutical companies that comprise the Macromolecular Crystallography Association. Chemical companies are also important participants in APS CATs.

X rays are historically best known for their ability to extract spatial information about the structure of materials. There are two principal experimental methods: imaging techniques and diffraction. These two techniques cover a spatial scale from about 1 mm down to the atomic size range. But there has been a gap in the spatial scale centering around a micron, which is a critical size scale, for example, for biology. This is the size scale in which substantial amounts of information can be stored in molecular patterns. With the progressive refinement of technology, it has gradually become possible to close the gap between imaging and diffraction techniques so that it is now possible to reach this range with both approaches.

Bragg diffraction spots can be separated out in great detail with very intense beams, which allows subangstrom resolution on the spatial scale. Enough data can be accumulated to decode the structures of a very complex biological molecule in about 15 minutes on the APS. That represents a qualitative change in structural biology. Thousands of structures can be obtained in a single year on a beam line.

On the imaging side, Fresnel zone plates developed at the APS focus x-ray beams to spots less than a micron in size. In the last few weeks, APS zone plates focused to less than 150 nanometers. These plates are 35 percent efficient optically. That makes a very bright spot and enables new techniques. For example, fluctuation spectroscopy is possible with such a small and intense spot of light. Autocorrelation functions can be measured. Another application of this microfocus capability is to use it as a microscope, getting spatial information on the distribution of trace elements. Another example is provided by the uptake of manganese by plant structures. Submicron spatial resolution can be achieved at sub-parts-per-million sensitivity to that particular ion. This capability enables detection of just a few thousand atoms.

Another method is more like a conventional radiograph. This relatively simple technique employs a small modification whereby a crystal collimates the transmitted radiation. This setup eliminates small-angle scattering that blurs the image in conventional radiographs. Heart tissue has fine structure from muscle-cell striations, and, in the usual radiograph, the image is blurred by the large amount of small-angle scattering caused by the fine spatial structure. But heart tissue stands out dramatically with the new technique. This technique also shows promise for mammography as it reveals substantially more detail.

Conclusion of the Meeting

The second day of the BPA meeting was devoted to reviewing studies in progress and program initiation efforts. Plans for studies of physics education and computational physics are going forward. The congressionally-mandated study of the impact of selling the helium reserve has started under the leadership of John Reppy and Ray Beebe. The cochairs of the new survey of astronomy and astrophysics, Joseph Taylor and Christopher McKee, discussed their plans for forming a committee and getting the study under way. John Bahcall, chair of the previous astronomy survey that was completed in 1991, described his very successful study and the elements that made it effective. ■

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The report suggests mechanisms to encourage increased public and private investment in the development of non-invasive optical monitoring of basic body chemistries, as well as a stronger focus in this area by the NIH.

• **Optical sensing, lighting, and energy:** Lighting accounts for almost 20 percent of total annual electricity use. New lamps and light sources could reduce consumer electricity bills in the United States by tens of billions of dollars a year, according to the report. These lighting efficiencies can reduce greenhouse gas emissions and, along with advanced solar cells, reduce the energy it takes to illuminate the world.

The committee recommends that various public and private agencies coordinate efforts to create a single program for lighting efficiency, with the goal of reducing America's consumption of electricity for lighting by a factor of two over the next decade, thus saving $10 billion to $20 billion a year in energy costs.

• **National defense:** Optics continue to play an indispensable role in defense programs and promise even greater capabilities in the areas of weapons targeting and detection of biological and chemical warfare agents. The report suggests that the Department of Defense needs to make a greater investment in research areas of photonics, sensors, and high-powered tunable lasers to gain maximum defense competitive advantage, and in low-cost manufacturing of precision components.

The report recommends a larger effort in the development of ultraprecise optical lithography in industrial manufacturing, possibly through a government-led consortium. It also urges that the National Institute of Standards and Technology become a leader in the development of international optics standards.

The committee encourages multiple agencies to support optics as a cross-cutting initiative, similar to recent efforts in high-performance computing. And it recommends that the National Science Foundation develop an agency-wide initiative to support multidisciplinary research and education in optics.

"We expect the field of optics to become a discipline," the report concludes, "as computer science has over the past few decades, and to become recognized as such in educational institutions around the world."

The study was funded by the Department of Defense, the National Science Foundation, and the National Institute of Standards and Technology. The National Research Council is the principal operating agency of the National Academy of Sciences and the National Academy of Engineering. It is a private, nonprofit institution that provides science advice under a Congressional charter. The study was overseen by the NRC's Board on Physics and Astronomy and the National Materials Advisory Board.

Other members of the committee include Aram Mooradian, Vice Chair; David Attwood, Lawrence Berkeley National Laboratory; Gary Bjorklund, Optical Networks, Inc.; Robert Byer, Stanford; Michael Campbell, Lawrence Livermore National Laboratory; Steven Chu, Stanford; Thomas Deutsch, Massachusetts General Hospital; Elsa Garmire, Dartmouth; Alastair Glass, Lucent Technologies; John Greivenkamp, University of Arizona; and Arthur Guenther, Sandia National Laboratories; Thomas S. Hartwick, TRW (retired); Robin Hochstrasser, University of Pennsylvania; Erich Ippen, MIT; Kristina Johnson, University of Colorado; Dennis Killinger, University of South Florida; Herwig Kogelnik, Lucent Technologies; Robert Shannon, University of Arizona; Glenn T. Sincerbox, University of Arizona; Brian Thompson, University of Rochester; and Eli Yablonovitch, UCLA. Thomas Baer, Biometric Imaging Systems, was a special consultant. The National Research Council staff, headed by Don Shapero, director of the Board on Physics and Astronomy, included Robert Schafrik, Dan Morgan, and Sandra Hyland.

Harnessing Light: Optical Science and Engineering for the 21st Century can be ordered through the National Academy Press, 2101 Constitution Avenue, NW, Lockbox 285, Washington, D.C. 20055, or by calling 800-624-6242. ■

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New Reports:

•*Elementary-Particle Physics: Revealing the Secrets of Energy and Matter.* Available from the BPA and on the BPA website (listed above).

•*Harnessing Light: Optical Science and Engineering for the 21st Century*