BPA NEWS

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Condensed-Matter and Materials Physics

by Venkatesh Narayanamurti, Chair, Committee on Condensed-Matter and Materials Physics

I chair the Committee on Condensed-Matter and Materials Physics (CCMMP), which was commissioned by the Board on Physics and Astronomy to prepare a volume on this field for the survey *Physics in a New Era*. Our Committee recently completed its report, and this article is based on its executive summary.

In addition to myself, membership of the Committee included James B. Roberto, Gabriel Aeppli, Arthur Bienenstock (who left the Committee to take up the position of Associate Director for Science at the Office of Science and Technology Policy), J. Murray Gibson, Steven Girvin, Mark Ketchen, Edward Kramer, James S. Langer, Cherry A. Murray, V. Adrian Parsegian, Paul S. Peercy, Julia M. Phillips, Robert C. Richardson, Frans Spaepen, and Katepalli R. Sreenivasan.

The CCMMP has already published a pamphlet that describes some of the forefront areas of the field in language accessible to a broad audience. The pamphlet, entitled *The Physics of Materials: How Science Improves our Lives*, is based on a workshop that the Committee held in July, 1996. Copies are available from the BPA office (bpa@nas.edu) and the report can be found on the web at www.nap.edu/readingroom/books/physics/.

The full report of the Committee contains recommendations aimed at continuing progress in the field. To be published early next year, the report will be the centerpiece of the Solid State Sciences Committee Forum that will be held on February 16-17 in Washington DC. [*See the following article.*]

Condensed matter and materials physics (CMMP) plays a central role in many of the scientific and technological advances that have changed our lives so dramatically in the last fifty years. CMMP gave birth to the transistor, the integrated circuit, the laser, and low-loss optical fibers so important to the modern computer and communication industries. The years ahead promise equally dramatic advances, making this an era of great scientific excitement for research in the field. Communicating this excitement and ensuring further progress are the main goals of the CMMP report.

Over the decade since the last major assessment of the field, important results and discoveries have come rapidly and often in unexpected ways. These advances range from development of new experimental tools for atomic-scale manipulation and visualization, to creation of new synthetic materials (such as bucky balls and high-temperature superconductors), to discovery of new physical phenomena such as giant magnetoresistance and the fractional quantum Hall effect.

An enormous increase in computing power has yielded qualitative changes in visualization and simulation of complex

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In this issue:

Solid State Sciences Committee Plans Forum

SSSC Forum to Feature Condensed-Matter and Materials Report at February, 1999 Gathering

EVERY few years the Solid State Sciences Committee holds a forum in Washington for discussion and information exchange among researchers and policy makers. Forum participants include leaders from academia, industry, government laboratories, federal agencies, and the Congress. The 1999 Forum, to be held February 16–17 at the National Academy of Sciences in Washington, will be entitled *Materials in a New Era.*

A member of Congress has been invited to present the keynote address in the opening session. In the first session, agency leaders such as Martha Krebs, Director of the newly-renamed DOE Office of Science, will discuss the R&D outlook from the point of view of the federal agencies.

The main focus of the forum will be the recently-completed report of the Committee on Condensed-Matter and Materials Physics. CCMMP Chair Venkatesh Narayanamurti will give an overview of the report and its conclusions and recommendations in the second session. Also included in this session will be perspectives of industry, universities, and government laboratories.

The third session will address materials education and infrastructure as well as the challenge of providing facilities at all scales.

The final session will provide a vision of the scientific frontier, including an outlook for fullerene research presented by Nobelist Richard Smalley of Rice University.

For more details, see page 4. If you would like to attend, please return the registration form on pages 5-6 of this newsletter as soon as possible. For the latest on plans for the forum, see the SSSC web page, http://www.nas.edu/bpa/sssc.■

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.

Condensed-Matter Physics (cont.)

phenomena in large-scale many-atom systems. Progress in synthesis, visualization, manipulation, and computation will continue to impact many areas of research spanning different length scales from atomic to macroscopic. Strong impact may also be expected in "soft" condensed-matter physics, particularly at the interfaces with biology and chemistry.

The priorities of society are shifting from military security to economic well-being and health. Changing societal priorities, in turn, create shifting demands on CMMP. Among these growing demands are improving public understanding of science, better education of scientists and engineers for today's employment marketplace, and making new contributions to the nation's industrial competitiveness.

