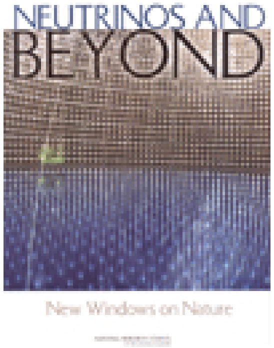
Neutrinos and Beyond: New Windows on Nature



Neutrino Facilities Assessment Committee, National Research Council

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NEUTRINOS AND BEYOND

New Windows on Nature

Neutrino Facilities Assessment Committee
Board on Physics and Astronomy
Division on Engineering and Physical Sciences

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Preface

The President's FY2003 Budget Request for the National Science Foundation (NSF) under the Major Research Equipment and Facilities Construction Account called for a National Research Council (NRC) review of the scientific merits of IceCube and other proposed U.S. neutrino projects in the context of current and proposed capabilities throughout the world. The NRC study request was formalized in a March 29, 2002, memorandum from John Marburger (director, Office of Science and Technology Policy) to Bruce Alberts, president of the National Academy of Sciences (see Appendix A). On April 8, 2002, Dr. Alberts agreed to form an assessment committee to conduct this review.

The NRC committee—the Neutrino Facilities Assessment Committee (NFAC)—was charged with providing scientific assessments of two possible future science initiatives: (1) IceCube, a very large volume detector of high-energy neutrinos proposed for the South Pole and (2) a possible deep underground science facility to be developed in the United States to pursue a broad range of fundamental questions in physics and astronomy. Fourteen persons were appointed to the committee, and the first meeting was held in June 2002, with delivery of the final report expected within 6 months.[1]

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[1] The complete charge to the committee is given in Appendix B. See Appendix C for the committee membership and Appendix D for agendas of the three full committee meetings.

The committee interpreted its charge to be to

- 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; and
- Assess the scientific importance of the identified science and whether it could be addressed by other existing, soon to be completed, or planned facilities.

The committee's assessment was to be performed in the context of current and planned neutrino capabilities throughout the world. Specifically, the study was to address the unique capabilities of each class of new experiment and any possible redundancy between the two types of facility.

The fast-track timeline required a very aggressive schedule and limited the breadth and depth of the committee's analyses. The committee itself assessed the primary science potential of both projects but relied heavily on community input in addressing some of the broader issues in the charge. Although it learned of other interesting potential applications of a deep underground laboratory (e.g., geology, national security, and geobiology), the committee had neither the expertise nor the time to study them in depth. Likewise, evaluation of project issues such as technical readiness, costs, management, and so on was outside its charge, so the committee limited its study to what was needed for a realistic assessment of the science.

Comparing IceCube and a U.S. deep underground facility to other facilities where similar science might be addressed proved a complicated issue. The three possible projects in the Mediterranean Sea with which IceCube can be compared are well behind IceCube in technical development, making a direct comparison difficult. For these potentially competing water detectors, sites have not been selected, and neither the detailed technology nor the configuration of detectors has been determined, pending completion of prototype phases that are now under way. Therefore, the committee was able to compare these projects with IceCube only in a general way, considering, for example, the advantages of ice versus water as a high-energy neutrino detector.

For a deep underground facility, the report discusses a broad array of potential experiments (some to be done in the very long term). Some of these can and certainly will be undertaken elsewhere in the world. However, at this time, the experiments themselves, as well as the programs in the major facilities elsewhere in the world, are yet to be defined. Therefore, the committee focused on determining the requirements for such experiments (e.g., size, depth, distance from accelerator facilities) and what the advantages of a deep underground laboratory in the United States might be for some of the science planned. It could draw only limited conclusions about what will be done elsewhere in the world, activity that will in fact depend to no small extent on what is undertaken in the United States. Considering a deep underground science facility, the committee did not focus on any particular site but, rather, discussed some of the science that would be possible at a generic deep underground laboratory, assuming that it would be operated as a shared-user facility and that proposals for experiments at such a laboratory would be reviewed on a case-by-case basis.

Given the limitations described, the committee sought to identify the major classes of science problems that could be addressed with the general features of the two proposed facilities; to consider the worldwide status of existing, planned, or proposed experiments in these major areas of research; and to critically assess their scientific importance. The committee focused principally on physics experiments and did not assess proposed experiments in other scientific fields, nor did it conduct any cost-benefit analyses or attempt any finite budget prioritization. This decision was influenced by the makeup of the committee, the fact that the physics experiments would be the primary factor in motivating these types of laboratories, and the extreme urgency with which the study was requested. Finally, since both IceCube and deep underground science emphasize physics involving neutrinos, the committee addressed the possible redundancy and complementarity between IceCube and a deep underground laboratory.

The committee held two open meetings and one closed meeting, and it solicited a wide variety of inputs from the science community in the form of letters and presentations to the committee. A Web site was created with information about the committee, its meetings, and the inputs that it received. The NSF-sponsored International Workshop on Neutrinos and Subterranean Science (NeSS2002),[2] held during the study period and attended by more than 300 scientists, produced much valuable information that the committee used in its assessments.

Finally, completing this report in a timely fashion depended on the dedicated work of the committee; numerous members of the scientific community who provided input, advice, and formal briefings; and the commitment of the staff of the Board on Physics and Astronomy, especially Joel Parriott and Timothy Meyer. The overall guidance of Don Shapero was invaluable, and the committee is also indebted to the reviewers, who suggested a number of substantial improvements to the report.

Barry Barish, *Chair*
Neutrino Facilities Assessment Committee

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[2] The NeSS2002 workshop was graciously and expertly organized by the University of Maryland at College Park on behalf of the NSF and held in Washington, D.C., September 19–21, 2002.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

David Arnett, University of Arizona,
Steve Barwick, University of California at Irvine,
Alessandro Bettini, Istituto Nazionale di Fisica Nucleare at Gran Sasso,
Roger Blandford, California Institute of Technology,
Norine Noonan, College of Charleston,
William Press, Los Alamos National Laboratory,
Burton Richter, Stanford University,
Bernard Sadoulet, University of California at Berkeley,
Norman Sleep, Stanford University,
Lawrence Sulak, Boston University, and
George Trilling, University of California at Berkeley.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by John Ahearne (Sigma Xi, The Scientific Research Society) and Jonathan Katz (Washington University in St. Louis). Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Executive Summary

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 would unify 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 within the United States that can house a broad range of important future experiments. This report was commissioned to review and assess the scientific merit of these two proposals (see

Appendixes A and B for the charge and Appendix C for brief biographies of the committee members).

In this report, the science that requires instrumenting a very large volume of ice deep under Earth's surface with photodetectors is assessed. The goal of such 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 therefore give insight into their sources and production mechanisms.

The second class of experiments assessed 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, and 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 onto the unraveling of some of the most fundamental 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 questions in physics and astronomy. Since the committee finds that the scientific goals of an underground laboratory go well beyond neutrino experiments, it has assessed the scientific potential for such a facility in a broader context.

In addition to providing a scientific assessment of IceCube and of a deep underground laboratory, the committee addresses their overlaps and complementarity, as well as how each initiative fits into international plans. Finally, the committee emphasizes 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 National Research Council report *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century* (National Academies Press, Washington, D.C., 2003) identifies 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 bridge traditionally separate disciplines. The recent Department of Energy/National Science Foundation long-range plans for nuclear physics and particle physics also endorse these projects. The DOE/NSF plans find IceCube and a deep underground laboratory to be important projects within the context of the scientific goals and priorities of nuclear and particle physics.

ICECUBE

The IceCube experiment planned for the South Pole will use a cubic kilometer of deep ice instrumented with photodetectors as a gigantic high-energy neutrino detector. 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 at this time they are not as developed as the IceCube concept. Furthermore, the water and ice detectors could 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 Antarctic Muon and Neutrino Detector Array (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 neutrino 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 cubic-kilometer scale of IceCube is sufficient to observe neutrinos from known astrophysical sources. In addition, it is known from AMANDA and other experiments that cosmic-ray interactions with our atmosphere at energies of a trillion electron volts (TeV) and above produce a copious supply of neutrinos; the study of these interactions will be of significant interest for investigating neutrino behavior at these energies. (The absence of such a point-source neutrino signal in IceCube, however, could still be significant as it would restrict 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.

The committee finds 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.

> ***Assessment:*** *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 research and development (R&D), prototyping, and conceptual design phases. When the funding is approved, it will be ready to transition to the construction phase. This 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 suggested the explanation, providing dramatic evidence that neutrinos oscillate from one type to another, in turn implying that neutrinos have nonzero mass. With these discoveries energizing the rapidly growing field of underground physics, and recognizing both the large U.S. commitments being made to underground facilities abroad and the future science opportunities for such facilities, it is now very timely to consider the building of a new deep underground facility in the United States. In fact, the development of a new underground laboratory with characteristics that are well matched to the needs of future experiments could regain for the United States its leadership in this important area of science.

Laboratories deep underground make it possible to study rare forms of penetrating radiation (e.g., neutrinos and dark-matter particles) and rare processes (e.g., double beta decay and proton decay) in a low background environment. 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 4,500 mwe (the equivalent of 4,500 meters of water), with the future possibility of siting experiments down to 6,000 mwe. (Although 4,500 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 interference from background processes.) Second, a facility located at large distances—over 1,000 km—from accelerator facilities capable of producing intense neutrino beams will be essential for the next generation of neutrino oscillation experiments and would represent 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 would be proposed separately, peer reviewed, and then funded for implementation at the laboratory. Every effort should be made to closely integrate the actual development of a new laboratory with the program of experiments that would be performed. A significant advantage of a central facility is the opportunity to share 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 finds that to fully exploit the potential science opportunities, a new underground facility must provide depths great enough 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 would offer another important advantage: the presence of powerful existing accelerators with proven and expandable capabilities for neutrino beam production, necessary for potential long-baseline experiments. A new, deep underground laboratory with this combination of features could fully exploit the science opportunities described in this report.

> ***Assessment:*** *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 an experimental research program. Critical decisions that are beyond the scope of this report remain: choosing between several viable site options, defining the laboratory's scope and the nature of its staff and its management organization, and determining the site infrastructure and the level of resident technical support. Developing sound proposals for experiments will require early access to deep underground facilities to perform the necessary preliminary R&D. Therefore, it is important to complete the process of setting the laboratory's scope and goals, soliciting and reviewing proposals, and building up the necessary infrastructure to allow timely initiation of the experimental research program.

REDUNDANCY AND COMPLEMENTARITY

The exploratory physics envisioned for IceCube and the broad science program enabled by a deep underground laboratory are truly distinct. IceCube would concentrate 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 would focus 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 those of a deep underground laboratory.

On the international scene of present and planned experiments, IceCube is unique in its technology and location (using ice as a detection medium 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 ensures that an additional underground laboratory would contribute substantially to international science efforts. 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.

1

Introduction

Recently, several large projects have been proposed related to the fundamental studies of various aspects of neutrino physics and astrophysics. First, a proposal to build IceCube, a cubic-kilometer-scale, high-energy neutrino detector, was submitted to the National Science Foundation (NSF), reviewed by the National Science Board, and recommended for funding. This project would be built at the South Pole, exploiting the large volumes of clear ice to make an extremely large volume detector for observing the secondary charged particle showers caused by high-energy neutrinos interacting with Earth's mass. Second, three proposals have been recently submitted to develop a deep underground laboratory in the United States that would host a variety of proposed or planned experiments requiring the extremely low background environment provided by the overburden at a deep subterranean location. There has been long-standing interest in the development of such a laboratory in the United States. Recently, various ad hoc committees, long-range planning committees in particle and nuclear physics in the Department of Energy (DOE) and the NSF, and a National Research Council (NRC) panel exploring science opportunities at the interface between physics and astronomy[1] have all endorsed the development of such a facility. Proposed sites

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[1] *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*, National Academies Press, Washington, D.C., 2003.

for a deep underground laboratory have included existing but closed mines, new excavation, and operating mines or repositories. The magnitude and scope of these proposals provide both a significant opportunity and a serious challenge: the breadth of the proposals attests to the substantial excitement for the potential science at these major facilities but demands a careful assessment of this potential in the face of the large long-term costs and responsibilities.

The obvious commonality between the two scientific initiatives included in the charge to the committee, IceCube and a deep underground laboratory, is that both explicitly involve neutrinos and both operate below the surface. A more accurate statement is that both deal with research requiring the detection of extremely rare phenomena. However, although neutrinos (or other rare phenomena) play a prominent role in both initiatives, the origins of the neutrinos, their energy range, and the science IceCube and a deep underground laboratory would address are very different. Furthermore, the two initiatives differ substantially in scope. The IceCube project is a specific, dedicated experiment exploiting the clear ice at the South Pole to construct a cubic-kilometer-scale detector for very high energy neutrinos from space. It addresses a variety of astrophysical problems and potential sources of high-energy neutrinos. In contrast, a deep underground laboratory would provide a general facility with attributes essential for a wide variety of important experiments for detecting neutrinos, rare decays, and extremely weak interactions. At this time, the specific experiments that might be conducted at a particular deep underground laboratory location have not been chosen, but the scientific questions they would address are evident.

Organized largely along the lines suggested by the formal charge to the committee, this report outlines some of the general science common to both initiatives and provides some of the historical and international context for subsequent discussions in this report. Second, it identifies the major science potential of the IceCube project and discusses it in the context of other large-volume neutrino observatories. The report then describes the major science potential of a deep, underground national science laboratory, considering it in the context of ongoing international activities in these research areas. Finally, it presents the committee's conclusions regarding the scientific merit of this research, the unique opportunities and capabilities of these two facilities, and the issue of possible redundancy between the two types of facility.

2

Science Overview: Neutrinos and Beyond

Seventy-two years ago, Wolfgang Pauli, desperate to preserve the principle of energy conservation, postulated the idea of an unseen particle—the neutrino. Enrico Fermi gave the neutrino its name and wrote down the first description of how neutrinos interact with other particles. Because neutrinos are so light and without electric charge, they are almost inert (see Sidebar 2.1, "The Neutrino"). In spite of the fact that trillions of neutrinos go through each of us every second, it took nearly 30 years for Pauli's hypothesis and Fermi's theory to be confirmed. In 1956, Frederick Reines and his team detected neutrinos produced by a powerful nuclear reactor in Savannah River, South Carolina. He was awarded the Nobel Prize in physics for this discovery.

THE NEUTRINO: FROM BACKSTAGE TO CENTER STAGE

The neutrino is now central to elementary particle physics, astrophysics, and cosmology. Neutrinos play a key role in theories that unify the elementary particles and forces. They yield clues about the dark matter holding the universe together, and they are critical in understanding not only how the Sun shines but also how stars exploded to create the majority of the elements in the periodic table. Recent discoveries, however, have created special opportunities to use neutrinos in new ways to advance our knowledge of the universe and the laws that govern it.

Some 15 years after Reines established the existence of the neutrino, Raymond Davis, Jr., opened the neutrino window to the universe by using 100,000 gallons of

SIDEBAR 2.1 THE NEUTRINO

Cosmic Gall

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass

—John Updike[1]

The mysterious neutrino entered the popular culture in John Updike's 1959 poem "Cosmic Gall." He stated neutrinos' two most important and puzzling features—masslessness and elusiveness. Today, we know that neutrinos are almost, but not quite, massless. The interaction between neutrinos and other forms of matter is extremely rare because they interact only through the weak nuclear force: It would take a wall of ordinary matter more than 100 light-years thick to stop a beam of neutrinos like those produced by the Sun. Precisely because they are so elusive, neutrinos produced at the center of the Sun traverse the entire mass of the Sun without being absorbed, allowing us to see deep into the Sun's center (see Figure 4.4).

There are three types of neutrinos: electron, mu, and tau neutrinos—so named because they are associated with the electron, muon, and tau particles. These six "leptons," together with the six types of quarks—up, down, charm, strange, top, and bottom—are the basic building blocks of matter (see Figure 2.1.1). The three neutrinos differ from the nine other building blocks of matter because they are so light and interact so weakly. These two differences are at the root of their importance to modern astrophysics and physics.

Said simply, the unique role of neutrinos is "seeing deep." By detecting neutrinos from astrophysical objects we can see deep into the Sun, into exploding stars (supernovae), and someday, one can hope, into the mighty explosions that power the mysterious gamma-ray bursts seen across the universe.

Neutrinos also allow us to study the forces of nature at the shortest distances by observing rare processes in which they participate. For instance, neutrinos permit us to "see deep" into the nuclei of atoms through the process of neutrino scattering from the quarks within the proton. Their tiny masses and the transformations of one neutrino type to another (see Figure 2.1.2) have even revealed physics beyond the Standard Model of particle physics. Studying and understanding neutrino mass and oscillation provide a unique view into how the forces and particles are unified.

Because neutrinos are uncharged, it is possible that, like photons, they are their own antiparticles. If this is so, it may explain the existence of the kind of matter we are made of. Shortly after the big bang, there were equal amounts of matter and antimatter. Were it not for the fact that a slight excess of matter over antimatter developed later, all matter and antimatter would have been annihilated long ago. If neutrinos (of nonzero mass) are their own antiparticles (unlike quarks), additional pathways for matter-antimatter differences become possible, and thus neutrinos are likely to have played a role in how the slight excess of matter arose in today's universe.

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[1] From *Telephone Poles & Other Poems* by John Updike, copyright © 1959 by John Updike. Used by permission of Alfred A. Knopf, a division of Random House, Inc.