The key challenges facing condensed-matter and materials physics are:

•Nurturing the intellectual vitality of the field—particularly the facilitation of the research of individual investigators and small teams in areas that cross disciplinary boundaries.

•Providing the facilities infrastructure for research—for example, creation of laboratory-scale microcharacterization facilities at universities and large-scale facilities at national laboratories.

•Enhancing efforts in research universities to improve integration of CMMP education and research, particularly at the boundaries of disciplines, and to prepare flexible and adaptable physicists for the future.

•Developing new modes of cooperation among universities, colleges, government laboratories and industry to ensure the connectivity of the field with needs of society and to preserve the fertile innovative climate of major industrial laboratories which have played a dominant role in CMMP research.

Research Themes in CMMP

- The quantum mechanics of large, interacting systems.
- The structure and properties of materials at reduced dimensionality.
- Materials with increasing levels of compositional, structural, and functional complexity.
- Nonequilibrium processes and the relationship between molecular and mesoscopic properties.
- Soft condensed matter and the physics of large molecules, including biological structures.
- Controlling electrons and photons in solids on the atomic scale.
- Understanding magnetism and superconductivity.
- Properties of materials under extreme conditions.
- Materials synthesis, processing, and nanofabrication.
- Moving from empiricism toward predictability in the simulation of materials properties and processes.

The different modes of research—benchtop experiments, larger collaborations, and so on—are evolving steadily. The work that is carried on in these varied venues is complex and diverse, and the Committee has paid special attention to describing the forefronts of research in terms of a small number of research themes. These themes, listed in the box at the left, are discussed in some detail in the Overview and reappear in each of the chapters of the report.

One of the themes that has captured the imagination of theorists and experimenters alike is the structure and properties of materials at reduced dimensionality—for example, in planar structures. Large-scale integrated circuits depend on understanding the behavior of semiconductors in such configurations, so the potential for impact is apparent.

A number of actions are required to maintain and enhance the productivity of the field of condensed-matter and materials physics. These actions involve each level of the hierarchy of research modalities *and the interactions among the various levels and the various performers*. The principal recommendations of the Committee are summarized as follows.

•NSF, DOE, and other agencies that support research should continue to nurture the core research that is at the heart of condensed-matter and materials physics. The research themes described in the overview provide a guide to the forefronts of this work.

•The agencies that support and direct research in CMMP should plan for increased investment in modernization of the CMMP research infrastructure at universities and government laboratories.

•The NSF should increase its investment in state-of-the-art instrumentation and fabrication capabilities, including centers for instrumentation R&D, nanofabrication, and materials synthesis and processing at universities. The DOE should strengthen its support for such programs at national laboratories and universities.

•The gap in neutron sources in the United States should be addressed in the short term by upgrading existing neutron scattering facilities and in the longer term by moving forward with the construction of the Spallation Neutron Source.

•Support for operations and upgrades at synchrotron facilities, including research and development on fourth-generation light sources, should be strengthened.

•The broad utilization of synchrotron and neutron facilities across scientific disciplines and sectors should be considered when establishing agency budgets.

•Federal agencies should provide incentives for formation of partnerships among universities and government and industry research laboratories that carry out research in condensed-matter and materials physics.

•Universities should endeavor to enhance their students' understanding of the role of knowledge integration and transfer as well as knowledge creation. In this area, experience is the best teacher.

Action on these issues will allow us to capture the opportunities for intellectual progress and technological impact that continue to emerge in condensed-matter and materials physics. ■

Novel Quantum Phenomena in Condensed-Matter Systems

Steven M. Girvin
Department of Physics
Indiana University

1 Introduction

ONE might imagine that, since condensed matter and materials physics deals with known objects (atoms) interacting via well-defined and well-understood forces (the Coulomb interaction among the charged particles), that there are no surprises and no fundamental intellectual challenges left to be discovered. Nothing could be further from the truth.

Quantum mechanics is a strange business, and the quantum mechanics of large collections of atoms and molecules can be stranger still. It inevitably happens that, when assembling a collection of atoms to form a material, the whole is greater than the sum of the parts in the sense that *emergent phenomena* such as phase transitions (quantum or classical) and spontaneously broken symmetries often appear in large collections of atoms.

For example, a set of widely spaced copper atoms has an energy gap for charge excitations and thus is an insulator. This is because the atoms are largely independent of each other and retain the discrete spectra of isolated atoms. Compressing the atoms into solid copper causes the electrons to "melt" (even at absolute zero) into a new "liquid" phase with no excitation gap and which is an excellent electrical conductor. If the same experiment is carried out with aluminum atoms, very subtle differences in the atomic properties lead not to an ordinary metal, but rather to a superconductor.