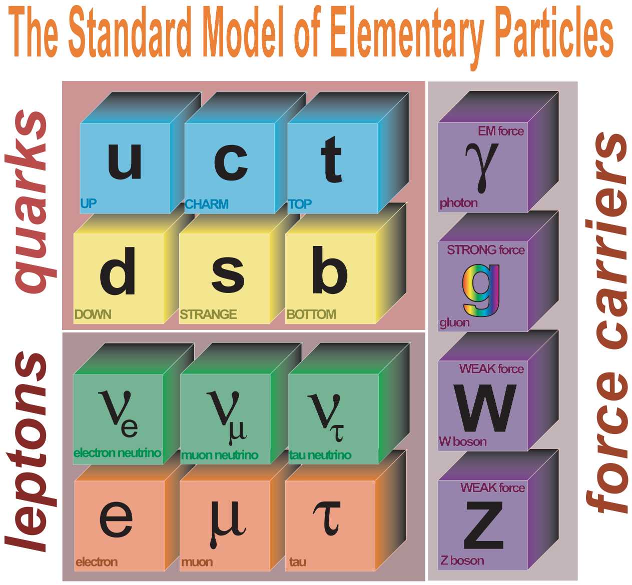

FIGURE 2.1.1 The Standard Model of particle physics describes the basic building blocks of the universe and the rules governing their interactions. This chart displays the basic quarks and leptons that make up matter and the four force-carrying boson particles. For each so-called family (columns in the chart), there are two quarks (an up type and a down type) and two leptons (a neutrino and an associated partner lepton). The neutrinos have been the most elusive part of the Standard Model because of their minimalist character—they were posited to interact only very weakly, to be massless, and to be independent of one another. Recent experiments have shown that neutrinos do in fact have mass, and that they can transform into one another. Figure courtesy of Paul Nienaber and Andrew Finn, BooNE Collaboration.

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SIDEBAR 2.1 CONTINUED

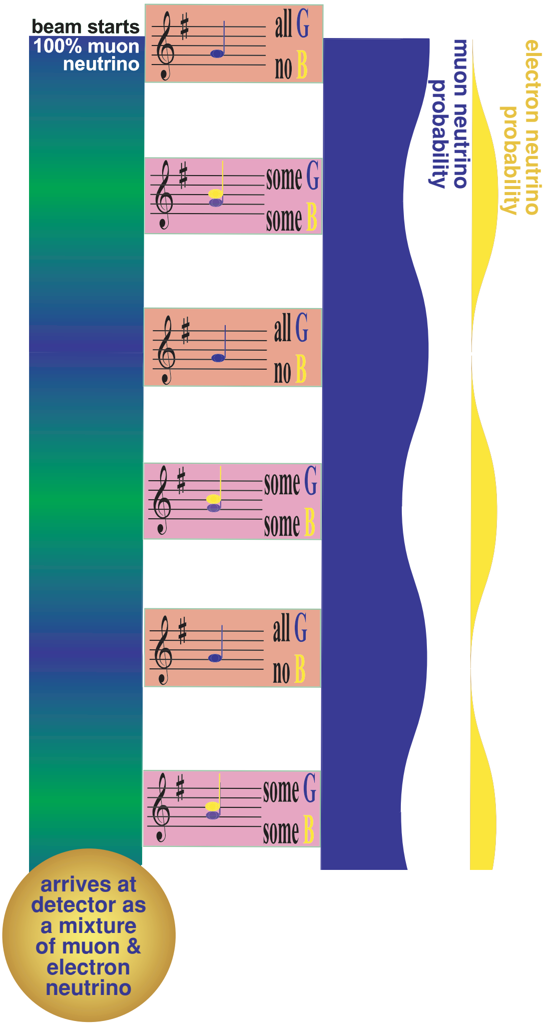

FIGURE 2.1.2 As described in the text, neutrinos have been shown to oscillate—an observation that shows, in effect, that they have mass. Understanding neutrino oscillations requires a trip into the world of quantum mechanics; this figure uses a musical analogy to represent the behavior of a simplified model. Imagine only two neutrinos that can oscillate into one another, and imagine representing each neutrino as a musical pitch. Further assume that only one pitch at a time can be detected. Let the muon-neutrino be represented by a G-note and the electron-neutrino by, say, a B-note. In the absence of neutrino oscillations, one could assume that a G-note originated as a G and would remain forever a G, and likewise for a B. However, with the possibility of neutrino oscillations, a muon-neutrino G-note can "de-tune" into a B-note as time passes, and vice versa. Since only one pitch at a time can be detected, the neutrino will sometimes "sound" like a G and sometimes like a B; the rate of de-tuning is related to the neutrino mixing parameters. The probability of observing the muon-neutrino as an electron-neutrino varies as a function of time (or distance if the neutrino is traveling), as shown by the sinusoidal curves alongside the scales. The detailed properties of neutrino oscillations are important to understanding how the Standard Model particles interact and how galaxies and the universe work. Figure courtesy of Paul Nienaber and Andrew Finn, BooNE Collaboration.

cleaning fluid 4,000 feet below the surface in the Homestake Gold Mine to detect neutrinos produced by nuclear reactions occurring at the center of the Sun. These two experiments—one with reactor-produced neutrinos and the other with solar neutrinos—paved the way for the recent discoveries.

The advent of intense beams of neutrinos produced by particle accelerators quickened the pace of neutrino research—and discoveries. First came the discovery of a second type of neutrino by Leon Lederman, Melvin Schwartz, and Jack Steinberger in a pioneering neutrino experiment at Brookhaven National Laboratory, for which they received the Nobel Prize in physics in 1988. In the mid-1970s neutrino beams at the European Organization for Nuclear Research (CERN) in Europe and at Fermilab in the United States were used to discover a new force of nature (the neutral-current weak interaction). This discovery (and others) revealed that the electromagnetic and weak forces are just different aspects of a unified electroweak force and led to a Nobel Prize for American theorists Sheldon Glashow and Steven Weinberg and the late Pakistani theorist Abdus Salam.

Roughly 160,000 years ago a star 20 times the mass of our Sun exploded in the Large Magellanic Cloud. In February 1987, neutrinos produced by this explosion were detected by large underground water Cerenkov detectors in the United States (the Irvine-Michigan-Brookhaven (IMB) detector in the Morton Salt Mine in Ohio) and in Japan (the Kamiokande II detector in the Kamioka Mine). This discovery marked the beginning of extragalactic neutrino astronomy. It also confirmed astronomers' basic picture of how massive stars explode and disperse the majority of the elements in the periodic table. Although supernovae are extremely bright—for a few days they produce as much visible light as the rest of the stars in their host galaxies—neutrinos carry away a thousand times more energy.

Both the IMB and Kamiokande II experiments also detected neutrinos produced by cosmic-ray interactions in Earth's atmosphere and found a curious deficit of muon neutrinos relative to electron neutrinos. The continued study of this deficit by the larger and better instrumented Super-Kamiokande (Super-K) detector provided compelling evidence that neutrinos have mass. Super-K showed that the deficit was due to muon neutrinos oscillating (transforming) to another type of neutrino (probably tau neutrinos). Oscillation experiments can only measure the differences in squares of the masses between two neutrino types, and by determining this difference the Super-K experiment set a lower limit on the mass of the heaviest neutrino: one ten-millionth the mass of the electron.

Such a tiny mass may not seem very important, but in fact, the implications for elementary particle physics, astrophysics, and cosmology are very profound. The highly successful Standard Model of particle physics cannot accommodate neutrinos with mass, even with masses this tiny. Thus, the existence of neutrino mass is the first sign of the long-sought grander theory that would unify the forces and particles of nature; the fact that neutrino masses are extremely small is an important clue about how the forces are unified.

Because the universe is awash with neutrinos left over from its big-bang beginning, even the smallest mass consistent with the Super-K experiment would mean that neutrinos contribute as much to the mass budget of the universe as do bright stars. Masses this small may also influence the dynamics of how massive stars explode to produce the chemical elements.

In 2001 and 2002, results from the Sudbury Neutrino Observatory (SNO) detector in the Inco Mine in Sudbury, Ontario, brought clarity to the long-standing solar-neutrino problem. Beginning with Davis's discovery experiment, every solar-neutrino experiment has seen far fewer solar neutrinos than astrophysical theory predicts. The SNO experiment, with its ability to detect tau- and muon-type neutrinos, showed that although the predicted number of neutrinos arrive at Earth, some of the electron neutrinos produced by the Sun have been transformed into other types of neutrinos along the way. The SNO experiment also identified a second mass difference in the neutrino family. For the three known neutrino types, there are only two independent mass differences; however, the absolute scale of neutrino mass remains undetermined.

Two other recent discoveries—mysterious flashes of gamma rays, which occur about once a day, and photons from distant galaxies with a trillion times the energy of visible light—suggest that there are observable astrophysical sources of neutrinos in addition to the Sun and supernovae (see Sidebar 2.2, "Cosmic Rays and Cosmic Accelerators").

Satellites monitoring Earth for nuclear explosions discovered sources of gamma-ray bursts serendipitously. Only in the last 5 years were their locations pinpointed to galaxies at the edge of the observable universe. These, the most energetic explosions known, which transform enormous energy into gamma rays over a few seconds, are thought to be associated with the collisions of neutron stars and black holes or with the violent collapse of massive stars. Large, Earth-based gamma-ray telescopes also discovered sources of constant emission of gamma rays with even higher energies in a handful of galaxies known to harbor supermassive black holes. The gamma rays we observe are likely to have been attenuated by material inside and outside the sources. Both gamma-ray bursts and the jets formed around supermassive black holes are thought to emit neutrinos as well.

If these new heavenly sources of neutrinos do exist, the neutrinos they emit have very high energies, more than a million times those produced by the Sun and supernovae. The ability of neutrinos to escape from deep inside objects across the universe opens a new window to study the most exotic astrophysical events and perhaps to learn more about the properties of neutrinos themselves.

SIDEBAR 2.2 COSMIC RAYS AND COSMIC ACCELERATORS

Shortly after the discovery of radioactivity more than 100 years ago, physicists discovered that Earth is constantly bombarded by cosmic rays from space. Today, the cosmic rays are known to consist of protons, photons, nuclei of atoms from helium to uranium, electrons and positrons, neutrinos, and possibly particles yet to be identified, with energies ranging from millions of electron volts to more than a billion trillion electron volts. Cosmic rays colliding with Earth's atmosphere produce tremendous numbers of muons and neutrinos.[1] Our Sun and exploding stars within our galaxy and others all produce cosmic rays. Not only do the cosmic rays provide samples of material from throughout the universe, but they also give us access to particles with energies well beyond those that can be produced by earthly accelerators. However, cosmic rays and their debris can interfere with very sensitive experiments looking for rare events. To escape these cosmic-ray muons, physicists have taken their experiments deep underground to search for rare events.

The existence of high-energy cosmic rays raises the question of how they originated and were accelerated. There are a variety of acceleration mechanisms, ranging from shock waves produced by exploding stars or by gamma-ray bursts to supermassive black holes with strong magnetic fields. Neutral particles like photons and neutrinos cannot be accelerated by electric fields, which are the primary means for accelerating electrons and protons to high energy. One explanation for the very high energy photons recently detected from supermassive black holes is that protons are accelerated to high energy and produce pi mesons when they encounter matter; the pi mesons ultimately decay and produce photons and neutrinos. There are also models for cosmic acceleration that do not include detectable neutrino emissions. Scientists are ready to turn to the universe to see which explanation is more correct.

If the proton acceleration explanation is correct, then there should also be very high energy neutrinos coming from these and other supermassive black holes.

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[1] In fact, this process served as the copious source for the experiments that identified neutrino oscillations.

BEYOND NEUTRINOS

Some 50 years after Pauli's desperate proposal to save the principle of energy conservation, physicists and astronomers proposed another particle to save another important principle of physics—gravity. Fritz Zwicky, Vera Rubin, and other astronomers showed that galaxies and clusters of galaxies do not contain enough matter in the form of stars to be held together by gravity as we understand it (see Sidebar 2.3, "Shedding Light on Dark Matter"). This means either that our present understanding of gravity is incorrect or that there must be a nonluminous form of matter (now called dark matter) that holds these objects and the universe together.

The case has grown more interesting in the past decade: By establishing that the total amount of ordinary matter (matter made of neutrons, protons, and electrons) falls short by a factor of seven of being able to account for the needed dark matter, astrophysicists have now raised the stakes. A new form of matter must explain the dark matter. Like the neutrino before it, the hypothesized dark-matter

SIDEBAR 2.3 SHEDDING LIGHT ON DARK MATTER

Light and other forms of electromagnetic radiation have taught us most of what we know about the universe, including the fact that there is much more to cosmology than meets the eye. In our own solar system the planets move with high speeds; they remain bound to the Sun because its gravitational force bends their motions into nearly circular orbits. Even if the Sun did not shine, we could infer its existence and measure its mass from the pattern of planetary motions observed, orbital speeds decreasing from 172,000 km/h for Mercury to 17,000 km/h for Pluto.

The same technique can be applied to the Milky Way and other spiral galaxies. When Vera Rubin and others measured the orbital velocities of stars and clouds of gas, they found a very different pattern: Beyond the centers of spiral galaxies, the orbital velocities of stars and gas clouds do not change. Unlike the solar system, where 99.9 percent of the mass is concentrated at the center, the mass of a galaxy is

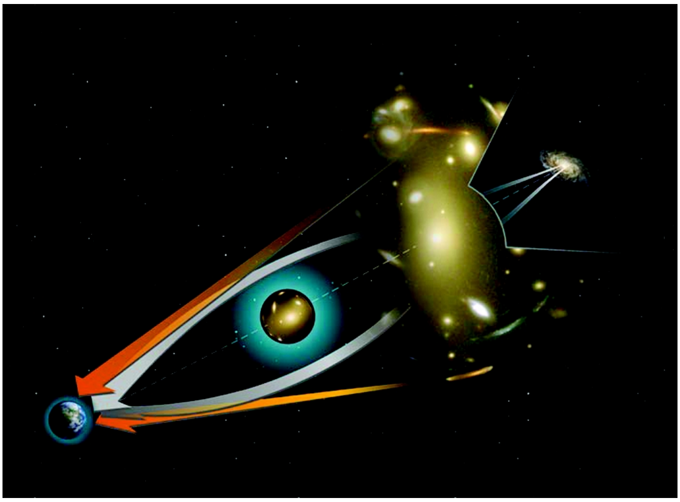

FIGURE 2.3.1 Just as a wanderer in the desert can experience mirages when light from remote objects is bent by the warm air hovering just above the sand, so also we may see mirages in the universe. The mirages we see with modern telescopes arise not from oases but from remote concentrations of galaxies—huge concentrations of mass. The light rays (the gray arrows) from the distant galaxy (to the right on the figure) are bent when passing a large gathering of mass—such as the galaxy cluster highlighted in blue. When the light finally arrives at Earth, we observe it as coming from a slightly different direction (the red-orange arrows). After passing the intervening galaxy, the original image has been distorted—there are multiple images and it has changed shape. This is the effect of gravitational lensing. Image and caption courtesy of NASA.

spread out, extending far beyond its visible edge. Astonishingly, stars account for only a small fraction of the galactic mass.

The bulk of the mass of a galaxy exists in an extended, almost spherical distribution known as the dark halo. The defining feature of the halo is this darkness, and so the needed additional matter is referred to as dark matter. We know the dark matter must be there because without its gravity, the stars within galaxies (including our own) would not remain together.

In recent years, evidence for dark matter has strengthened. Dark matter holds all structures larger than galaxies together and accounts for most of the matter in the universe. In clusters of galaxies, the effects of dark matter are so pronounced that it distorts the images of distant galaxies beyond the cluster by its gravitational bending of their light (see Figures 2.3.1 and 2.3.2).

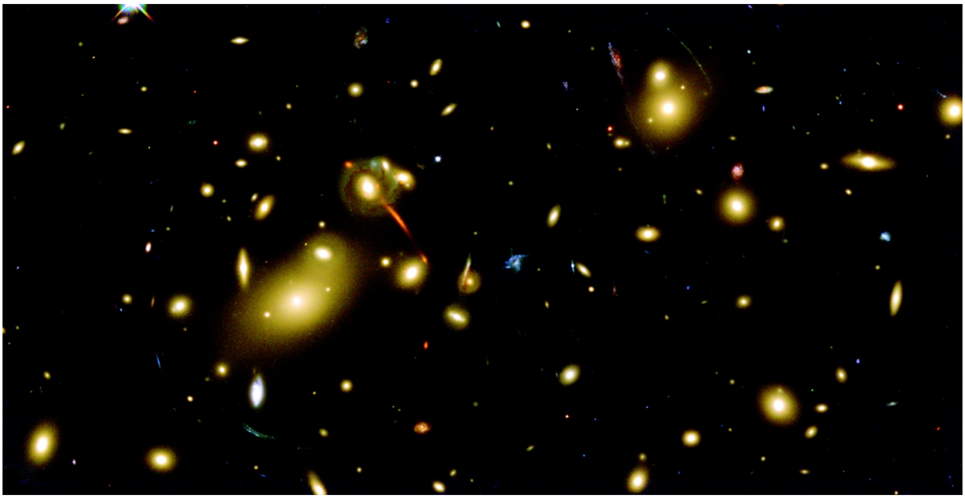

FIGURE 2.3.2 This Hubble Space Telescope image shows how the dark matter in the cluster of galaxies (seen as the yellow images) bends the light from more distant faint blue galaxies, creating multiple images of some galaxies and distorting the shapes of others. The use of gravitational lensing allows astronomers to map the dark matter in clusters of galaxies and to directly reveal the enormous amount of dark matter. Image courtesy of NASA, A. Fruchter, and the ERO team.

particle must be neutral and must interact very weakly with ordinary matter, making it challenging to detect.

Could neutrinos be the cosmic dark matter? While we are now confident that they account for at least some part of it, upper limits to the masses of neutrinos from experiments involving the nuclear decay of tritium (a heavy form of hydrogen) already preclude the possibility that neutrinos constitute all of the dark matter.

There is now a strong case for the existence of a new particle, which, like the neutrino, must be uncharged and almost inert but may account for the bulk of the dark matter in the universe. This idea has resonated with particle theorists, whose unified theories predict the existence of new types of stable particles with just the properties needed for dark matter.

In addition to predicting a dark-matter particle and neutrino mass, unified theories make a third prediction—the instability of the matter of which we are made. Needless to say, the rate of the decay of protons must be exceedingly slow: Current experiments indicate that the average lifetime of the proton exceeds 10^{33} years, so that very few have decayed since the big bang. The prediction of matter instability is bolstered by evidence that the strengths of the strong and electroweak forces approach a common value at very high energies, an indication of the unification of the forces that sets a possible energy scale for the undiscovered forces responsible for proton decay. Some theoretical predictions of the lifetime of the proton are within the reach of a new generation of experiments; the absence of observed decays will also constrain theory.

The decay of the proton and dark-matter interactions with ordinary matter are extremely rare events—more challenging to detect than even neutrinos. Like neutrinos, however, they offer a new window on nature and the possibility of learning about the universe and about the deepest inner workings of the physical laws that govern it.

SPECIAL OPPORTUNITIES

The recent discoveries involving neutrinos, dark matter, and sources of very high energy photons have deepened our understanding of both the universe and the laws that govern it. In addition, these discoveries point to new opportunities for even greater advances. The questions that we are now poised to answer include these:

- Why do neutrinos have tiny masses, and how do they transform into one another?

- Are the existence and stability of ordinary matter related to neutrino properties?
- Are there additional types of neutrinos?
- What is the mysterious dark matter, and how much of it consists of neutrinos?
- What causes the most powerful explosions in the universe?
- What role do neutrinos play in the synthesis of the elements in the periodic table?
- How do supermassive black holes produce very high energy gamma rays?
- Is there a deeper simplicity underlying the forces and particles we see?

No single experiment can realize all of these opportunities. A concerted program of experiments is required. For instance, rare nuclear-decay experiments (such as double beta decay) have the potential to probe the absolute scale of neutrino mass down to the minimum mass indicated by the Super-K and SNO experiments, but only if the neutrino meets certain other conditions (that is, if it behaves as a Majorana particle). To observe and study these rare events requires laboratories shielded from the cosmic rays that bombard Earth (see Sidebar 2.2, "Cosmic Rays and Cosmic Accelerators").

The technology has now been developed to detect a wide spectrum of weakly interacting dark-matter particles, candidates for the composition of the halo of our galaxy. The current experiments are ready to be scaled up and operated in laboratories well shielded from cosmic rays.

To sort out precisely how the different neutrino types transform into one another will likely require intense accelerator-produced neutrino beams aimed at large, faraway detectors. (A large distance is required for the neutrinos to oscillate; the intense beams and large detectors are needed to observe the rare neutrino interactions, which become more diffuse at large distances.) A new generation of solar-neutrino experiments focused on the lowest-energy solar neutrinos will likely also be needed.

Astronomers have learned much about the universe by observing the different kinds of electromagnetic radiation that exist in nature (see Figure 2.1). The different forms of light are distinguished by their wavelengths and energies and require different kinds of detectors. Visible light, familiar because it can be seen with our eyes, reveals the presence of stars similar to and at the same stage of (stellar) life as our Sun, but this light offers only a small window on the full spectrum. Infrared radiation is able to penetrate the clouds that obscure the birth of stars and planets. Microwaves reveal the birth of the universe in the form of the cosmic microwave background. X rays and gamma rays provide a window onto the most energetic

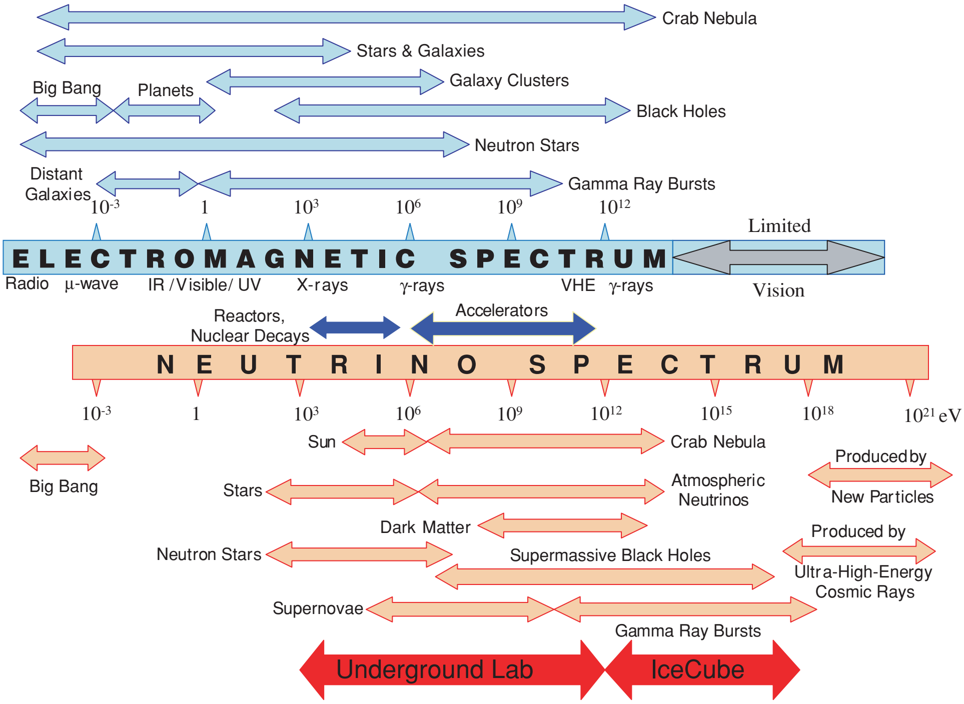

FIGURE 2.1 A comparison of the electromagnetic and neutrino windows on the universe, which is important because both IceCube and a deep underground lab will be sensitive to neutrinos. Astronomers view the universe with light of greatly different wavelengths and energies, from long-wavelength microwaves whose energies are 10,000 times less than that of visible light to very short wavelength gamma rays whose energies are a trillion times greater than that of visible light. By exploiting the full electromagnetic spectrum, astronomers have revealed a great variety of objects in the universe, from the microwave glow of the big bang, to infrared radiation from planets, to the gamma rays emitted by supermassive black holes. Neutrinos of vastly different energies should also be produced by objects in the universe, from relic neutrinos left over from the big bang to those produced by the interaction of the most energetic cosmic rays with the cosmic microwave background radiation. Photons with energies between 10^{13} eV and 10^{19} eV can reach us only from our local neighborhood. The cause of this "limited vision" (i.e., partial electromagnetic blindess) is the interaction of photons with the diffuse background of infrared and microwave photons. Because their interactions with other particles are so much weaker, neutrinos are not so affected, so IceCube could allow us to see into these processes for the first time. Detection of sources of astrophysical neutrinos will give us new windows on the universe.

events in the universe, from matter falling into a black hole to nature's most powerful accelerators.

Because they interact with matter so rarely, neutrinos have the potential to probe even deeper than the highest-energy gamma rays. Already the neutrinos detected from our Sun have shown us the nuclear fires burning at its center, and the neutrinos from Supernova 1987A have revealed the second-by-second progress of a supernova explosion. The potential of neutrinos as new "eyes" on the universe is far from being fully realized. Because very high energy neutrinos are more interacting than low-energy neutrinos (i.e., they have a larger cross section), the chance of observing them in a terrestrial detector is greater. Thus, it is more likely that with "eyes" sensitive to very high energy neutrinos, researchers will see astrophysical sources. Even so, enormous detectors (at least a kilometer on a side) are required. The sources visible to such a detector include supermassive black holes, the mysterious gamma-ray bursters, and the high-energy neutrinos produced by the annihilation of dark-matter particles that are captured by our Sun.

While detecting very high energy cosmic neutrinos requires the largest-volume detectors yet proposed by scientists, a host of additional frontier experiments require laboratory space of a different nature. Double beta decay experiments, solar-neutrino projects, detectors to observe accelerator-produced neutrinos at great distances, experiments to detect the dark matter that holds together our own galaxy, and searches for proton decay all require laboratory space that is well shielded from the cosmic rays that bombard Earth. These projects address complementary sets of questions and require a dedicated environment to research and develop the answers.

3

Science Potential of IceCube

High-energy neutrinos are unique messengers of some of the most extreme processes occurring throughout the universe. Unlike high-energy photons, high-energy neutrinos are not absorbed as they traverse the universe. Also, unlike charged particles such as protons and nuclei, neutrinos are not deflected by magnetic fields, and thus they point directly back to their sources. These unique properties of neutrinos make possible the discovery of new astrophysical systems and new physical processes through the detection of neutrinos with energies from about 10^{12} eV, which is as high as the current terrestrial accelerators reach, to much higher energies. The possibility of new discoveries in this very high energy range is the main motivation for building large neutrino detectors such as IceCube. IceCube could address some of the questions posed in the last chapter:

- What is the mysterious dark matter, and how much of it consists of neutrinos?
- What causes the most powerful explosions in the universe?
- How do supermassive black holes produce very high energy gamma rays?

INTRODUCTION

IceCube is an exploratory experiment in that it will search for astrophysical neutrinos in the very high energy range with much greater sensitivity than previous efforts. It is key to realize that IceCube is a discovery instrument, more akin to a particle physics project than to a telescope—it may be that we will not see what we are looking for because there might not be any discrete sources of astrophysical neutrinos to discover. In that case, other techniques to address these science questions will certainly be needed. The discovery of very high energy neutrino sources, though, would clearly demonstrate the existence of the acceleration of hadrons (e.g., protons or nuclei) in known astrophysical discrete sources. By the same token, however, it cannot be said with certainty what IceCube will in fact detect—source flux predictions are uncertain and rely on the extrapolation from known astrophysics at lower energies. Possible sources include gamma-ray bursts, which are powerful explosions that release in seconds the same energy as a typical galaxy emits in years; active galaxies and quasars, which can be more than 1,000 times more luminous than normal galaxies and are believed to be powered by supermassive black holes at their centers; and neutron stars, which are ultracompact stellar remnants that have collapsed to densities comparable to those inside atomic nuclei. In addition, the possibility exists for new and unexpected types of sources, both astrophysical and exotic, at these energies.

The lack of strong and electromagnetic interactions gives neutrinos the special ability to traverse the universe unimpeded, but it also makes them extremely hard to detect. To achieve sufficient sensitivity to detect high-energy neutrinos from distant sources, experiments on the scale of one cubic kilometer or a billion tons of detector mass are required. Such experiments use Earth as a converter and detect neutrinos as they traverse Earth from below and interact near the experiment. Neutrino interactions produce upward-going muons that generate Cerenkov light in a suitably transparent medium such as water or ice and that are recorded by an array of light sensors (photomultiplier tubes) spread throughout the volume of the detector. IceCube is to be constructed at the South Pole, making use of Antarctic ice as the detecting medium. The IceCube sensors are deployed by lowering strings of photomultiplier tubes into melted ice and allowing the strings to be frozen in place. See Figures 3.1 and 3.2 for a description of IceCube and its operation.

Although IceCube is a major undertaking in a rather remote location, its design and prospects for success are bolstered by the strength of the existing polar infrastructure and, in particular, by the successful deployment and operation of AMANDA, a smaller precursor to IceCube. The properties of the South Pole ice as a detection medium are now better understood, and AMANDA has shown that the technique of detecting upward-going muons works well—it has reconstructed about 1,000 upward-going muons that are signatures of neutrinos produced in the atmosphere that lies below the horizon. IceCube will substantially improve on AMANDA's capabilities, both through a larger detection volume and through the use of improved technology.

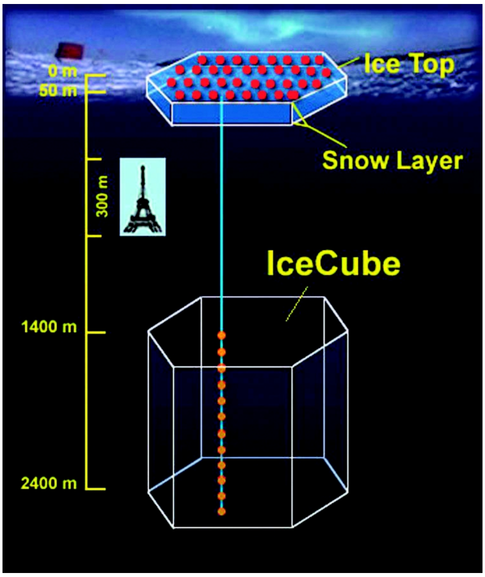

FIGURE 3.1 The IceCube detector is shown in schematic form. It will be located near the South Pole, in Antarctica. It consists of 80 strings of photomultiplier light sensors suspended more than 2 km below the surface of the ice. Each string has 60 light sensors. The 1.4-km depth is required to obtain sufficiently clear and impurity-free ice. Image courtesy of the AMANDA Collaboration, the IceCube Collaboration, and the National Science Foundation.

In the global perspective, IceCube is the only cubic-kilometer-scale neutrino telescope ready for construction now. There are efforts in Europe, notably the Astronomy with a Neutrino Telescope and Abyss Environmental Research (ANTARES) project, the Neutrino Extended Submarine Telescope with Oceanographic Research (NESTOR) project, and the Italian Neutrino Mediterranean Observatory (NEMO) project, to build detectors that use the Mediterranean Sea as the detecting medium. These groups are currently building smaller detectors and plan to propose cubic-kilometer-scale experiments in the near future for approval and construction starting within the decade. The experiments planned for the South Pole and for the Mediterranean are largely complementary in nature, in terms of both their observational targets and their capabilities. By detecting upward-going muons, IceCube is sensitive to astrophysical sources in the Northern Celestial Hemisphere, whereas a Mediterranean Sea experiment would study Southern Celestial Hemisphere sources. In comparison with water, ice typically scatters more light than it absorbs. Thus ice can provide a larger effective detector volume than water for the same number of optical sensors deployed. Conversely, water experiments can achieve better angular resolution than those using ice. The lower resolution of IceCube (about 1 arc-degree) is, however, adequate for observing the expected sparse distribution of sources, which can be more precisely localized with electromagnetic telescopes in any case. Finally, the committee mentions that novel techniques using radio and acoustic detection technologies for observation of neutrino interactions in ice or in natural salt deposits are currently being explored and might offer long-range possibilities for this field. Such large-scale efforts with new technologies, at even higher energies, will be much sought after as a follow-up to well-established signals from a present-day experiment like IceCube.

THE SOURCES OF HIGH-ENERGY NEUTRINOS

The potential sources of high-energy neutrinos can be classified into several broad categories: astrophysical point sources, diffuse cosmic backgrounds, and new physics sources. Astrophysical objects can produce neutrinos via processes involving the extreme acceleration of hadrons. These processes are similar to those that take place at particle accelerators such as Fermilab or the Stanford Linear Accelerator Center (SLAC) but under much more extreme conditions and reaching much higher energies, by factors of a thousand up to a billion. A variety of astrophysical measurements using photons or cosmic rays support the idea that there are sources of high-energy neutrinos, but their exact flux levels are uncertain. Gamma-ray telescopes on Earth and in space have shown that both galactic sources, such as pulsars and supernova remnants (produced when massive stars explode), and extragalactic sources, such as active galaxies, are capable of accelerating particles to at least 10^{13} eV. In addition, the charged particle cosmic-ray spectrum extends to 10^{20} eV and beyond. Particles accelerated to such extreme energies will unavoidably produce ultrahigh-energy neutrinos. Based on these high-energy cosmic-ray and gamma-ray studies, the detector scale of IceCube (1 km^3) is the minimum size that offers a reasonable chance of detecting neutrino emission from known sources. Understanding the processes that lead to such powerful accelerators and deciphering the mystery of the cosmic rays are the prime motivations for exploring the high-energy neutrino universe.

Astrophysical Point Sources of Neutrinos

The leading candidates for high-energy neutrino point sources are extragalactic objects such as active galactic nuclei (AGN), powered by supermassive black holes, and gamma-ray bursts (GRBs), whose origin is not yet understood (see Figure 3.3). Galactic phenomena such as pulsars and supernovae are also possible sources. Given typical neutrino-producing models for cosmic accelerators (i.e., hadronic models), IceCube's sensitivity restricts its observations to only the most powerful or closest sources. For example, for a steady emitter located at cosmological distances, the source must have the power equivalent of 10^{13} solar luminosities to generate 10 neutrino events per year in a cubic-kilometer-scale detector. Some AGN can maintain such high luminosities for relatively long periods of

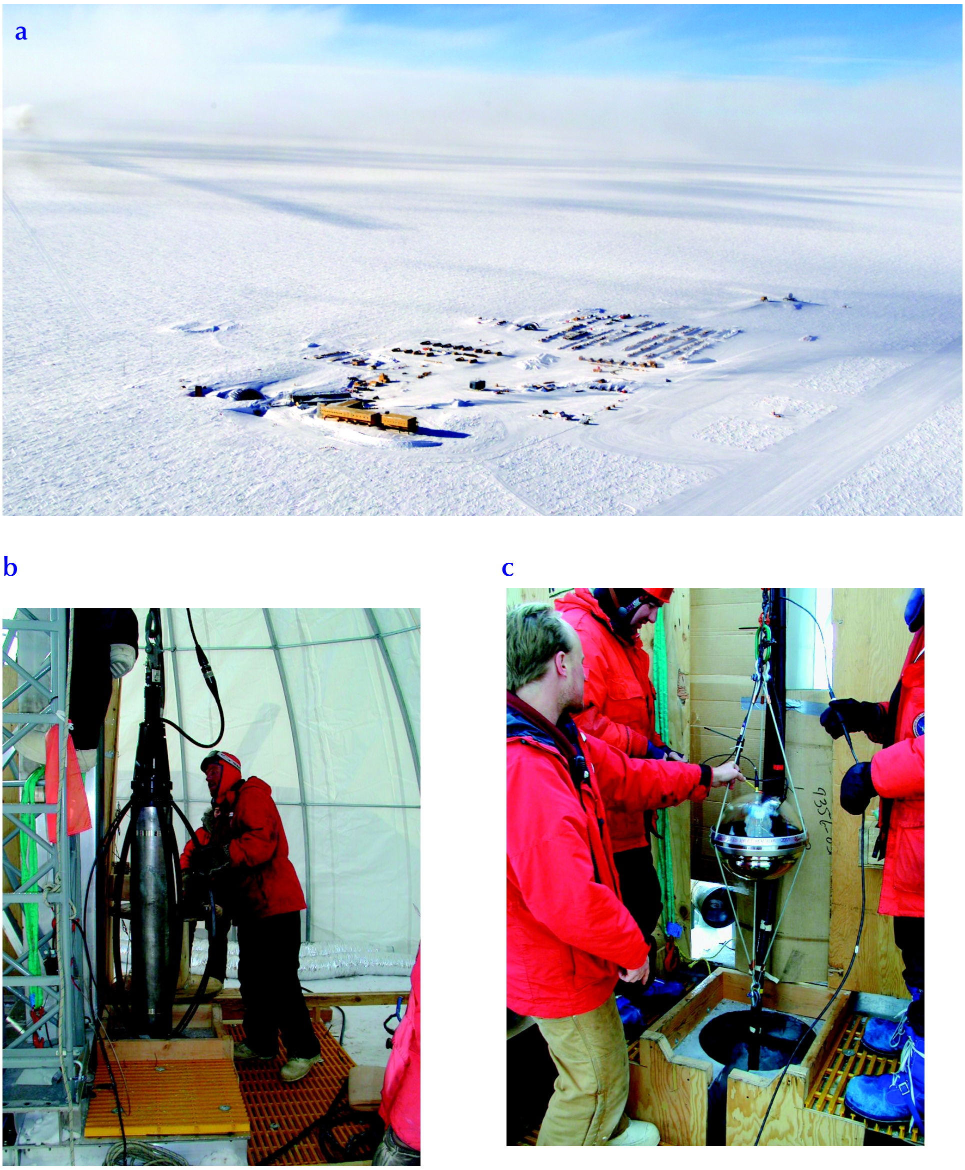

FIGURE 3.2 (a) An aerial view of the Amundsen-Scott South Pole research station, where IceCube will be located. The station sits on a 2,700-m thick plateau of snow-covered ice. Image courtesy of USAF MSgt. David McCarthy and the National Science Foundation. (b) Teams of scientists and engineers use a hot-water drill to bore holes deep into the ice. Strings of light sensors are deployed in the holes. (c) Lowering one of the strings of light sensors; the glass capsule encases the photomultiplier tube. Once the water in the bore-hole refreezes, it will be impossible to access the sensors. Images courtesy of the AMANDA Collaboration, the IceCube Collaboration, and the National Science Foundation.