The idea of emergent phenomena teaches us that, even though we understand and can relatively easily compute the properties of individual atoms, materials constructed from large collections of atoms will routinely surprise us

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Materials in a New Era

The 1999 Solid State Sciences Committee Forum
Lecture Room
National Academy of Sciences
Washington, DC
February 16-17, 1999

Tuesday, February 16, 1999

Opening Session

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

Session I: Materials and the Federal Role

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

Session II: Materials R&D: The Next Decade

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

Reception

Wednesday, February 17, 1999

Session III: Materials Education and Infrastructure

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

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

The Science of Modern Technology – *Paul Peercy, SEMI/SEMATECH*
Novel Quantum Phenomena – *Steven Girvin, Indiana University*
Nonequilibrium Processes and the Mesoscale – *James S. Langer, University of California at Santa Barbara*
Soft Condensed-Matter and Macromolecular Science – *V. Adrian Parsegian, National Institutes of Health*
The Future of the Fullerenes – *Richard Smalley, Rice University*
Open discussion: Issues and opportunities in CMMP

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1999 Solid State Sciences Committee Forum

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Materials in a New Era

TO REGISTER FOR THE 1999 SSSC FORUM

By *January 15, 1999*, send a filled-out copy of this form to the address below with your early registration fee* of $100 (make your check out to "1999 SSSC Forum") or use the form as a self-mailer, folding it and *sealing it on all three sides* so that your check stays inside.

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National Research Council
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Washington, DC 20418
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*After January 15, the registration fee is $150.

- ❑ My early registration fee of $100 made out to "1999 SSSC Forum" is enclosed.
- ❑ I plan to attend the reception on February 16, 1999, following the first day of the Forum.
- ❑ I plan to take advantage of the block of rooms that has been reserved at the State Plaza Hotel in Washington, DC. To reserve a room, call National Academies Travel at 800-801-6696 and give them the event code 12280. You may also email NAT at natreser@nas.edu. Please copy bpa@nas.edu. You must reserve before January 25 in order to take advantage of this block of rooms.
- ❑ I would like to receive a copy of the *Proceedings of the 1996 Solid State Sciences Committee Forum*, the report of the previous SSSC Forum summarizing the presentations.

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with completely unexpected properties. A prime example of this is one of the biggest surprises of the last decade, high-temperature superconductivity. It is hard to imagine a less likely candidate for a superconductor than an insulating ceramic compound with properties similar to those of a china coffee cup. Yet when chemically doped to introduce charge carriers, these compounds not only superconduct, they do so at record high temperatures.

The characteristic energy scale for individual atoms is 1–10 electron volts (eV). However, as we look on larger length scales at collections of atoms, the characteristic energies become smaller and smaller and the excitations become more and more collective in nature. At low energies the effective elementary degrees of freedom may be collective objects very different from individual electrons and atoms, and their effective interactions may be very different from the original "bare" Coulomb interactions. This is the source of the surprises that emerge.

It is instructive to compare this situation with that in high-energy elementary-particle physics. There we know the effective degrees of freedom and their interactions at low energies—it is the world of atoms around us. The intellectual challenge is to understand degrees of freedom at shorter and shorter length scales and higher and higher energy scales. This is done by constructing high-energy particle accelerators to act as microscopes with ever greater magnification, or by study of extreme conditions in astrophysical systems and the early universe. This is just the reverse of what is done in condensed-matter physics where we strive to understand collective effects at longer and longer length scales. The analog of the particle accelerator is the refrigerator which lowers thermal energy scales and increases the distance over which particles suffer inelastic collisions. The analog of extreme astrophysical conditions is putting a sample in a dilution refrigerator. The intellectual challenge is the same in both fields however: to find correct descriptions of the physics that work over a wide range of scales.

There has been tremendous progress in the last two decades in the discovery and study of a variety of novel quantum phenomena in condensed matter and atomic systems. A few examples include: superfluidity in ^{3}He, high-temperature superconductivity, Bose-Einstein condensation of alkali metals and spin-polarized hydrogen, quantum magnetism and the quantum Hall effect. Electron "wave guides" have been constructed and the quantization of their electrical conductance in units of e^2/h has been observed. It is now also possible to construct mesoscopic metallic grains large enough to be superconducting but small enough that one can observe significant changes in transport properties depending on whether the number of electrons on the grain is even or odd.