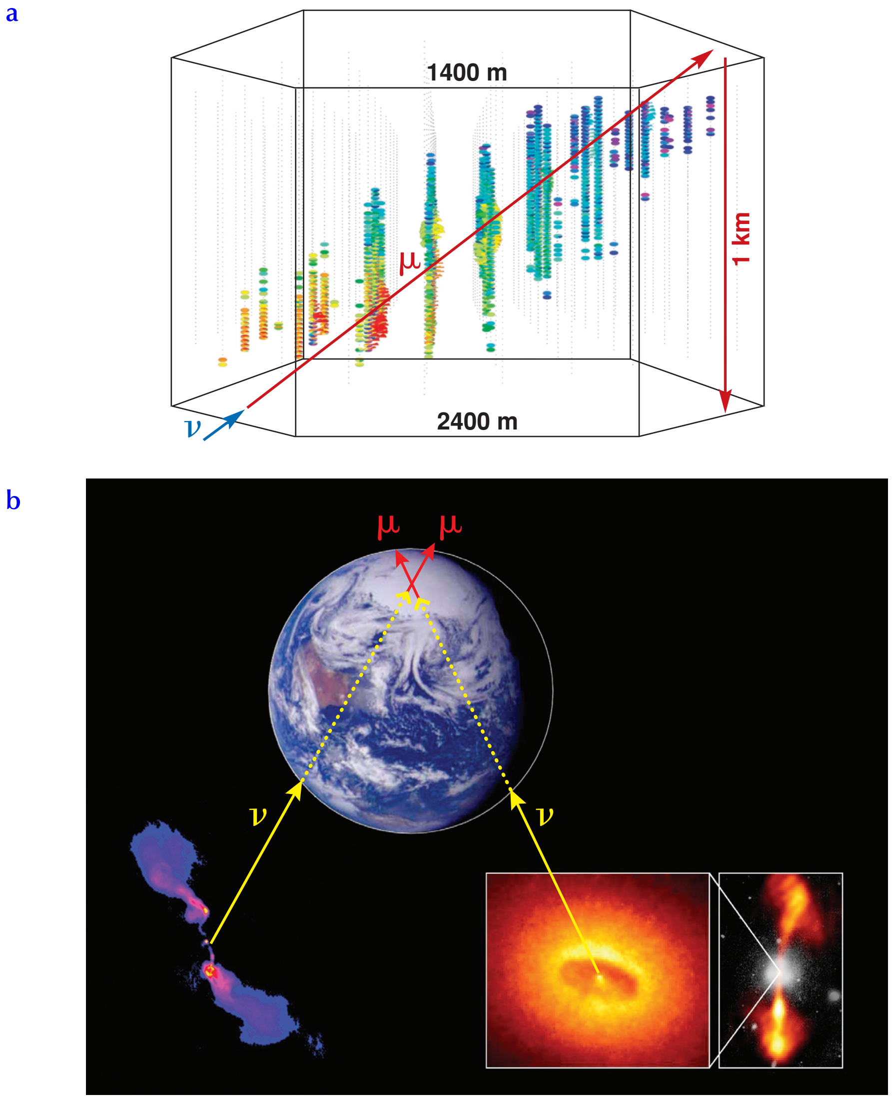

FIGURE 3.3 (a) An image from a computer simulation showing IceCube's principle of operation. A neutrino incident from below scatters in the ice, creating a muon. The high-energy muon leaves behind a trail of Cerenkov light whose direction and intensity are monitored by the strings of light sensors. The different colors in the figure represent the different times of arrival of the light signal. (b) IceCube will detect muons generated by cosmic neutrinos as they traverse and interact in Earth. Two candidate sources of extragalactic cosmic neutrinos are pictured here, NGC 4261 on the left and Hydra A on the right. (a) Image courtesy of the AMANDA Collaboration, the IceCube Collaboration, and the National Science Foundation. (b) Image of Earth courtesy of the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California; image of NGC 4261 courtesy of Greg Taylor/NRAO; image of Hydra A courtesy of NASA/Jeffe, Ford, Ferrarese, Van Den Bosch, O'Connell, and NRAO.

time (i.e., weeks, months). Transient objects, such as GRBs, can reach much higher peak power levels (higher by a factor of 100,000), but over shorter periods of time, such as tens of seconds.

Certain types of AGN, called blazars, are copious sources of high-energy gamma radiation. A blazar is thought to be an AGN with a relativistic jet powered by matter falling into a black hole (with a mass about a billion times the mass of the Sun) nearly aligned with the direction to Earth. Detection of neutrinos at 10^{12} eV to 10^{15} eV energies from these sources can determine if jets are powerful accelerators of hadrons (i.e., protons and nuclei). If relativistic hadrons were accelerated with power comparable to that of the observed gamma rays, then detectable fluxes of neutrinos would be produced in the jet through pion production by nuclear and photohadronic interactions. If inelastic nuclear interactions are important, the neutrino spectrum is expected to reflect the spectrum of the relativistic particles from 10^9 eV to the highest energies.

The electromagnetic gamma radiation from AGN has been studied by satellite- and ground-based telescopes. IceCube can probe these objects using neutrinos, extending the energy range by a factor of several hundred or more. The Energetic Gamma-Ray Experiment (EGRET) satellite detected almost 100 AGN at gamma-ray energies up to 10^{10} eV, while ground-based telescopes such as Whipple detected 5 AGN at energies up to 10^{13} eV. Many more AGN will be detected with the next generation of ground-based and satellite instruments. Neutrino fluxes from known gamma-ray-emitting AGN are detectable by IceCube, under two assumptions. First, a substantial fraction (e.g., 50 percent) of the power in the high-energy beam in the AGN jet must go into the acceleration of hadrons. Second, the energy spectrum of the neutrinos produced by the source must be relatively flat (i.e., it must extend to very high energies, decreasing slowly, at most as the inverse energy squared).

Gamma-ray bursts represent another important potential source of high-energy neutrinos. Current models of GRBs involve the dissipation of the kinetic energy of a relativistically expanding fireball, caused by some explosive event, possibly the collapse of a massive star or the coalescence of two compact objects. The shocks resulting from this dissipation can accelerate particles to very high energies (gamma rays up to 10^{10} eV energies have been detected from GRBs). In most GRB models, the observed MeV gamma rays, as well as the recently discovered lower-energy afterglows (x ray, optical, radio), are attributed to emission from shock-accelerated electrons in magnetic fields. Under certain model assumptions, the neutrino emission from GRBs should be detectable by IceCube. With these assumptions, one derives an estimate of approximately 10 neutrino events per year at energies of 10^{14} eV in IceCube, detected from an ensemble of GRBs in the Northern Celestial Hemisphere. Gamma-ray bursts produced in the collapse of massive stellar progenitors could lead to about 10 neutrino events per individual burst, detected a few times a year in IceCube at energies of 10^{12} eV. Because these events would be correlated in position and in time with the gamma-ray bursts themselves, they would be largely background free, since the background outside this position and time window can be rejected. If detected, these neutrinos would help unveil the mysterious progenitors of GRBs by testing the gamma-ray emission model and the shock acceleration physics.

Although AGN and GRBs are the likeliest high-energy neutrino source candidates, a variety of other astrophysical objects could be sources of neutrinos. As a very wide field telescope, IceCube could search for neutrino emission from most of the Northern Celestial Hemisphere. Among potential sources, young pulsars, which are highly magnetized, rapidly rotating neutron stars, are known to accelerate electrons and are likely to accelerate hadrons. Microquasars, smaller versions of AGN located in our galaxy, also show jets that may be observable with neutrinos, if the jets are sites of hadronic acceleration. Microquasar jets are associated with accreting stellar-mass black holes or neutron stars. Finally, supernovae—the very bright explosions of massive stars—and the remnants of supernova explosions are also likely to be sites of hadronic acceleration and neutrino emission.

Diffuse Astrophysical Sources of Neutrinos

Cosmic neutrinos coming from point sources in the sky are more easily detected than those neutrinos from diffuse sources because of the atmospheric neutrino background. Atmospheric neutrinos are constantly being produced from all directions in the sky at the low-energy range of IceCube's reach. The exact level of this atmospheric neutrino background depends on the unknown forward production of neutrinos from charm quark decays. On the one hand, if this production channel is very efficient, the flux of atmospheric neutrinos as well as the flux of astrophysical neutrino point sources will increase accordingly. On the other hand, if the charm production of neutrinos is suppressed, astrophysical diffuse backgrounds could be correspondingly easier to resolve. Another potential source of background, however, is charm decay into high-energy muons at sufficient energies. The impact of this effect is not yet well understood, but it could influence IceCube's abilities at the highest energies.

The observation of cosmic rays with energies in excess of 10^{20} eV reaching Earth isotropically from all directions indicates that hadrons are accelerated to ultrahigh energies in extragalactic sources. IceCube can help determine the origin of these highest-energy cosmic rays by observing neutrinos generated at the same acceleration sites. A number of ultrahigh-energy astrophysical accelerators, proposed to explain the origin of the highest-energy cosmic rays, could be detectable by IceCube. Optically thin sources of protons at energies greater than 10^{19} eV are constrained to have neutrino fluxes that lie below the Waxman-Bahcall (or W-B) limit. This limit is based on the consideration that the energy input into neutrinos cannot exceed the observed cosmic-ray flux at high energies. IceCube can reach fluxes down to one-tenth of the W-B limit. In addition, there may be "hidden" sources that exceed this bound for neutrinos. In such sources, the high-energy hadrons are prevented from leaving, but the neutrinos escape.

Whatever the source of the ultrahigh-energy cosmic rays, they are likely to produce a flux of high-energy neutrinos. In addition, the ultrahigh-energy cosmic rays can themselves produce neutrinos as they propagate through and interact with the remnant radiation from the big bang, the cosmic microwave background (CMB) radiation. The interactions between the CMB and protons with energies of 10^{20} eV and above produce pions, which subsequently decay, generating neutrinos. The flux of these photopion neutrinos rises around 10^{17} eV, where it is marginally accessible to IceCube at the level of one event per year. In the ultrahigh-energy range, IceCube is complementary to cosmic-ray experiments such as the Auger project, where the energy threshold for neutrinos starts around 10^{18} eV.

Signatures of New Physics

In addition to launching neutrino astronomy at the very high energies, IceCube has the potential to discover new interactions and new or possibly exotic relics from the early universe. Among the early universe relics that IceCube can study are the likeliest form of dark-matter particles, called neutralinos, whose collective gravitational force appears to dominate that of the ordinary visible matter in galaxies.

Neutralinos may be indirectly detected by high-energy neutrino telescopes (e.g., IceCube) through their annihilations in the Sun. These searches are complementary in several ways to the direct searches that are discussed in the next section. IceCube will be sensitive to heavy neutralinos because the expected number of events does not depend sensitively on the neutralino mass, while the event rate falls linearly in direct detection experiments. It should also be noted that IceCube is sensitive to spin-dependent neutralino interactions on nuclei since neutralinos interact with protons in the Sun before they annihilate at the center, while the direct detection experiments are mostly sensitive to spin-independent neutralinos' interaction with heavy nuclei. Therefore, the two types of experiments are sensitive to different parts of the parameter space of neutralinos. It must be borne in mind, however, that the neutralino-detection capabilities of IceCube are in some ways more speculative and more limited (i.e., they require certain assumptions and sample a smaller area of the parameter space).

Some other proposed relics of the early universe, such as topological defects, can be copious emitters of neutrinos along with gamma rays and cosmic rays. Gamma rays and cosmic rays from these sources become severely depleted when propagating across the universe, while neutrinos reach Earth unimpeded. Finally, the detection of high-energy neutrinos from a known astrophysical source can be used to test the assumption of special relativity that photons and neutrinos have the same limiting speed, as well as the weak equivalence principle, according to which photons and neutrinos should suffer the same time delay as they pass through the gravitational potential of galaxies. Other departures from the Standard Model predictions, such as new physics at scales of beyond 10^{12} eV—the highest energies currently available from terrestrial accelerators—might also be inferred by studying the neutrino cross section on hadrons at energies well above 10^{12} eV.

ICECUBE IN AN INTERNATIONAL CONTEXT

IceCube is not the only option for a high-energy neutrino telescope. As mentioned, there are alternative technologies including the use of water (instead of ice) as the detector medium as well as techniques using radio or acoustic detectors still under development. As established above, a so-called gigaton detector is required to answer some of the key science questions. Will IceCube be unique in its abilities to address the questions? The jury is still out as to whether ice or water is a better detector and signal-transmission medium. (Detectors in ice suffer from scattering losses higher than those underwater, but ice is generally more transparent and possesses lower backgrounds, for example, from radioactive potassium-40 and bioluminescent marine life.) An expert panel of the International Union of Pure and Applied Physics (IUPAP) recently endorsed an underwater cubic-kilometer-scale follow-up to the NESTOR Mediterranean project, but no concrete proposals have been submitted as there is significant remaining research and development to determine the best design. As such, then, IceCube is unique in its stage of development, in its employment of ice as the detector medium, and in its location in the Southern Hemisphere.

The IceCube project involves scientists from institutions in the United States, Belgium, Germany, Japan, Sweden, the United Kingdom, and Venezuela and so in itself is an international effort. Plans call for the detector to be built in stages toward the full cubic-kilometer volume, over a 5- or 6-year period. Unlike many large-scale experiments, IceCube will be operational during the construction period. Currently, IceCube has a head start on its competitors, so its timely deployment will give it a lead in the exploration of this new window onto astrophysics.

4

Science Potential of a Deep Underground Laboratory

Our understanding of the physical world of quarks and leptons and of their relation to astrophysics and the evolution of the so-far-visible universe is extensive and profound. However, we know this understanding is very incomplete. The questions scientists would like to answer include these:

- Why do neutrinos have tiny masses, and how do they transform into one another?
- Are the existence and stability of ordinary matter related to neutrino properties?
- Are there additional types of neutrinos?
- What is the mysterious dark matter, and how much of it consists of neutrinos?
- What role do neutrinos play in the synthesis of the elements in the periodic table?
- Is there a deeper simplicity underlying the forces and particles we see?

These are important and very basic questions whose resolution will have a major impact on physics and our knowledge of nature. A common element in answering these questions involves the study of rare processes.

A clean, quiet, and isolated setting is needed to study such rare phenomena free from environmental background. Such a setting can be obtained only deep underground, where we can escape the rain of cosmic rays from outer space. The cosmic rays create background events that mask the critical events being searched for. It takes 2 miles of rock to absorb the most energetic of the muons created by cosmic-ray protons striking Earth's atmosphere.

At such great depths, the only backgrounds are made by neutrinos (which easily penetrate the whole Earth but, by the same token, interact very seldom) and by local radioactivity in the rock itself. The latter can be shielded by the use of specially purified but otherwise ordinary materials, such as water. For instance, the Sudbury Neutrino Observatory (SNO) in Canada is built as a high-tech clean room 10 stories tall and more than a mile underground. Only in this laboratory could the collaboration achieve an experiment that is 10 billion times cleaner than our typical living room in terms of natural radioactivity. SNO is the most background-free environment ever achieved on Earth.

Some experiments do not require the greatest depths and can tolerate less stringent conditions either because the process being sought has a higher signal rate or because some special experimental tag can be used to identify the important events even in the presence of background. For other experiments, however, there is no option but depth and extreme cleanliness. Only in such an isolated environment can we hope to detect the faintest signals of our universe.

Scientists addressing issues of intense international interest—solar neutrinos, double beta decay, and dark matter—are poised to develop next-generation detectors that require low background, and they need an underground facility for technology development in the next few years. Once the neutrino mixing and mass parameters have been measured with some accuracy, a long-baseline experiment should be developed. The KamLAND, Borexino, MiniBooNE, and MINOS experiments are expected to lead—over the next 5 years—to the synthesis necessary for the long-baseline program. A long-baseline target detector is likely to also carry out a proton decay experiment and serve as a supernova neutrino telescope, as well as many other purposes.

NEUTRINO PROPERTIES

The neutrino has had a very rich history. As described in the science overview (Chapter 2), the neutrino was postulated to preserve important conservation principles in the decay of nuclei and, as a consequence, had to possess novel properties: zero charge, zero mass, spin 1/2, and very weak interactions with other particles. It took the advent of nuclear reactors, which were able to produce neutrinos in profusion, to clearly demonstrate that the neutrino indeed existed. Furthermore, not one but three distinct types of neutrinos exist: an electron, muon, and tau type of neutrino, each coupled to its respective electrically charged partner. After intensive efforts to directly measure neutrino masses, an upper limit of 1–3 eV has been established. This can be compared to the electron's mass of 511,000 eV. The Standard Model of particle physics was therefore built with the key assumption that neutrinos are massless.

This tidy picture has been dramatically changed by recent experimental discoveries. For both atmospheric and solar neutrinos, there is now strong evidence that they change from one type to another (oscillate) as they travel through space. Because, according to Einstein's theory of relativity, particles with no mass, such as photons, do not sense time, any change in their neutrino character signals that neutrinos do, in fact, experience time and hence must have a mass, which challenges one of the assertions of the Standard Model. Observations of the oscillation, however, determine only mass-squared differences rather than masses themselves; that is, they measure the absolute value of the difference in the squares of the neutrino masses. The mass-squared differences inferred from the data are very tiny, tenths of electron volts and less. This is very small compared with the typical masses of quarks and other leptons, and it is more than 10 orders of magnitude lighter than the top quark.

Why are the neutrino masses so tiny? Another new puzzle uncovered since these discoveries is that the compositions of neutrinos with definite mass values are highly mixed up, as shown in Figure 4.1, with large fractions of electron, muon, and tau types in a given neutrino. This must be compared with the situation among quarks, where the amount of mixture is very small, 0.01 to 5 percent. The aim of the next-generation experiments is to establish the newly emerging picture and to determine yet unknown parameters in the neutrinos, and then to understand how the Standard Model must be revised. The mixtures can be quantified in terms of angles, with an angle of 0 degrees signifying no admixture and 45 degrees the maximum admixture of a second flavor. With three flavors, there are three angles, θ_{12}, θ_{23}, and θ_{13}. The mixture of the electron type in the third neutrino is related to θ_{13} and is known to be small, but scientists do not know how small. There may be additional neutrino species (sterile) beyond those we currently know. If so, how many are there?

We do not know if the neutrinos are their own antiparticles. If the answer is yes, they may have played a crucial role in creating a tiny imbalance between matter and antimatter in the universe, so that some matter survived the annihilation and led to our existence. For this to be the case, there must be a subtle difference between the behavior of neutrinos and antineutrinos, called charge-parity (CP) violation.[1]

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[1] The charge-parity transformation should not be confused with charge conjugation, the transformation that connects a particle with its corresponding antiparticle.

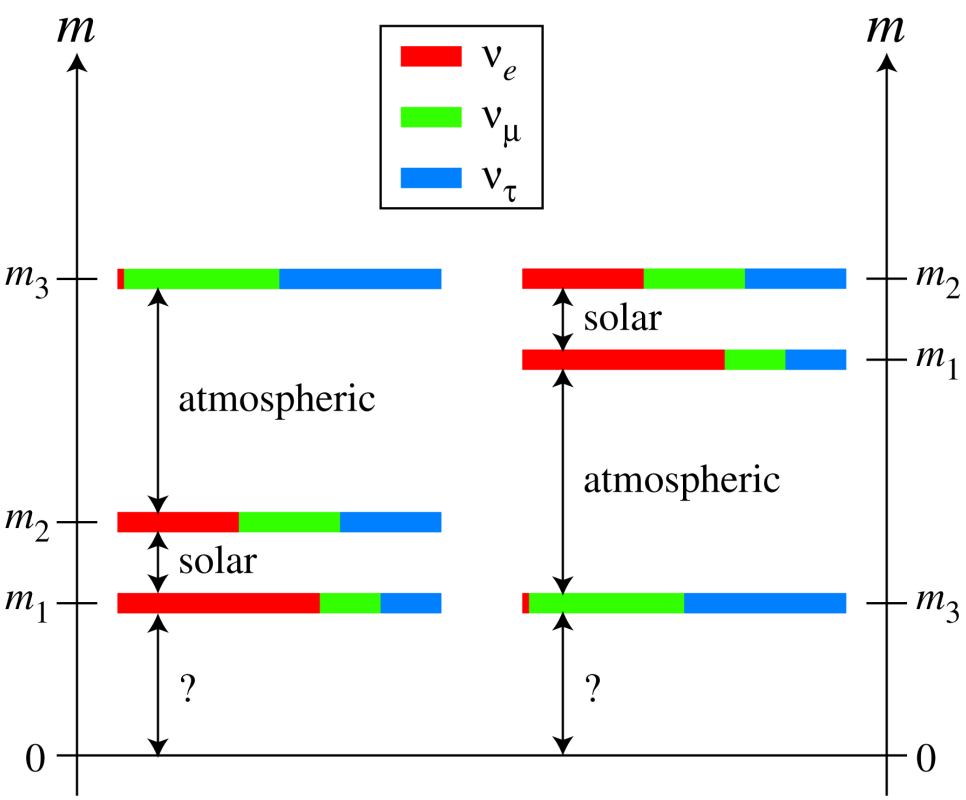

FIGURE 4.1 Shown are two possible patterns of masses and admixtures of three neutrinos that explain current solar and atmospheric neutrino data. The different colors represent the admixture of the electron, mu, and tau neutrinos in each mass value. Scientists do not yet know which pattern is correct. The differences in mass and the admixtures are known only crudely. The absolute scale of neutrino masses is largely unknown, but it is not greater than 2.2 eV. Next-generation neutrino oscillation experiments aim to determine the admixtures and mass-squared differences but not their absolute scale. Experiments on the neutrinoless double beta decay would supply crucial information on the absolute scale. The potential differences between neutrinos and antineutrinos are also unknown. Image courtesy of H. Murayama, University of California at Berkeley.

As discussed in the subsequent sections, these issues can be studied in a variety of experiments involving more accurate studies of solar and atmospheric neutrinos, double beta decay, and accelerator-based neutrino experiments, especially those with long baselines. A deep underground laboratory will play a crucial role in these proposed experiments.

Solar Neutrinos

The Sun, powered by nuclear fusion, is an abundant and pure source of electron neutrinos. Trillions of solar neutrinos pass through our bodies every second. Solar neutrinos were first detected in an experiment in the Homestake Gold Mine in South Dakota by Raymond Davis, Jr. That experiment also gave the earliest indication for a finite neutrino mass when only a third of the expected number of neutrinos was seen.

This shortfall is now understood quantitatively. The SNO in Canada has recently shown that all the neutrinos are there as expected, but two-thirds have changed from their original electron flavor to flavors not detectable in the Homestake experiment—muon and tau neutrinos. Strong indications of this conversion were already apparent when data from the Super-Kamiokande, SAGE (Soviet American Gallium Experiment), Gallex, and Homestake solar neutrino experiments were considered together. A new solar neutrino experiment, Borexino, and a reactor antineutrino experiment, KamLAND, are now being used to provide tighter constraints on the neutrino mass and mixing parameters responsible for flavor conversion.

The dominant mechanism of neutrino production is referred to as the *pp* (proton-proton) neutrino reaction: In the standard solar model the flux from the *pp* reaction is predicted to an accuracy of 1 percent. Further, the total flux is related directly to the measured solar optical luminosity. Such a copious and well-understood source of neutrinos is ideal for precisely determining the neutrino masses and mixings where accelerator techniques are limited. It also affords a way to search for hypothesized sterile neutrinos as much as a million times lighter than those explored by present experiments, provided they mixed sufficiently with the active neutrinos. Unfortunately, the *pp* neutrinos have very low energies (see Figure 4.2).

A program of low-energy solar neutrino measurement is straightforward in concept but difficult to carry out in practice. Two types of experiment are required, both sensitive to the lowest-energy neutrinos. One experiment measures the electron-flavor component by the charged-current (CC) reaction, while the other measures a combination of electron, mu, and tau neutrinos via elastic scattering (ES) from electrons. Taken together, these measurements provide model-independent determinations of the electron and nonelectron neutrino flux components at each energy and solar-model-dependent determinations of the sterile components. Because the electron and nonelectron rates are similar, a good measurement of the difference places great demands on the quality of the CC and ES experiments.

At these low energies, backgrounds become formidable. The background

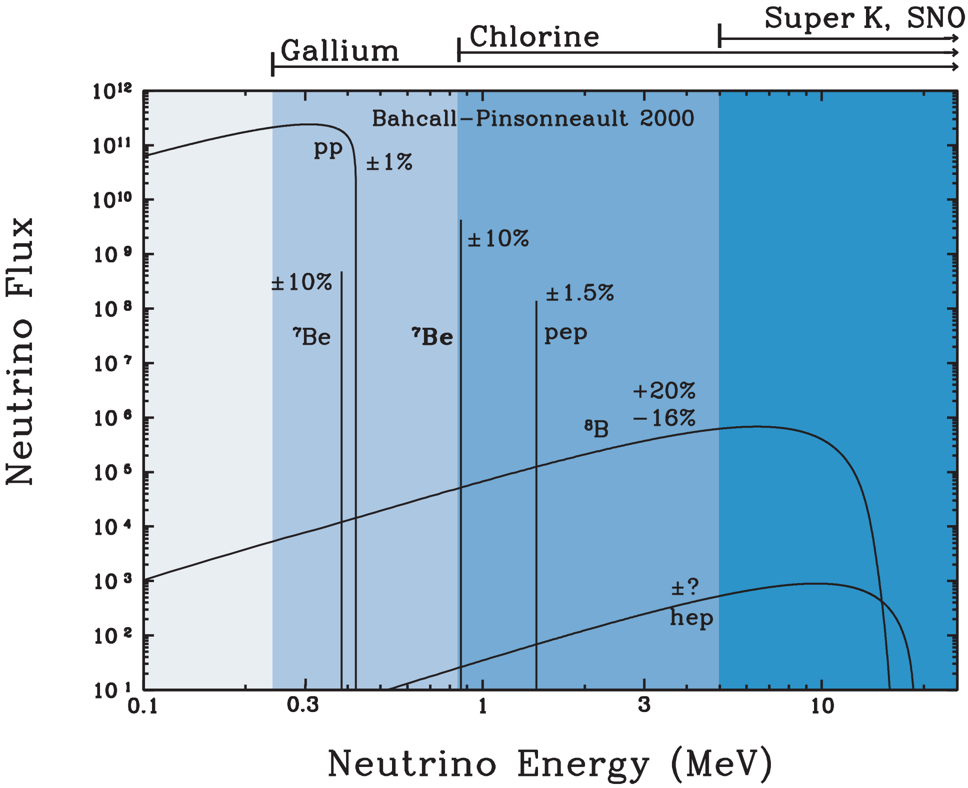

FIGURE 4.2 The flux of neutrinos per unit energy of neutrinos produced by the Sun during the course of fusion reactions. The three regions labeled across the top indicate the expected energy-range sensitivity of different solar neutrino detectors. The different curves on the plot correspond to the neutrino energy spectra for neutrinos from different fusion processes within the Sun, such as the *pp* reaction or the *pep* chain. Figure courtesy of J. Bahcall and M. Pinsonneault.

problem can be to some degree circumvented in CC experiments by selecting target nuclei (^{100}Mo, ^{115}In, ^{176}Yb, etc.) that provide a "tag" for neutrino capture—that is, a subsequent decay at the same position and almost the same time that specifically identifies the neutrino event in a welter of irrelevant background events. Such tags cannot be arranged for ES experiments, but the rates are higher and the targets simpler.[2] Good ideas exist for both types of experiment. They are cur-

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[2] It is key to realize that although the effective rates of solar electron and nonelectron neutrinos are similar, the two reactions discussed (CC and ES) do not occur with the same frequency per incident neutrino.

rently in an R&D phase—some of them will need underground space for tests soon, and some are already taking place (i.e., the Low Energy Neutrino Spectroscopy (LENS) project at Gran Sasso).

Clever experimental strategies and extreme measures to remove radioactive contaminants are only a part of a successful response to the low-energy challenge. Cosmic rays continuously create new radioactivity in the detector, and the only remedy is to place the detectors beneath hundreds or thousands of meters of rock. While every experiment will have a different tolerance to this type of activation, a conservative estimate can be made by comparing the rate of solar neutrino interactions with the background rate of nuclear transmutations caused by muons.

The ES experiments expect a signal event per day in roughly 2 tons of detector, which equals the transmutation rate at a depth around 3,000 mwe. Since no tag exists for the ES experiments (other than that the scattered electrons point away from the Sun), a substantial margin of signal over background is desirable, which could be achieved at depths of 6,000 mwe. The CC experiments expect rates 10 to 100 times smaller (for unenriched isotopic material) but, in most of the cases proposed, have a tag that helps with background rejection. The signal rate equals the transmutation rate at a depth of about 6,900 mwe.

Although current-generation solar neutrino observatories could significantly advance the state of the science, there is still much to learn, especially in low-background, high-precision physics. It cannot be said that these difficult experiments would be impossible at depths less than 6,000 mwe, but it is clear that at such a depth a major background source is under control, whereas at lesser depths it remains uncertain. A laboratory sited at 6,000 mwe thus offers a unique and powerful advantage to physicists seeking to observe low-energy solar neutrinos.

Long-Baseline Experiments

Particle accelerators can provide a precisely understood source of neutrinos. In the study of neutrino properties, neutrino beams from particle accelerators can provide information complementary to that from future solar neutrino experiments that address measurements not accessible to accelerator experiments (see Figure 4.3). Protons from accelerators produce an almost pure beam of muon neutrinos, while solar neutrinos are purely electron neutrinos. With such beams, researchers may even observe CP violation, a possible subtle difference in properties between neutrinos and antineutrinos that may be fundamentally related to the matter-antimatter asymmetry of the universe. Solar neutrino beams are generated at the far end of an extremely long baseline; thus the arriving beam of neutrinos at Earth has gone through many oscillations.

The dramatic discovery of neutrino oscillation was made using a natural source

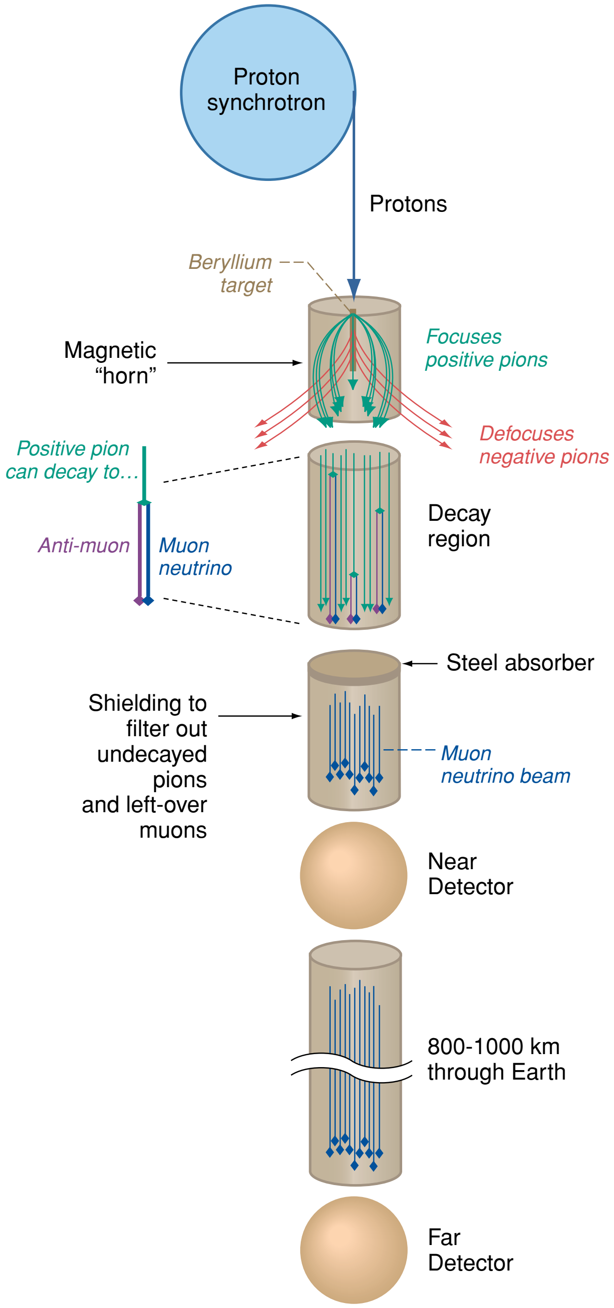

FIGURE 4.3 Shown here is one depiction of a long-baseline neutrino oscillation experiment. The neutrino beam is produced by focusing an intense beam of high-energy protons on a proton-rich target such as beryllium. The particle debris is cleaned and focused by a powerful electromagnetic system called a magnetic horn. The resulting beam consists of almost entirely pions, which will decay in flight into muons and muon-neutrinos. A steel absorber is used to stop the remaining pions and newly born muons. In the long-baseline experiment, the berm of earth in the figure is actually formed by Earth itself; a neutrino beam would travel thousands of kilometers before arriving at the target, where the neutrinos are detected and identified by their interactions with the detector. Figure inspired by illustrations from Prof. Paul Nienaber and undergraduate Andrew Finn, BooNE Collaboration.

of neutrinos. When cosmic rays hit Earth's atmosphere, neutrinos are created that enter underground experiments. Even those created on the other side of Earth easily penetrate Earth and reach these experiments. These atmospheric neutrinos were studied in great detail by the Super-Kamiokande experiment that provided convincing evidence for neutrino mass. The oscillation effects in this case occur only over distances comparable to the size of Earth. For quantitative measurements of neutrino mass and mixing parameters, however, accelerator-based neutrino oscillation experiments are crucial. With particle accelerators, scientists can control the energy, direction, flux, and even the composition of neutrino beams. To study this phenomenon and make accurate measurements requires a long distance between the accelerator, where neutrinos are produced, and the experiments, where they are detected. Funded or newly operating experiments designed to more accurately determine them include KEK to Kamioka (K2K) in Japan, ICARUS/OPERA (Imaging Cosmic and Rare Underground Signals/Oscillation Project with Emulsion Tracking Apparatus) in Europe (on hold), and NuMI/MINOS (Neutrinos as the Main Injector/Main Injector Neutrino Oscillation Search) in the United States, all relatively long-baseline experiments (200-800 km) using neutrinos from accelerators. These are expected to provide data over the next decade that should corroborate the specific qualitative description of neutrinos and should measure some parameters to about 10 percent. It is expected that the evidence for oscillations in atmospheric neutrinos will be found by these experiments to be primarily mixing between the muon and tau types. However, the remaining critical mixing parameter, known as θ_{13}, will be poorly determined at best. This parameter is different from zero if each of the three neutrino types (electron, muon, and tau) mixes with all the others. The value of θ_{13}, now known to be less than 10 degrees, will be measurable by currently planned experiments only if its value is larger than 1 degree.