2 Superfluidity and Superconductivity

Superfluids and superconductors have the remarkable property of carrying matter or charge currents completely frictionlessly. In helium 4, the atoms undergo Bose-Einstein condensation and become superfluid a few degrees above absolute zero. In a superconductor, pairs of electrons join together to form an effective bosonic degree of freedom. In an ordinary low-temperature superconductor, these Cooper pairs of electrons have a diameter which is much larger than the spacing between the electrons. Hence it is not usually appropriate to view the superconducting phase transition as Bose-Einstein condensation, though it is closely related.

The Nobel Prize in Physics was awarded in 1996 for the discovery of superfluidity in helium 3. This isotope of helium is a fermion and it is Cooper pairs of atoms that (barely manage to) condense at temperatures exceedingly close to absolute zero. Unlike the electrons in an ordinary superconductor which form pairs in a state of zero relative angular momentum, helium-3 atoms pair in a p-wave ($\ell = 1$) angular momentum state. This feature gives superfluid helium 3 many novel properties since the state of the system is determined not just by the complex phase of the condensate wave function, but also by the local orientation of the pair angular-momentum vector.

The exotic pairing state of helium 3 is naturally connected with high-temperature superconductors for two independent reasons. First it has recently been established via several ingenious experiments that the pairing state in high-temperature superconductors is d-wave ($\ell = 2$), rather than the usual $\ell = 0$ (s-wave). Unlike the case of helium 3 however, the direction of the angular momentum is not free to change but is fixed by the underlying lattice. In fact, the d-wave is actually a standing wave with the angular positions of its anti-nodes parallel to the axes of the square copper oxide planes.

One novel feature of d-wave superconductivity is that non-magnetic scattering by disorder and scattering at interfaces can be pair-breaking. This effect has recently come to the fore because of evidence that has been obtained suggesting that certain crystal faces of high T_c materials spontaneously break time-reversal symmetry by nucleating an additional pairing channel (for which surface scattering is not pair-breaking) to form a complex gap function.

The second similarity between the oxides and superfluid helium 3 is that the coherence length (the size of a Cooper pair) is very small, and is comparable to the spacing between the particles (in this case the electrons). This may mean that the superconducting transition bears closer resemblance to Bose-Einstein condensation and certainly means that fluctuation and correlation effects are much more important than in an ordinary superconductor. This is because mean field theory relies for its validity on there being a very large number of particles within the volume occupied by each Cooper pair.

Understanding strong correlation effects is an important challenge both for the superconducting state and the very unusual normal state in these materials. At this point there is no clear understand-

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ing of the mechanism for high temperature superconductivity. (We do not know for example whether the superconductivity occurs because of, or in spite of, antiferromagnetism.) Indeed, it is not unreasonable to ask whether the phrase "*the* mechanism" is even meaningful in this case.

Superfluid helium 3 is a strongly correlated fermi liquid which just barely manages to form Cooper pairs. It is not yet clear how to describe the corresponding strong correlations in high-temperature superconductors. The strange properties of the normal state may mean that the standard theory of fermi liquids can not be used to describe them. If so, a totally new paradigm must be developed. We now have a good general understanding of one-dimensional conductors. The availability of exact or essentially exact solutions in this special case shows us one scenario by which the Landau theory of fermi liquids can fail in strongly-correlated systems. Little success has yet been achieved however in seeking greater understanding of these effects in higher dimensions.

Ideally, it will be possible to develop a simple picture which captures the essential physics and which will allow us to construct new materials with even higher critical temperatures, perhaps even above room temperature. One of the lessons we have learned, however, is that there exist vast families of complex materials containing many atoms per unit cell, whose surprising properties are still extremely difficult to predict *a priori*. This is an especially important challenge for theoreticians in the coming decade.

The small size of Cooper pairs in high-temperature superconductors has the benefit that it (at least naively) increases their tolerance for very strong magnetic fields. However it also may be one of the (many) factors that limits the critical currents in these materials. Despite the technological problems caused by this latter effect and the difficult materials problems, progress is being made toward practical applications of high-T_c materials.

Study of the short coherence length and associated strong fluctuations of the order parameter in high-T_c materials has led to some very interesting and fundamental advances in statistical mechanics. The theoretical ideas that have been developed are of direct relevance to technological problems presented by the strong suppression of the critical current by magnetic fields. High-T_c superconductors are, because of their short coherence length, strongly type II. This means that an applied magnetic field penetrates the sample relatively uniformly inducing a high density of vortex lines.