Though the entire picture could be changed as a result of these experiments, such as the U.S. MiniBooNE effort, it is more likely that they will reinforce the need for accurately determining all the mixing parameters. Extrapolating to the time frame of a U.S. facility for underground experiments, accurate measurement of θ_{13} will be the critical goal and the gateway to exciting new issues, like CP violations and establishing the neutrino family mass hierarchy (see Figure 4.2). Both can be addressed if the value of θ_{13} is large enough. Sensitivity to all these questions depends on many factors, but mostly on (1) the neutrino energy, (2) the distance between neutrino production and observation, (3) the neutrino source flux, and (4) the detector mass and sensitivity.

The most likely route to determining θ_{13} is measuring the (small) oscillations that take place between muon and electron neutrinos in an experiment designed with specific combinations of energy and distance. For accelerator-produced neutrino energies higher than 1 GeV, the optimal distances are longer than about 500 km, depending on the exact value of the mass splitting, which will be determined in the next few years. Since the probability of oscillation is small and the fraction of the neutrino beam intercepted by the target decreases with distance, very high fluxes of neutrinos will be required. If measuring θ_{13} goes reasonably well, measuring the mass hierarchy and the CP properties of the neutrino admixtures will be compelling. For these goals, the massive target/detectors and high-flux sources will have to be more substantial. It has been shown that it is not easy to disentangle effects of θ_{13}, different mass hierarchies, and CP violation, because all of them affect the oscillation probabilities simultaneously. Researchers will need at least two different baselines and/or energies to resolve each of them separately. In Japan and Europe, the baselines currently envisaged are relatively short. Therefore it makes sense to develop plans for experiments with baselines longer than 1,000 km in the United States in the context of the international program. Indeed, distances from the two major proton laboratories (Fermilab and Brookhaven) range from 1,200 to 2,600 km for the several proposed underground sites.

Already-planned long-baseline experiments involve neutrino energies of the order of gigaelectron volta, beam powers of ~100 kW, detectors of 5-50 kt, and distances of 200-700 km. Future experiments to explore the longer-term issues will require similar neutrino energies but higher beam power (megawatts) and larger detector masses (megatons). They will also likely be planned for modestly longer distances (~2,000 km). An important issue to be resolved for such experiments is the high-power source, whether it is more intense (a superbeam) or supplies a storage ring serving as a neutrino factory. Superbeams are being considered in many parts of the world. The neutrino factory concept is undergoing substantial accelerator R&D, and demonstrating its feasibility will take time.

Such experiments in the United States are probably still a few years away. It may be wisest to finalize plans after the mixing parameters are better known. More important, the neutrino source requires careful planning and has to be coordinated with optimization of a large, well-instrumented detector. An operating underground laboratory would facilitate this planning. Also, laboratory infrastructure and staff would greatly expedite the installation, commissioning, and operation of large detectors. Positioning at even a modest depth will reduce the cosmic-ray-induced backgrounds. However, the neutrino beam energy (high) and the duty cycle possible from accelerators (short) should reduce the need for great depth to keep backgrounds to acceptable levels, although some overburden is desirable. (In fact, the more critical detector feature for a successful long-baseline program is the size of the detector, as this directly affects the flux of incoming accelerator neutrinos that can be analyzed.) It should be noted that the large detector might well serve other scientific functions, such as searching for proton decay and/or observing supernova neutrinos. The depth-location of such a detector may be determined by these considerations.

The neutrino mixing parameters form a gateway to understanding fundamental features of matter and energy unanticipated in the Standard Model. Measuring them, in long-baseline experiments, represents an opportunity for which the United States has important (and somewhat unique) historical, scientific, and geographical advantages. If the United States is to capitalize on this opportunity to lead in such experiments, planning should start in the near future, take into account forthcoming experimental results, and be finalized in about 5 years. Such plans are likely to be much more reliable if an underground facility is available to house the target detector.

Double Beta Decay

The major discovery of the past decade regarding the properties of elementary particles has been the confirmation that neutrinos, the most elusive of the known elementary constituents of the world, have mass. Oscillation experiments have shown that there are nonzero differences between the squares of the masses of different kinds of neutrinos and therefore prove that neutrinos have a finite mass. However, the absolute value of the mass and whether the neutrino is distinct from its antiparticle are still open questions. If the neutrino is distinct from its antiparticle, it is a Dirac particle, as are all the other known elementary particles with spin 1/2. If it is indistinguishable, it is a Majorana neutrino. The search for neutrinoless double beta decay is motivated by the need to determine the mass and antiparticle nature of the neutrino.

In most nuclei found in nature with even numbers of protons and neutrons, simple beta decay (with the emission of an electron and a neutrino) is energetically forbidden. However, the simultaneous emission of two electrons with a daughter nucleus differing by two charges (double beta decay) can be possible. This process is expected and observed within the Standard Model of particle physics when it occurs with the emission of two neutrinos in addition to the two beta particles, and it is called two-neutrino double beta decay. In this type of decay, since the neutrinos go undetected, one observes a spectrum of the sum of the energies of the two beta particles that extends up to the total energy available for the decay. A more interesting process is that of neutrinoless double beta decay, in which no neutrinos are emitted and the two beta particles share the total energy. If neutrinoless double beta decay exists, it implies that neutrinos are Majorana particles, and its rate is proportional to the square of the Majorana mass. Should the existence of neutrinoless double beta decay be convincingly proven, the resulting qualitative physics conclusion regarding neutrino properties would have an extremely important impact on our understanding of the fundamental properties of nature.

There is a consensus that the atmospheric neutrino measurements by the Super-Kamiokande collaboration can only be interpreted as a consequence of the nearly maximal mixing between the muon-like and the tau-like neutrinos with the corresponding mass-squared difference $\Delta m_{atm}{}^2 \sim 3 \times 10^{-3}$ eV^2. Thus at least one neutrino has a mass greater than 50 meV, and this value sets the goal for the next generation of double beta decay experiments. Although the oscillation properties can be pinned down better by further oscillation experiments, to determine the neutrino mass requires either a direct mass measurement or an observation of neutrinoless double beta decay. Furthermore, only double beta decay has the potential to elucidate the antiparticle nature of the neutrino. Hence, measurement of a nonzero rate would be truly unique and truly spectacular.

For an effective mass of 50 meV, the predicted half-lives of the various neutrinoless double beta decay candidates are about 10^{27} years. To reach this level of sensitivity in a few years of running, an experiment requires approximately 1 ton of a particular isotope. In addition, since the discovery of neutrinoless double beta decay requires observation of a peak superimposed upon a continuous background, the background must be very low in the peak region. The various causes of background can be sorted into three classes: two-neutrino double beta decay, natural (or sometimes manmade) radioactivity, and radioactivity induced by cosmic rays. Since the two-neutrino double beta decay rate is at least 10^7 times faster than neutrinoless double beta decay and its energy spectrum extends up to the peak region, good energy resolution is essential. Certain members of the naturally occurring uranium and thorium chains are radioactive and have large enough decay energies to pollute the peak region. Since the half-lives of the parent uranium and thorium isotopes ($\sim 10^{10}$ years) are much shorter than that of double beta decay, very low uranium and thorium impurities in a detector are critical. In addition, the detector must be shielded from the ambient radiation of the surrounding environment by shielding that is also free of activities, and any volume near the detector must be purged to prevent the ingress of radon. The activities of cosmogenic isotopes produced while the critical materials reside on the surface can be especially high, so it will be necessary to purify, fabricate, and assemble parts underground. Cosmic rays can also either directly produce background in the experiment or give rise to radioactivity in situ through their secondaries. The former can be completely mitigated with overburden, and the latter requires depth that depends on the material in question. Most of the proposed experiments will require a depth of 4,000 mwe or deeper to mitigate the cosmic-ray-related background.

There are several proposals in the United States and around the world for next-generation double beta decay experiments with sensitivity to 50 meV. The Enriched Xenon Observatory (EXO), Majorana, and the Molybdenum Observatory of Neutrinos (MOON) proposals have U.S. participation and will very likely be carried out in the United States if acceptable underground sites can be found. These three and the Germanium Nitrogen Underground Setup (GENIUS) and the Cryogenic Underground Observatory for Rare Events (CUORE) proposals are the most advanced efforts, in the committee's opinion, for reaching the 50-meV target. There are a large number of experienced double beta decay experts in the United States and an even greater number of low-background experts. Many of these experts involved are involved in emerging U.S. collaborations. These collaborations are currently expanding their personnel and performing research and development measurements. They have obtained seed money and are writing proposals. Two of these experiments (EXO and Majorana) will be looking for an underground site for initial detector systems later this year. There are also U.S. collaborators on the CUORE project, which is being assembled in Europe. All in all, the United States is in a strong position to make a significant contribution to this next generation of experiments. Deep underground laboratory space is essential to success, and a national underground facility is a natural way to meet this need.

DARK MATTER

Over the past decade, strong evidence has led to the conclusion that neither ordinary matter nor even massive neutrinos can account for most of the missing matter. A strong case has been made for a new form of elementary particle as the resolution of the dark-matter problem, and this idea has become the working hypothesis of both astronomers and particle physicists. One of the leading particle candidates is a hypothetical particle motivated by supersymmetric theories, the neutralino. The committee focuses on the neutralino here since its study is within the purview of underground experiments. This type of candidate is often termed a weakly interacting massive particle, or WIMP for short.

The planned direct detection experiments are particularly well suited to complement IceCube since they search for relatively light WIMPs using neutralino–heavy nuclei interactions. (Recall that IceCube's primary sensitivity to WIMPs is through detection of neutrino decay products when pairs of WIMPs trapped in the Sun annihilate.) As such, the two methods are sensitive to neutralinos in different environments—Earth and heavy nuclei, the Sun and ionized hydrogen—and thereby provide complementary sensitivity to different types of neutralinos through so-called spin-independent and spin-dependent interactions.[3]

In the mid-1980s, new calculations showed that WIMP detection is a tractable though difficult experimental challenge. More recent calculations predicted that neutralinos in the galactic halo could be expected to interact in terrestrial detectors at most about once per day for every kilogram of detector material. Ordinary detectors under ordinary laboratory conditions would be overwhelmed by the rates of natural radioactivity and cosmic rays compared with this signal. The general methods for defeating these backgrounds are careful screening and cleaning of materials, active and passive shielding, protection against contamination, and siting in underground locations to reduce cosmic-ray-related activity. Additional tools include detectors with intrinsic rejection of background events, such as recoil discrimination or insensitivity to low-energy-density depositions, and approaches that take advantage of secondary features such as directional or seasonal modulation.

At this time, no conclusive evidence exists for WIMPs. Early WIMP detection experiments in the late 1980s using existing detector techniques were able to make progress, but it was clear that new technologies with the capabilities outlined above were required. Following a decade of successful development, new techniques have led to greater sensitivity and hold promise for significant experimental improvements. New technologies will give their promised sensitivities only with larger detectors, with improved background suppression, and preferably with the means to distinguish terrestrial backgrounds from galactic WIMP sources. Technologies that scale to 1 ton will be needed to fully explore the range of currently favored models. Internationally, groups with strong U.S. representation are advancing this broad array of technologies.

Two broad classes of background events must be addressed. First, electromagnetic backgrounds, which generally have their origin in radioactive contamination or cosmic rays, give rise to events that can be distinguished from WIMPs because they recoil from electrons, whereas WIMPs recoil from nuclei. Since the tools to distinguish these backgrounds are never perfect, it is crucial to reduce the level of contamination through screening and fabrication techniques, as with the double beta decay experiments. Second, neutrons, which come from a variety of sources, are not directly distinguishable from WIMPs because they, too, recoil from nuclei. Most sources of neutrons—for example, natural radioactivity in rock—are relatively low energy and can be effectively shielded against. A troublesome source is

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[3] Recall the discussion in the Chapter 3 section entitled "Signatures of New Physics."

more penetrating high-energy neutrons produced by cosmic rays interacting in the rock. These neutrons are difficult to shield or detect.

There are several experiments under way in the United States and worldwide to detect the dark matter. The leading efforts include the French Edelweiss experiment in Fréjus and the U.S. Cryogenic Dark Matter Search (CDMS) at the Soudan Mine, both using low-temperature detectors; the Italian experiment Dark Matter (DAMA) in the Gran Sasso laboratory using a large array of sodium iodide detectors; and the U.K./U.S. Zoned Proportional scintillation in Liquid Noble Gases (ZEPLIN) experiment using liquid xenon in the Boulby Mine in the United Kingdom. The challenge for these collaborations is to avoid claims of a false signal by fully understanding each experiment's systematic effects. The other experiments mentioned, along with a range of other approaches—including gas detectors with directional sensitivity (the U.S.-led Directional Recoil Identification From Tracking (DRIFT) experiment); a competing liquid xenon experiment (the U.S.-led XENON collaboration); ultrapure germanium diode detectors (the U.S.-led Majorana and German-led GENIUS efforts); and superheated droplet detectors (U.S.-led Superheated Instrument for Massive Particle Experiments (SIMPLE) and Canadian-led PICASSO efforts)—are in various stages. Each of the approaches attacks the electromagnetic backgrounds with a variety of methods, with a common aspect being that some suppression and screening of radioactive contamination are required. Common to all is the need to suppress the muon-induced neutron background by operating deep underground.

At present, the efforts range widely; some teams are using fully instrumented small-scale prototypes, and others are already working with several-kilogram experiments of proven technology. The field is very active, and there will be a worldwide race to prove approaches that support up to 1 ton of detector mass. While 1- to 10-kilogram-scale experiments get under way, the various investigators will be learning what is required to realize ton-scale detectors. Proposals for such experiments, which typically aim for 100-kg submodules, are expected in the next 2 to 4 years and could run concurrently with the Large Hadron Collider, which will explore in a complementary fashion the same underlying physics of supersymmetry or other new physics at the electroweak interaction scale.

To a degree, improvements in detector technology or assaying and screening of detector components can reduce the level of electromagnetic backgrounds at any given depth. However, neutron backgrounds are very difficult to reduce once the depth is set and the experiment is in place.

An important question is, How deep underground? The answer depends on the relative immunity to electromagnetic and neutron backgrounds and is therefore experiment-specific. In general, the committee anticipates reduction of electromagnetic backgrounds by further technological improvements that are independent of depth. Such improvements will increase the overall sensitivity to WIMPs only if there is a concordant reduction in the neutron background. With only a modest reduction in electromagnetic backgrounds—which looks achievable in the coming decade—siting at less than 4,500 mwe could leave neutrons as the dominant source of background. By siting these next-generation ton-scale experiments at depths of 4,500 mwe or greater, the risk of being background limited by neutrons will be considerably reduced. A depth of 6,000 mwe may be required for more sensitive subsequent-generation experiments. In general, siting the lab as deep as possible will extend its ultimate reach or, alternatively, the time it will operate at the forefront of the field. With kilogram-scale experiments already under way, work on the underground lab must begin as rapidly as possible to allow the R&D for ton-scale experiments to get started. The creation of a unique, well-equipped, deep underground lab will maximize the chance for the United States to play a major role in dark-matter detection.

When astronomer Fritz Zwicky found the first evidence for dark matter many decades ago, little did he realize that the answer to his mystery would involve not faint stars but—most likely—a new form of matter whose existence is key to understanding the union of the basic forces of nature.

PROTON DECAY

It is an important question whether the kinds of matter we are made of, ordinary atoms with ordinary nuclei and electrons, are stable. In the Standard Model of particle physics, the so-called baryon number is conserved. The proton that makes up atomic nuclei is the lightest particle with nonzero baryon number and, hence, is absolutely stable. In most extensions of the Standard Model, however, baryon number is not conserved, so the proton is predicted to decay. Ultimately all known forms of matter would decay, albeit with lifetimes many orders of magnitude longer than the age of the universe. The discovery of proton decay would have an enormous impact on the understanding of nature.

There are many arguments for why the proton should decay. The simplest one is that our universe consists of matter only, with no antimatter. When the universe was born, both matter and antimatter were created in equal amounts. If it had stayed that way, all matter and antimatter would have annihilated each other by now and we could not exist. The matter we are made of has survived this great annihilation because a tiny fraction of antimatter (1 part in 10 billion) has transmuted to matter. This implies that baryon number is not conserved, in turn implying that the proton must decay.

Einstein dreamed of a simplicity underlying the diverse phenomena we see. The recent discovery of a tiny neutrino mass strongly suggests that such a unified simple description of nature exists. If all forces of nature are indeed unified at extremely short distances, such as in so-called grand unified theories, then quarks (constituents of protons) and leptons (such as electrons and neutrinos) are ultimately the same objects. These particles appear distinct because we usually study them at large distances, where the forces between them behave differently for the various particles. However, in this picture, quarks in the proton sometimes approach each other within the very short distances where the forces are unified, permitting the conversion from quark to lepton and, hence, a decaying proton.

Another argument is based on the marriage of the theory of the microscopic world—quantum mechanics—with the theory of the macroscopic world, Einstein's theory of gravity. Because a proton could be sucked into a virtual black hole and quantum gravity is believed to violate any law of conservation not associated with long-range forces, protons will decay. However, within the context of the Standard Model, proton stability arises because no known particle species can mediate the process for the proton to decay. So, researchers expect that particles in nature that have yet to be discovered could mediate proton decay.

Probably the most important aspect of the search for proton decay is that it is a unique probe for the shortest distance scales available, with the possible exception of the neutrino mass. Past experiments have already shown that the proton lifetime must be greater than 10^{32} years for many of the possible decay modes. If the proton decays at all, it must be an extremely rare phenomenon. The current limit implies that the constituents of a proton, distributed over 10^{-13}cm, must come as close as 10^{-29}cm for the reaction to occur. In other words, the search for proton decay provides a unique opportunity to probe physics to very small distances, where forces may be unified and the physics is simplified.

A long series of experiments were constructed to search for proton decay, such as Fréjus, IMB, Kamiokande, Soudan, and Super-Kamiokande, all situated underground. Because proton decay, if it occurs at all, must be an extremely rare phenomenon, the only way to find it is to amass a large number of protons and watch them carefully over a long period of time, looking for them to decay. The most recent experiment, Super-Kamiokande, houses 50 kt of water. Watching carefully for a proton to decay in this tank of water over many years has enabled setting the best lower limits on proton lifetime so far, 1.6×10^{33}years for $p \to e^+\pi^0$ and 6.7×10^{32} years for $p \to \nu K^+$. These lifetimes may be compared with the age of the universe, which is about 1.4×10^{10} years. This very important result has excluded the simplest models of nonsupersymmetric and supersymmetric grand unified models.