Application of a current produces a driving force which pushes the vortices sideways, leading to dissipation of energy. Naturally occurring or artificially introduced disorder produces a random pinning potential which tends to resist the motion of the vortices. One of the deep questions about this random statistical mechanical system is the following. In the limit of weak driving force, are the vortices perfectly pinned or not? That is, is the linear response resistivity ever truly zero at any finite temperature? Or to put it more colloquially, "Is a superconductor in a magnetic field really a superconductor?"

For many years it was thought that the answer to this question was no. The rate of vortex "creep" was known to become extremely small at low temperatures but it was believed to be thermally activated giving a resistivity of the form $\rho \sim e^{-\varepsilon/k_B T}$ and hence never vanishing. The physical picture behind this phenomenon is that there is a characteristic energy barrier ε associated with the random pinning which is finite and can be overcome by thermal fluctuations.

In low-temperature superconductors this question, while important in principle, is nearly moot in practice because the barrier ε tends to be large relative to typical thermal energies at T_c and the pinning is thus extremely effective at all temperatures where superconductivity exists. In high-T_c materials, the pinning barrier ε is smaller (another side effect of the short coherence length) and T_c is much larger. Hence magnetic fields induce very large dissipation whose temperature dependence can then be followed over a significant range below the zero-field T_c.

It is now understood that the correct answer to our question is the affirmative. As the temperature is lowered, the highly fluctuating "tangled spaghetti" of vortex lines begins to exhibit collective correlations over a length scale ξ which diverges at a characteristic 'vortex glass' temperature T_g. Associated with this diverging length is a divergence in the effective collective pinning barrier $\varepsilon \sim |T - T_g|^{-\theta}$. Below this temperature the barrier is infinite and can not be overcome by (equilibrium) fluctuations. The linear response resistivity is thus truly zero, not merely small.

There exists a beautiful analogy between the classical statistical mechanics of fluctuating vortex lines and the world lines of quantum bosons moving in space-time. This analogy is quite precise and has proved extremely useful in advancing our understanding of the statistical mechanics of this 'tangled spaghetti.'

Because of the unusual "floppiness" of vortex lines in high-T_c materials (due to the short coherence length, the extremely weak coupling between copper oxide planes along the *c* axis, and the high temperature), random point defects are not very effective at pinning. The pinning efficiency for extended columnar defects is much better. These can be constructed using the linear damage tracks produced by heavy ions from an accelerator. The quantum boson analogy clearly demonstrates the existence of a phase transition in which the vortices can become localized by columnar pins leading to a state with truly zero resistivity in linear response.

3 Summary

High-temperature superconductivity is currently posing great challenges to experimentalists and theorists alike. The 1998 Nobel Prize in physics was awarded for the discovery of another novel quantum phenomenon, the fractional quantum Hall effect. There are now well-understood collective excitations of the coherent quantum electron fluid which have the bizarre feature of carrying fractional charge. More on this phenomenon in the next issue of *BPA News*. ■

Nuclear Physics: The Core of Matter, the Fuel of Stars

John Schiffer, University of Chicago and Argonne National Laboratory

The Committee on Nuclear Physics was commissioned by the Board on Physics and Astronomy to assess the field of nuclear physics as part of the survey *Physics in a New Era*. The committee consists of Sam Austin, Gordon Baym, Thomas Donnelly, Bradley Filippone, Stuart Freedman, Wick Haxton, Walter Henning, Nathan Isgur, Barbara Jacak, Witold Nazarewicz, Vijay Pandharipande, Peter Paul, and Steven Vigdor, and it is chaired by me. The following is the Summary of our report.

Nuclear physics addresses the nature of matter making up 99.9 percent of the mass of our everyday world. It explores the nuclear reactions that fuel the stars, including our Sun, which provides the energy for all life on Earth. The field of nuclear physics encompasses some 3,000 experimental and theoretical researchers who work at universities and national laboratories across the United States, and the experimental facilities and infrastructure that allow these researchers to address the outstanding scientific questions facing us. The CNP report provides an overview of the frontiers of nuclear physics as we enter the next millennium, with special attention to the state of the science in the United States.

The current frontiers of nuclear physics involve fundamental and rapidly evolving issues. One is understanding the structure and behavior of strongly interacting matter in terms of its basic constituents, quarks and gluons, over a wide range of conditions—from normal nuclear matter to the dense cores of neutron stars, and to the Big Bang that signalled the birth of the universe. Another is to describe quantitatively the properties of nuclei, which are at the centers of all atoms in our world, in terms of models derived from the properties of the strong interaction. These properties include the nuclear processes that fuel the stars and produce the chemical elements. A third active frontier addresses fundamental symmetries of nature that manifest themselves in the nuclear processes in the cosmos, such as the behavior of neutrinos from the Sun and cosmic rays, and in low-energy laboratory tests of these symmetries.

With recent developments on the rapidly changing frontiers in nuclear physics, the Committee on Nuclear Physics is greatly optimistic about the next ten years. Important steps have been taken in a program to understand the structure of matter in terms of quarks and gluons. The United States has made two major and far-sighted investments in this program. The Continuous Electron Beam Accelerator Facility (CEBAF) has recently come into operation and is now delivering beams of unprecedented quality. It will serve as the field's primary "microscope" for probing the building blocks of matter such as the nucleons (protons, neutrons) and the nuclei of atoms, at the small length scales where new physics phenomena involving quarks and gluons should first appear. It will provide new insights into the structure of both isolated nucleons and nucleons imbedded in the nuclear medium. The Relativistic Heavy Ion Collider (RHIC), whose construction is now nearing completion, will produce the world's most energetic collisions of heavy nuclei. This facility will allow nuclear physicists to probe the properties of matter at energies and densities similar to those characterizing the cores of neutron stars and the Big Bang. RHIC experiments should teach us about the expected transition to a new phase of nuclear matter in which the quarks and gluons are no longer confined within nucleons and mesons.

The theory supporting these new efforts has produced new bridges between quantum chromodynamics (QCD)—the theory of quarks and gluons—and the field's more traditional models of nuclear structure, which involve nucleons and mesons. Nuclear theorists have begun to construct "effective theories" that are equivalent to QCD at low energies, yet share many of the properties of traditional models that view nuclei as quantum fluids of protons and neutrons. This work is providing the field with new tools for more critically addressing the structure of nuclei and the properties of bulk nuclear matter.

An area that at present is generating intense interest is related to nuclear processes in the cosmos. Experiments measuring neutrinos from the Sun and from cosmic-ray interactions in the Earth's atmosphere strongly suggest that neutrinos are massive, a result that would imply new physics beyond the current "Standard Model" of particle physics. U.S. nuclear physicists, who have worked in the field since initiating the first experiment more than 30 years ago, are currently partners in the Sudbury Neutrino Observatory, the first detector that will distinguish solar neutrinos of different types, or "flavors." Such experiments are part of a larger effort to carefully test the Standard Model at low energies. The nucleus is a powerful laboratory for probing many of the fundamental symmetries of nature, because it can magnify subtle effects that may hide beyond the direct reach of the world's most energetic accelerators.

Another frontier area is the study of how the nucleus changes when subjected to extreme conditions, such as very rapid rotation or severe imbalances between the numbers of neutrons versus protons. Exotic nuclei play essential roles in the evolution of our galaxy: the "parents" of about half of the heavy elements are very neutron-rich nuclei, believed to have been created within the spectacular stellar explosions known as supernovae, at temperatures in excess of a billion degrees. Remarkable advances in accelerator technology have now provided the tools needed to produce such unusual nuclei in the laboratory, opening the door to new experiments on the properties of nuclear matter near the limits of binding.

The recommendations by this committee should be considered in the context of the careful planning in the nuclear physics community summarized by the long-range plans developed by the Nuclear Science Advisory Committee (NSAC). NSAC advises the two principal funding agencies for this field, the

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Department of Energy and the National Science Foundation. The Division of Nuclear Physics of the American Physical Society also played an important role, joining with NSAC to organize various town meetings for the purpose of gathering input from the community. The NSAC long-range plans have been prepared at about 6-year intervals (1979, 1983, 1989, and 1996). They have been influential in expressing new priorities of the field and in justifying new initiatives. The 1979 and 1983 long-range plans, for example, identified CEBAF and RHIC as the most promising new initiatives for decisively advancing the scientific frontiers of the field. The recent adoption of a similar planning process by the European nuclear physics community is an indication of the perceived effectiveness of the long-range plans.