The committee notes that in a broad class of supersymmetric grand unified models (SUSY-GUT) the predicted lifetimes for $p \to e^+\pi^0$ and $p \to \nu K^+$ are only a factor of 10 to 30 beyond the present limits, motivating the next generation of detectors. Grand unified models aside, many theoretical arguments point to proton instability, as mentioned above. The search for proton decay is therefore compelling science.

For the proposed proton decay experiments, shielding from the bulk of cosmic rays is necessary, requiring a depth of about 2,000 mwe or greater. Detection of some modes of nucelon decay (e.g., proton decay to a lepton and two neutrinos, or even neutron decay into three neutrinos), may, however, require a much cleaner environment and, hence, much greater depth.

It is worth remarking that these proton decay detectors, thanks to their large masses, sensitive particle detection methods, and long lifetimes, made discoveries beyond their original purpose. Kamiokande and IMB detected neutrinos from a supernova in the Large Magellanic Cloud (SN1987A), and they confirmed the theory of Type II supernova as the death of a massive star forming a neutron star. These two proton decay experiments studied neutrinos produced in the atmosphere from the collision of cosmic rays and saw the first hint of neutrino oscillations and hence finite neutrino mass. This observation was later established by the bigger proton decay experiment Super-Kamiokande and corroborated by the Soudan-II and Monopole Astrophysics and Cosmic Ray Observatory (MACRO) experiments. Kamiokande and Super-Kamiokande have demonstrated that neutrinos come from the Sun, confirming the Sun's power source as the nuclear fusion process. They have also shown that there is a deficit in the neutrino flux relative to the predictions by the standard solar model. And now Super-Kamiokande also serves as a target detector for accelerator-based, long-baseline neutrino oscillation experiments using the neutrino beam produced at KEK (the Japanese high-energy accelerator research laboratory) at a distance of 275 km.

The increasing cost and size of next-generation proton decay experiments make it important for such an experiment to serve multiple purposes. A proton decay experiment that can act as a target detector for an accelerator-based, long-baseline neutrino oscillation experiment seems particularly attractive. The technology for building a detector 20 to 40 times bigger than Super-Kamiokande (that is, megaton-scale) is in hand. New technologies are being proposed and studied actively. In a few years, we will know more about the feasibility of these new options.

NEUTRINOS, SOLAR ENERGY, AND THE FORMATION OF THE ELEMENTS

Apart from the interest in their properties, neutrinos can also be used to probe the nuclear processes that fuel our Sun and the processes that create the elements.

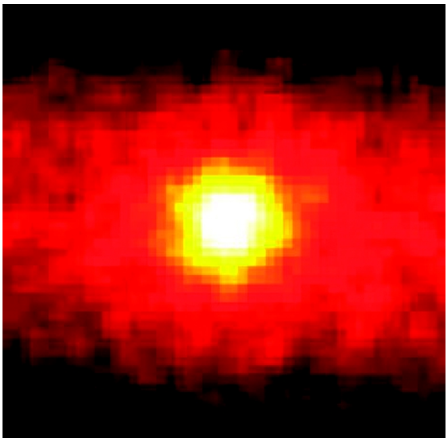

FIGURE 4.4 The Super-Kamiokande neutrino events created this false-color image of the center of the Sun from events produced by the nuclear reactions deep in the center of the Sun. Because neutrinos are so noninteracting, they can be used to probe deep inside stellar objects to gain unique information on how they are powered. The angular resolution of neutrino astronomy is still poor compared with that of optical telescopes; in this figure, the visible light image of the Sun would be about one pixel. Image courtesy of the Institute for Cosmic Ray Research, University of Tokyo.

Because neutrinos can escape from an enormously dense material, they carry direct information about the interiors of stars and gas that cannot be studied by optical telescopes. A number of measurements can potentially be carried out in an underground laboratory.

The "burning" of hydrogen in the Sun (the conversion of protons into helium) is the source of energy that makes life possible on our Earth. The reactions believed to be responsible for most of this energy production cannot be observed directly because they occur in the interior of the Sun—what can be measured well is the total thermal energy radiated from the solar surface. Neutrinos provide a direct window on these processes (see Figure 4.4).

The solar neutrino detectors using water Cerenkov technology, such as Super-Kamiokande and SNO, are able to look at higher-energy neutrinos only. Direct experimental confirmation of the basic features of the solar neutrino spectrum is lacking. And despite our confidence in understanding the Sun's operation, some questions do remain. In addition to the main cycle, in which hydrogen converts into helium, a second cycle of thermonuclear reactions can occur, in which the elements carbon, nitrogen, and oxygen (CNO) serve as nuclear catalysts for converting hydrogen to helium. Only about 2 percent of the Sun's energy is believed to come from the CNO cycle (this percentage depends on the presolar abundances of these elements relative to hydrogen and helium). Additionally, the differences in relative abundances on the surface and in the solar interior may be revealed by the solar neutrino spectrum. Direct measurements of the associated neutrinos below 2 MeV in energy may resolve these issues.

There are smaller experiments in Europe and Russia that are sensitive to the much more abundant lower-energy neutrinos. But precision experiments to determine the spectrum and absolute total neutrino flux in the key low-energy region will be difficult and certainly will require very carefully controlled background conditions, which a sufficiently deep underground facility would provide.

The processes in the Sun are typical of similar stars that are too far away for their neutrinos to be detected on Earth. A detectable signal from distant stars is the result of extreme conditions, and by far the most likely cause is a supernova.

When a star's nuclear fuel has been sufficiently exhausted, it begins to contract, and if its mass is sufficiently high, it will collapse under gravitational forces. This collapse leads to a supernova: an enormous explosive release of energy during which the star can outshine a galaxy in visible light, yet 99 percent of the energy is released in the form of neutrinos. It is only in such very hot environments that elements heavier than oxygen can be released—the heavier elements in the solar system, such as iron, gold, and platinum, are the product of past supernova explosions. The details of this cataclysmic collapse and the location of the rapid neutron capture that must produce the elements from iron through uranium are still poorly understood. At the extremely high densities that are reached, neutrinos are momentarily trapped and escape over many seconds, cooling the star. The intense flux of neutrinos is believed to reenergize the explosive shock wave that is otherwise stalled by infalling matter and that ultimately flings the mantle of the star into space. The remaining matter will be captured and form a neutron star.

Supernova events have caught the attention of astronomers since ancient times. They are visible when sufficiently close and not hidden by dust. This happens roughly once every few hundred years in a typical galaxy. The light from most supernovae in our galaxy is obscured by galactic dust—it is believed that there may be a few such events per century—but the neutrinos are undeterred by dust. Indeed, some estimates suggest that there are more nearby, optically clouded supernovae (i.e., visible primarily through neutrinos) than there are optically visible ones. In 1987, light from a supernova in the Large Magellanic Cloud (a nearby dwarf galaxy) was seen by telescopes, and simultaneously, 17 neutrinos were detected in the large water volumes of two operating underground proton decay experiments. To understand the mechanism of supernovae better will require detecting many more (thousands) of neutrinos from a single supernova and measuring the flux of the emitted neutrinos, the energy spectrum, the time distribution (the pulse lasts a few seconds), and the distributions among the different flavors of neutrinos and antineutrinos.

The best signals will come from nearby supernovae, but the times of their occurrence are not predictable. Existing detectors such as the Large Volume Detector (LVD), Super-Kamiokande, SNO, and KamLAND, as well as planned future detectors, would primarily detect electron antineutrinos and provide a wealth of information about the temperature evolution of a supernova as well as neutrino properties. The sensitive detectors that are likely to be built in an underground laboratory for proton decay and long-baseline neutrino oscillation experiments, as well as those for solar neutrinos or double beta decay, will certainly provide a signal (and information) when subjected to a supernova neutrino pulse. However, a novel type of detector may be required to obtain new information about the inner workings of the supernova explosion by studying the spectrum of the muon and tau neutrinos. New designs have been proposed for this purpose.

Coordinating the observation time of supernova neutrino signals with the observation of a visible light signal and possibly with a gravitational wave pulse would provide yet more information. Neutrinos are a unique source of information about supernovae and will provide a better window on how the elements heavier than oxygen that are essential to life came to exist on Earth.

OTHER SCIENCE AT AN UNDERGROUND LABORATORY

Other uses of a laboratory deep underground have been suggested. Some are studies of neutrinos from other sources of geological and astrophysical origins; the committee did not assess these. Others range over a wide variety of interesting possibilities that were beyond the charge and expertise of this committee, from geologic processes to subterranean life forms to other uses of such environments with ultralow backgrounds, including, possibly, applications related to national security.

UNDERGROUND SCIENCE IN AN INTERNATIONAL CONTEXT

Underground science is a burgeoning effort in most scientifically advanced countries outside the United States, with laboratories of various sizes and at various depths in operation or planned for operation. Historically, the United States has been the leader in underground physics because of the pioneering Homestake and IMB (the precursor to the Japanese Kamioka experiment, in fact) experiments, which gave it a tradition of excellence and discovery. Currently operating labs are summarized in Figure 4.5, which plots the depth of the laboratory against the cosmic-ray muon flux at that depth. The “depth” is not the actual depth, but rather the equivalent water depth in meters (mwe) that would reduce the muon rate by the same factor.

The Baksan Laboratory in Russia is the first deep facility (4,700 mwe) specifically excavated for physics. It played a major role in solar neutrino physics with the discovery in the SAGE (Soviet-American Gallium Experiment) experiment

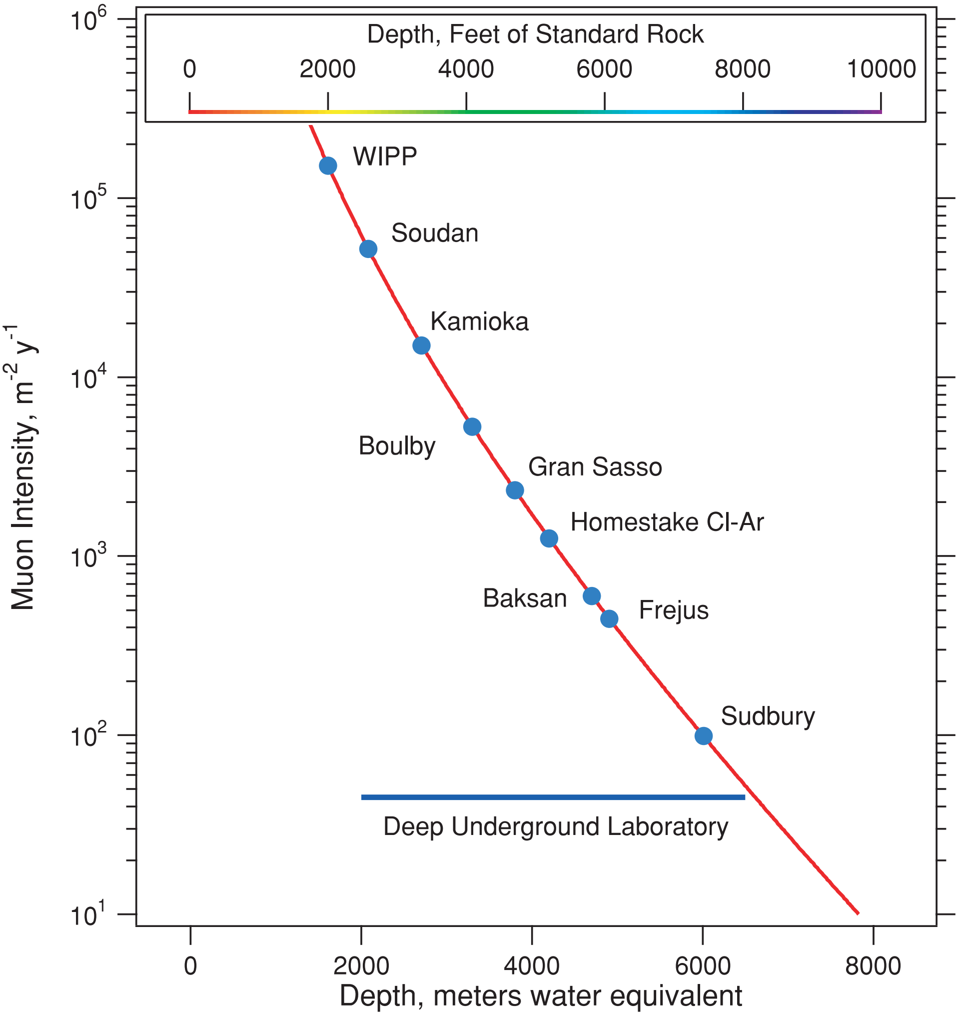

FIGURE 4.5 Variation of the flux of cosmic-ray muons with overburden. Standard rock has a density of 2.650 g cm^{-2}, but actual rock density depends significantly on location. The horizontal bar indicates the range of depths that would be available for experiments in a multipurpose underground laboratory. Note that there are diminishing returns; at about 12,000 mwe the rate of muons generated from neutrinos equals the rate from cosmic-ray-induced muons. Figure courtesy of R.G.H. Robertson.

that the flux of low-energy neutrinos from the Sun was also suppressed. The research in Baksan on solar neutrinos and cosmic rays continues, despite difficult conditions.

In Europe several small laboratories have been built contiguous to road tunnels (Canfranc Underground Astroparticle Laboratory (LSC), Fréjus-Modane Underground Laboratory (LSM), Gotthard, and Mont Blanc), as well as a large multipurpose installation, the Gran Sasso National Laboratory in Italy. While some are no longer in use, Fréjus (4,900 mwe) is in demand, and Canfranc (2,450 mwe) and Gran Sasso (3,800 mwe) are being expanded. The Gran Sasso Laboratory hosts the Gallium Neutruino Observatory (GNO) experiment; Borexino (a liquid scintillator detector for solar neutrinos); and two long-baseline experiments to detect neutrinos from CERN. A 1,000-ton supernova detector, LVD; two double beta decay detectors (Heidelberg-Moscow and Cuoricino); a dark matter detector, DAMA; and two accelerators for nuclear astrophysics round out the scientific program. In addition, R&D for new detectors such as the LENS low-energy solar neutrino detector, is proceeding in Gran Sasso. Although at present oversubscribed, Gran Sasso's 18,000 m^2 of laboratory space is being expanded, with two new halls and an independent access tunnel for safety. Fréjus, with 3,400 m^2 of space at one of the deepest locations, is home to two double beta decay experiments (NEMO-3 and Telescope Germanium Vertical (TGV)); the Edelweiss bolometric-ionization hybrid dark matter detector; and a low-background counting facility. The laboratory is 130 km from CERN and is a possible site for a megaton-scale detector for neutrino oscillations, solar neutrinos, supernovae, and proton decay.

A recent and noteworthy addition has been SNO in Canada, situated in an operating nickel mine. At 2,092 m (6,000 mwe), SNO is currently the deepest operating laboratory. With new funding from the Canada Foundation for Innovation, the underground and surface experimental facilities at Sudbury are being expanded with the excavation of a new 15,000 m^3 cavity at the 2,092-m level and a 2,000-m^2 laboratory building, respectively. The first of the new experiments is PICASSO, a supercooled droplet detector for dark matter WIMPs. A cadmium-tellurium detector is under investigation to search for double beta decay in both ^{116}Cd and ^{130}Te simultaneously in a single device. Proposals from the international community for other physics experiments are being actively encouraged. The first new underground space will be available in 2003, and the facility will be complete in 2005. Eventually, when the present program in the SNO detector is completed, that 10,000 m^3 cavity will also become available for new research.

In Finland, scientific work is being carried out at 90, 210, 400, 660, and 900 m in the Pyhäsalmi Mine in Pyhäjärvi (Center for Underground Physics in Pyhäsalmi

Mine—CUPP), and a maximum depth of 1,440 m (4,050 mwe) is available for new projects. There is access by both a vehicle ramp and a single-shaft hoist. Experiments currently under way are measuring cosmic-ray interactions and the fast neutron background from radioisotopes in the rock. Proposals exist for a search for multimuon events and for a large long-baseline experiment with a beam from CERN, 2,288 km away.

The Boulby Mine (3,350 mwe) in the United Kingdom is operated by the U.K. Dark Matter Collaboration and contains dark matter detectors using xenon and sodium iodide. It is being augmented with new surface facilities in preparation for the next generation of ton-scale detectors (DRIFT and ZEPLIN).

The most ambitious and successful program in underground science has been developed in Japan. There are two major centers, one at the Kamioka Mine (2,700 mwe) and the other in a disused rail tunnel near Oto (1,400 mwe). Kilogram-scale double beta decay and dark-matter searches are in progress at Oto, but the shallow depth will not permit significant future increases in detector sensitivity. The large water Cerenkov detectors Kamiokande and Super-Kamiokande, built principally to study proton decay, have recorded one milestone after another in neutrino physics. Kamiokande was the first active solar neutrino detector, demonstrating the solar origin and the ^{8}B spectrum of the solar neutrinos. It recorded for the first time the burst of neutrino emission from a supernova. Super-K confirmed Kamiokande's indications for oscillation of atmospheric neutrinos and is in the process of searching for the same phenomenon with a neutrino beam from the KEK accelerator 250 km to the east.

Kamiokande was dismantled and replaced by the KamLAND detector, a 1,000-ton liquid scintillator experiment that is well positioned to observe oscillations of reactor antineutrinos now that the mixing parameters are known well enough from solar neutrino data. Such a measurement, if successful, will precisely determine the two parameters that define two-flavor mixing. KamLAND may also be a detector of low-energy solar neutrinos (from ^{7}Be), but at a depth of 2,700 mwe the cosmic-ray production of ^{11}C is a serious background.

Other new experiments at Kamioka include a small lithium fluoride dark-matter experiment, a gravitational wave detector, and a 100-kg prototype liquid xenon detector for dark matter, low-energy solar neutrinos, and double beta decay. The xenon project (Xenon Massive Detector for Solar Neutrinos—XMASS) is to be scaled up eventually to reach 10 tons. Further in the future (about 2007 or later), to take advantage of the "superbeam" of neutrinos from the new Japan Hadron Facility being built in Tokai 295 km east of Kamioka, a megaton-scale water Cerenkov detector, "Hyper-K," is under consideration both for a proton decay search and for long-baseline precision studies of neutrino oscillations and CP violation.