In parallel with CEBAF and the construction of RHIC, the NSAC long range plans have also identified and recommended several smaller targets of opportunity. Among those currently being implemented with agency funding are an upgrade to the capabilities for producing energetic beams of short-lived nuclei at Michigan State University, the construction of new detectors for studying solar neutrinos, and the adaptation of RHIC to the investigation of previously inaccessible aspects of the proton's structure.

Both the Department of Energy and the National Science Foundation support user facilities of world-class capability and both have strong university programs. DOE supports the largest user facilities and university groups, while NSF supports user facilities at universities and many university user groups. The committee believes that the continuing programs in the two agencies are essential to the field, with the DOE emphasis on national laboratory facilities and the NSF emphasis at the universities providing complementary strengths and opportunities.

Because there exists a tradition of successful deliberation and planning within the nuclear physics community, the Committee on Nuclear Physics chose to emphasize the science rather than the process in the recommendations presented below. However, it would be remiss if it failed to bring into focus the funding stresses that now severely threaten the field.

At present it seems to be generally agreed by policymakers on all sides that the support of basic research is in the public interest, and there is considerable talk of increasing the corresponding budgets. However, the reality in nuclear physics, as in many other fields of research, is quite different. In 1996 the budget guidance provided by the DOE and NSF to help formulate the most recent *Long Range Plan* for nuclear physics was for roughly constant manpower budgets. This goal has been undercut by the budgets of recent years. The cumulative result of a dollar-flat budget in the case of the DOE is that it now is 3 to 10 percent below the range of the guidance. In the case of NSF, there has been a larger decline, to about 15 percent below the 1996 guidance.

These decreases will curtail the utilization of new facilities and instrumentation, and jeopardize our nation's world-leading role in the field. This situation has arisen even as the efficient commissioning of CEBAF, the approaching completion of RHIC, new technical advances in the exploration of nuclei near the limits of binding, and discoveries in low-energy neutrino physics have made execution of the 1996 *Long Range Plan* all the more urgent, requiring the level of funding given in the guidance by the agencies.

Recommendation I: Discoveries in nuclear physics—new phenomena connected with the role of quarks and gluons in the nucleus, the structure and dynamics of nuclei, the nuclear physics of the cosmos, and the limits of the Standard Model—are within reach due to our recent investments in new facilities and instrumentation. With CEBAF having started on its research program of the quark-gluon structure of matter, RHIC about to embark on the study of matter at the limits of energy density, and with other recent advances in technical capabilities, a rich scientific harvest is limited by severely constrained budgets. The committee recommends the near-term allocation of resources needed to realize these unique experimental and theoretical opportunities.

Careful laboratory measurements of nuclear reactions that take place in stars have provided the foundation for some of the field's most important achievements in understanding the nuclear bases of the cosmos, including the solar neutrino problem and the origin of the light chemical elements in the Big Bang. Beams of exotic short-lived nuclei are opening up new opportunities for measuring nuclear properties and reactions in the poorly understood regions near the limits of stability. The properties of these barely stable nuclei have direct quantitative connections to the processes that fuel the stars and create the chemical elements of our world. Beams of exotic nuclei hold great promise as tools for probing new nuclear properties and in testing fundamental symmetries at low energies. These considerations provide a compelling argument for constructing a next-generation facility that will use isotope separator online (ISOL) techniques to produce high-intensity, high-resolution beams of short-lived nuclei over a broad mass range.

Recommendation II: The committee recommends the construction of a dedicated, high-intensity accelerator facility to produce beams of short-lived nuclei. Such a facility will open up a new frontier in nuclear structure near the limits of nuclear binding and will strengthen our understanding of nuclear properties relevant to explosive nucleosynthesis and other aspects of the physics governing the cosmos.

Frontier research in nuclear physics relies on both large accelerators, such as CEBAF and RHIC, and smaller facilities, where specialized low-energy measurements can be made. These smaller facilities include several university and national laboratory accelerators where weak interaction, nuclear structure, and nuclear astrophysics studies are done. Both small and large accelerators rely critically on innovative instrumentation to make new discoveries. In the case of

CEBAF and RHIC, the quality of the physics programs depends on specialized detectors. The development of much of this equipment is on a scale that is suitable for university laboratories, where graduate students can participate in the construction and gain experience with cutting-edge technology. Many of the equipment needs at the smaller facilities are equally specialized. Examples include atom and ion traps designed for precision studies of weak interactions and sensitive detector arrays for measuring nuclear reactions at the very low energies characteristic of stars like our Sun.

Recommendation III: The committee recommends continued investment in instrumentation for research. As new discoveries come to light and new ideas for experiments emerge, upgrades of detector systems at CEBAF and RHIC, and instrumentation needs at smaller laboratories should be considered in accordance with their potential for new discoveries. NSAC is well positioned to provide DOE and NSF appropriate advice on relative priorities and specific major upgrades.

To foretell the course of a science beyond the near term is always difficult, as it depends both on the discoveries of the next few years and the doors that new advances in technology will open. The following represents some of the future options, among a number of attractive possibilities that can be perceived at the present time, for possible implementation in the early part of the next century.

CEBAF probes nuclei at length scales where the quark and gluon substructure of nuclei should first become apparent. It thus represents a first step in probing the relationship between standard nuclear physics based on protons, neutrons, and mesons; and the underlying fundamental degrees of freedom—quarks and gluons. To understand the transition between these regimes, it may be necessary to extend the measurements to even finer resolution, such as that offered by a 15- to 30-GeV electron accelerator. The construction of a 25-GeV machine is now under discussion in Europe, and future upgrades of CEBAF are being considered in the United States.

RHIC is about to open a new door to ultra-high energy densities in nuclear matter. The potential discovery there of a new phase of matter—a plasma of quarks and gluons—could point the way to issues requiring still higher beam intensities or energies. Construction of the Large Hadron Collider (LHC) at CERN in Europe has recently begun, with U.S. participation. Early in the next century, this facility will allow collisions of nuclei at 40 times the beam energy of RHIC. Future discoveries at RHIC will guide upgrades of RHIC and the participation of U.S. nuclear physicists in the LHC effort.

The impact of the discovery that neutrinos may have mass will be felt throughout physics. Thus, following the Sudbury Neutrino Observatory (SNO), there may be an urgent need to develop and deploy detectors capable of exploring the spectrum of lower-energy solar neutrinos, or of greatly improving the sensitivity to neutrinos from the next supernova neutrino burst. Terrestrial neutrino experiments have put important constraints on neutrino properties; a compelling case may arise for new terrestrial experiments.

Studies of fundamental symmetries in nuclei can isolate and enhance new phenomena beyond the Standard Model. In particular, new experimental searches for a neutron electric-dipole moment and precision measurements of beta-decay correlation coefficients can become the most stringent constraints on our understanding of fundamental symmetries. Promising possibilities exist for developing sources of cold and ultracold neutrons of unprecedented intensity

Recommendation IV: Within the ten-year time frame envisioned for this report, new discoveries will provide strong arguments for one or more major new endeavors. Possible candidates include a higher-energy electron machine, capability for the study of heavy-ion collisions with increased energy densities, new detectors to explore mass effects on the solar and supernova neutrino fluxes, and an ultracold neutron facility providing an order-of-magnitude increase in the neutron densities for studies of fundamental symmetries. The committee recommends the continuation of frequent NSAC long-range plan efforts to help retain the responsiveness of the field to the most promising new opportunities.

Nuclear physics not only advances the frontiers of knowledge but also makes remarkable contributions to the needs of society. The generation of nuclear energy, both for civilian power consumption and for nuclear weapons, has had a profound impact on our society in the last 50 years. Equally far-reaching has been the impact of nuclear physics in medicine; results of nuclear physics and nuclear physics techniques, from magnetic resonance to detector technologies to the use of isotopes, have led to remarkable advances in diagnostic and therapeutic power. Nuclear diagnostic techniques have a growing and pervasive role in industry, national security, nonproliferation, geophysics, global climate research, and paleontology. Nuclear physics is the basis of important technologies in the design and preparation of materials. Through such applications, through the technical and intellectual intersections of nuclear physics with other fields of science, and through its intrinsic intellectual challenges, nuclear physics stands as one of the core sciences in continuing advancement of knowledge.

Facilities and instrumentation are essential for progress, but science ultimately depends on the people who carry it out—on their individual creativity, drive, and enterprise. The scientists who conduct experiments and develop the theoretical framework for interpreting the results are the most essential components of the field. The continued intellectual vitality of nuclear physics as a science, and the continuation of the field's more direct contributions to societal needs, depend critically on the capacity to educate the next generation of physicists. Past performance has demonstrated that students trained in solving the enormously challenging problems of forefront physics research develop the array of skills needed to lead the nation in harnessing the rapidly advancing technology that often emerges from the research itself. ■

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