Within the United States, there are two operating underground laboratories, the Waste Isolation Pilot Plant (WIPP) in Carlsbad, New Mexico (1,600 mwe) and the Soudan Mine in Minnesota (2,080 mwe). Until recently, the pioneering chlorine solar neutrino experiment was active in the Homestake Mine in South Dakota. This mine is scheduled for closure, and there is a proposal that it be converted to a deep underground laboratory. Among its assets are its great depth (7,000 mwe or more) and existing infrastructure. Other sites in the United States are also being considered for such a national laboratory. One is a new site at San Jacinto Mountain in California, where the laboratory could be situated at a depth of 6,500 mwe and would be accessible by vehicle via a level tunnel. Greater depths would be possible with a sloping tunnel. The other is at WIPP, which is currently used as an active safe repository for low-level nuclear waste and could be expanded to accommodate an experimental physics program.

The scientific community in the United States has played a very significant role in the accomplishments in underground science in the past 30 years. For instance, the U.S. experiments at Homestake and IMB pioneered the field of underground physics. Started as a proton decay experiment, IMB also served as an atmospheric neutrino detector and was one of only two experiments to observe the neutrino flux from supernova 1987A (the other being the Japanese Kamioka project). U.S. researchers are now actively engaged in preparation for the next generation of experiments. As described elsewhere in this document, the experiments have important and fundamental objectives. Do they require a new facility, one that could be sited in the United States, and would such a facility then be unique?

In the case of the megaton-scale detectors, no underground cavity of this scale exists anywhere in the world. Such a detector serves many purposes, one of which is long-baseline neutrino oscillations, and for that purpose a relevant matter is the distance to the neutrino source. (Great depth is not required.) Possible baselines are limited in Japan, but the sizes of the North American and European continents offer a range of possibilities.

Double beta decay, solar-neutrino, and dark-matter detectors are more demanding with respect to depth. Each experiment has a different tolerance to cosmic-ray-induced backgrounds. For instance, at the depth of the Homestake chlorine-argon experiment, 4,200 mwe, cosmic-ray activation was a source of background with an attendant experimental uncertainty, whereas at the depth of the SNO experiment, 6,000 mwe, there is no significant contribution from cosmic-ray activation. Only the expanded Sudbury site appears to be both deep enough and large enough to meet the needs of some of these experiments. However, that site has only 25 percent of the excavated volume of the expanded Gran Sasso site.

With the intense activity in this field at laboratories elsewhere, will the science move forward faster than a U.S. facility and its experimental program can be built? In general, that appears not to be the case, although important exceptions exist. Megaton-scale detectors are long-term projects at an early stage. Since long-baseline neutrino physics is an objective, it is desirable to know more about the neutrino mixing parameters before committing to a design. That may take several years. Of the five ton-scale double beta decay experiments proposed, one is committed to Gran Sasso, two are sufficiently advanced that underground sites will be needed soon, and the other two are in the R&D stage. The low-energy solar neutrino experiments that will follow Borexino and KamLAND are also still in the R&D stage. Large dark-matter detectors are under construction now and can be sited at a number of locations.

In principle any of the intended experiments can be carried out at an existing site somewhere. The added value of a dedicated U.S. deep underground laboratory derives from such factors as priority use for science rather than commercial mining, freedom of access, expandability, common use of infrastructure to support many experiments, and the opportunity for the United States to retain a position of equity and leadership in a major worldwide scientific endeavor.

5

Conclusions

One of the more intriguing developments of recent years has been the growing connection between understanding the physics of the fundamental constituents of nature and understanding the universe. These constituents and their interactions shaped the very early history of the universe, as well as its evolution to the present state. The complex sets of questions involved in untangling this picture are being probed through a multiprong approach with experiments deep underground, on land, and in space. This close coupling between the science at the largest scales known and the science at the smallest scales imaginable is manifested in the science initiatives considered in this report. The proposal to develop a cubic-kilometer-scale neutrino observatory will exploit the properties of elementary particles to open a window into an unexplored region of our universe. The proposals to develop an underground laboratory describe a national facility hosting a variety of experiments that will probe some of today's most compelling questions in elementary particle physics, astrophysics, and cosmology.

The committee's scientific evaluation of the IceCube and deep underground initiatives presented in this report should be viewed in the context of the broader planning for future projects in physics and astronomy. The NRC report *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century* addresses a set of important questions at the interface of astronomy and physics, citing the goals to "determine the neutrino masses, the constituents of the dark matter, and the lifetime of the proton."[1] The report recommends "that DOE and NSF work together to plan for and to fund a new generation of experiments to achieve these goals. We further recommend that an underground laboratory with sufficient infrastructure and depth be built to house and operate the needed experiments."[2]

By their nature, IceCube and a deep underground laboratory are interdisciplinary and have strong overlaps with existing fields. The recent DOE/NSF long-range plan for nuclear physics states, "We strongly recommend immediate construction of the world's deepest underground science laboratory."[3] It gives a new deep underground laboratory second highest priority for future projects. The neutrino science of IceCube has less overlap with the scientific goals of nuclear physics and is therefore not included in that report.

The DOE/NSF long-range plan for particle physics has also endorsed both initiatives, although it ranks them below the highest scientific priority—participation in the worldwide efforts to build a linear collider. Regarding the scientific goals of IceCube, the long-range plan says that it is an "example of a mutually beneficial cross-disciplinary effort between astrophysics and particle physics,"[4] and that experiments in a deep underground laboratory "will make important contributions to particle physics for at least the next twenty years, and should be supported by the high energy physics community."[5]

The committee's assessments of the scientific opportunities presented by IceCube and a new deep underground laboratory are consistent with these reports. The committee finds that the scientific opportunities for both in astrophysics, nuclear physics, particle physics, and their intersections make for impressive and exciting research programs. The committee believes that both are well worth pursuing.

ICECUBE

Experiments that detect very high energy particles from space can explore the physics of extreme conditions in the universe. For example, gamma-ray bursts, among the most powerful explosions since the big bang, may be sources of ultra-

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[1] National Research Council, *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*, Washington, D.C., National Academies Press, 2003, p. 7.

[2] Ibid.

[3] DOE/NSF Nuclear Science Advisory Committee, *Opportunities in Nuclear Science,* 2002, p. 2.

[4] DOE/NSF High-Energy Physics Advisory Panel, *Subpanel Report on Long Range Planning for U.S. High-Energy Physics,* 2002, p. 80.

[5] Ibid., p. 77.

high-energy neutrinos and cosmic rays. Astrophysical sources are capable of accelerating particles to energies well beyond what we can produce here on Earth. So it is no surprise to find that experiments studying such ultrahigh-energy phenomena have important consequences for our understanding of both the universe and the physics of the basic constituents of nature.

IceCube is an exploratory experiment in a new area of science, the detection of high-energy neutrinos from astrophysical sources. That is, the primary objective is to determine whether astrophysical neutrinos exist (and are detectable) and, if so, what they can tell us about the far and extreme universe. Possible sources include gamma-ray bursts, active galaxies and quasars, and neutron stars. Since IceCube is breaking new ground, there is significant discovery potential not only for these sources but also for new and unexpected sources.

Neutrinos traverse the universe almost unimpeded, making them a powerful new probe, but because of their small interaction cross sections, a very large detector is needed to make detections possible. To achieve sufficient sensitivity, experiments on the scale of a cubic kilometer (a billion tons of detector mass) are required. The idea in IceCube and underwater detectors is to use the material of Earth itself (ice or water) as a converter and to detect the products of these neutrino interactions. IceCube is to be constructed at the South Pole, making use of Antarctic ice as the detecting medium.

Although IceCube is a major undertaking in a rather remote location, its design and prospects for success are bolstered by the strength of the existing infrastructure at the South Pole and, in particular, by the successful deployment and operation of AMANDA, a smaller precursor to IceCube. IceCube will substantially improve upon AMANDA's capabilities, by virtue of a larger detection volume and improved technology. IceCube is ready for construction now, while the underwater detectors in the Mediterranean are in a preliminary development stage.

The IceCube project is international and involves collaboration between scientists from institutions in the United States, Belgium, Germany, Japan, Sweden, the United Kingdom, and Venezuela. The plan is to incrementally build IceCube over about a 6-year period. The committee notes that if construction starts promptly IceCube will become the first detector to embark on these high-energy neutrino observations, an important requirement for such an exploratory experiment. By operating the partially completed detector even as it is being constructed, the project team will have early performance feedback to guide its work; furthermore, initial results could be available even before the complete detector is finished.

Technically, the IceCube concept is well founded, based on an existing U.S. effort at the South Pole. The AMANDA project has demonstrated the feasibility of deep-ice neutrino detectors, and engineering efforts have advanced to the stage that a full-scale detector for IceCube can be constructed that meets the performance requirements of the experiment. Before construction can begin, it will be necessary to install appropriate management for the project, make final technical and design decisions, and strengthen the collaboration to leverage the experiment to its full potential.

To summarize, the committee's scientific assessment is that 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.

A NEW DEEP UNDERGROUND LABORATORY

Laboratories deep underground are required for several reasons: They make it possible to study rare forms of penetrating radiation (e.g., neutrinos and dark matter) and rare processes (e.g., double beta decay, proton decay, etc.) in a low-background environment. A variety of physics areas have been examined in some detail to determine what will be needed to address the critical and exciting scientific questions that have recently emerged on topics such as solar neutrinos, double beta decay, dark matter, long-baseline neutrinos, proton decay, and stellar processes. In all cases, numerous experiments of varying size and complexity are being devised, proposed, and discussed that would greatly increase our knowledge of these complex physics phenomena.

The committee finds that a common feature of the future experimentation in this field is the importance of depth. Most of the experiments envisaged for exploring solar neutrinos, double beta decay, and dark matter require an overburden of about 4,500 meters water equivalent (mwe) or more. There are a few other experiments that, because of special detector features, may be done at 2,000 mwe, but even they would benefit from greater depth. The depth requirements for long-baseline neutrino experiments and searches for proton decay are less stringent and depths of 2,000 mwe are deemed adequate, but both of these types of experiment share a need for large, massive detectors and hence a sufficiently large site for the underground lab. Greater depth could still be an asset in accomplishing the physics goals. These requirements, of course, apply for studies undertaken with our present knowledge. Historically, it has always been prudent to anticipate unexpected backgrounds, more stringent requirements, or new physics whose study requires greater sensitivity—contingencies that argue for greater depths to leverage the science further, although there are necessarily other considerations when making a siting decision.

To optimize long-baseline studies of neutrino oscillations, a new underground facility should be located farther than 1,000 km from existing, high-intensity proton accelerators. The United States has advantages in this siting requirement: the large size of the North American continent and the proven and expandable capability for producing intense neutrino beams at Brookhaven National Laboratory and at Fermilab.

A new laboratory should have the potential to host a broad spectrum of experiments. Both significant depth and sufficient underground space will be needed to realize the full range of opportunities. This will result in economies coming from shared resources, as well as the development of a stimulating scientific center. A compelling collection of science experiments that could utilize a deep underground laboratory to address some of the most fundamental questions in particle physics and cosmology are, or soon will be, feasible. The committee finds that the science motivation for mounting large-scale experiments underground has increased markedly in the recent past and that the prospects for the next generation of experiments are particularly bright.

Physicists in the United States pioneered the use of underground locations to conduct the sensitive experiments required to detect rare phenomena. Today, U.S. physicists continue to play a leading role in initiating and implementing many of the important subterranean experiments. In recent years, however, some of the most important new experiments have been sited outside the United States, not because there is insufficient U.S. participation, but because the major facilities for underground experiments are located in other countries.

The breadth and quality of the future experimental program requiring an underground location suggest a major opportunity for the United States if it can soon develop a large new underground facility able to meet the requirements of the broad range of proposed experiments. To do this will require detailed planning over a complex and extensive set of scientific goals to determine the best site and a detailed strategy for an experimental program.

In summary, the committee's assessment is that a deep underground laboratory in the United States 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, together with new ideas and technologies, make possible a broad and rich experimental program. Considering the commitment of the U.S. community and the existing scientific leadership in this field, the time is ripe to build such a unique facility.

REDUNDANCY AND COMPLEMENTARITY

The two scientific initiatives assessed in this report (IceCube and a deep underground laboratory) have largely distinct science goals. Although neutrinos play a prominent role in both projects, the origins of the neutrinos, their energies, and the science they address are very different. IceCube takes advantage of the very clear ice available at the South Pole to develop an observatory for ultrahigh-energy neutrinos that might be produced by energetic sources in the universe. IceCube has secondary goals too: the detection of neutrinos from supernovae and the search for some forms of dark matter. A deep underground laboratory would host a very broad range of science experiments in fundamental physics and astronomy, including studies of the underlying nature of neutrinos, direct searches for dark matter, studies of proton decay, solar neutrino measurements, and experiments on neutrino oscillations. Direct dark-matter experiments at an underground laboratory are different from and complementary to searches that might use the IceCube detector, as they are suited to different mass ranges and different types of interactions of dark-matter particles with nuclei. Likewise, the large detectors for proton decay and long-baseline neutrino oscillation studies deep underground could also serve as a detector for supernovae. The committee finds essentially no redundancy in the primary science goals and capabilities of IceCube and those of a deep underground laboratory. Although some of the science may overlap between the two projects, both are critical investments that address key science questions in different ways.

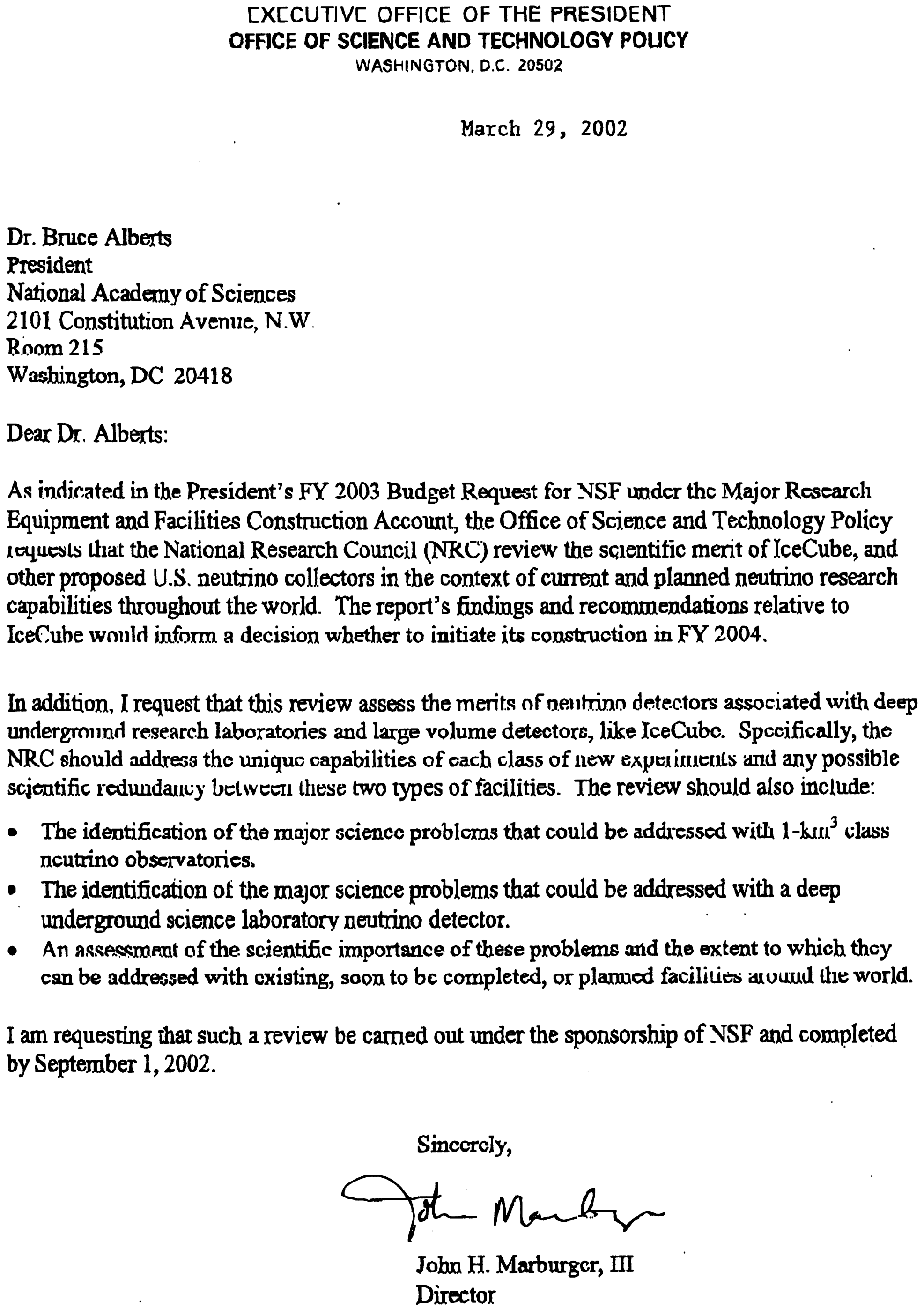
Finally, the committee finds that on the international scene each project has exciting potential and much-needed scientific value. IceCube will employ what looks to be a unique technology for gigaton-sized detectors and will take advantage of the opportunity for high-energy neutrino detection. A national underground laboratory offers the United States some vital scientific opportunities that will affect a number of important international efforts and provide a center in the United States for some of the most exciting physics at the beginning of the 21st century.

Appendixes

A

Formation of the Committee

See next page.



EXECUTIVE OFFICE OF THE PRESIDENT
OFFICE OF SCIENCE AND TECHNOLOGY POLICY
WASHINGTON, D.C. 20502

March 29, 2002

Dr. Bruce Alberts
President
National Academy of Sciences
2101 Constitution Avenue, N.W.
Room 215
Washington, DC 20418

Dear Dr. Alberts:

As indicated in the President's FY 2003 Budget Request for NSF under the Major Research Equipment and Facilities Construction Account, the Office of Science and Technology Policy requests that the National Research Council (NRC) review the scientific merit of IceCube, and other proposed U.S. neutrino collectors in the context of current and planned neutrino research capabilities throughout the world. The report's findings and recommendations relative to IceCube would inform a decision whether to initiate its construction in FY 2004.

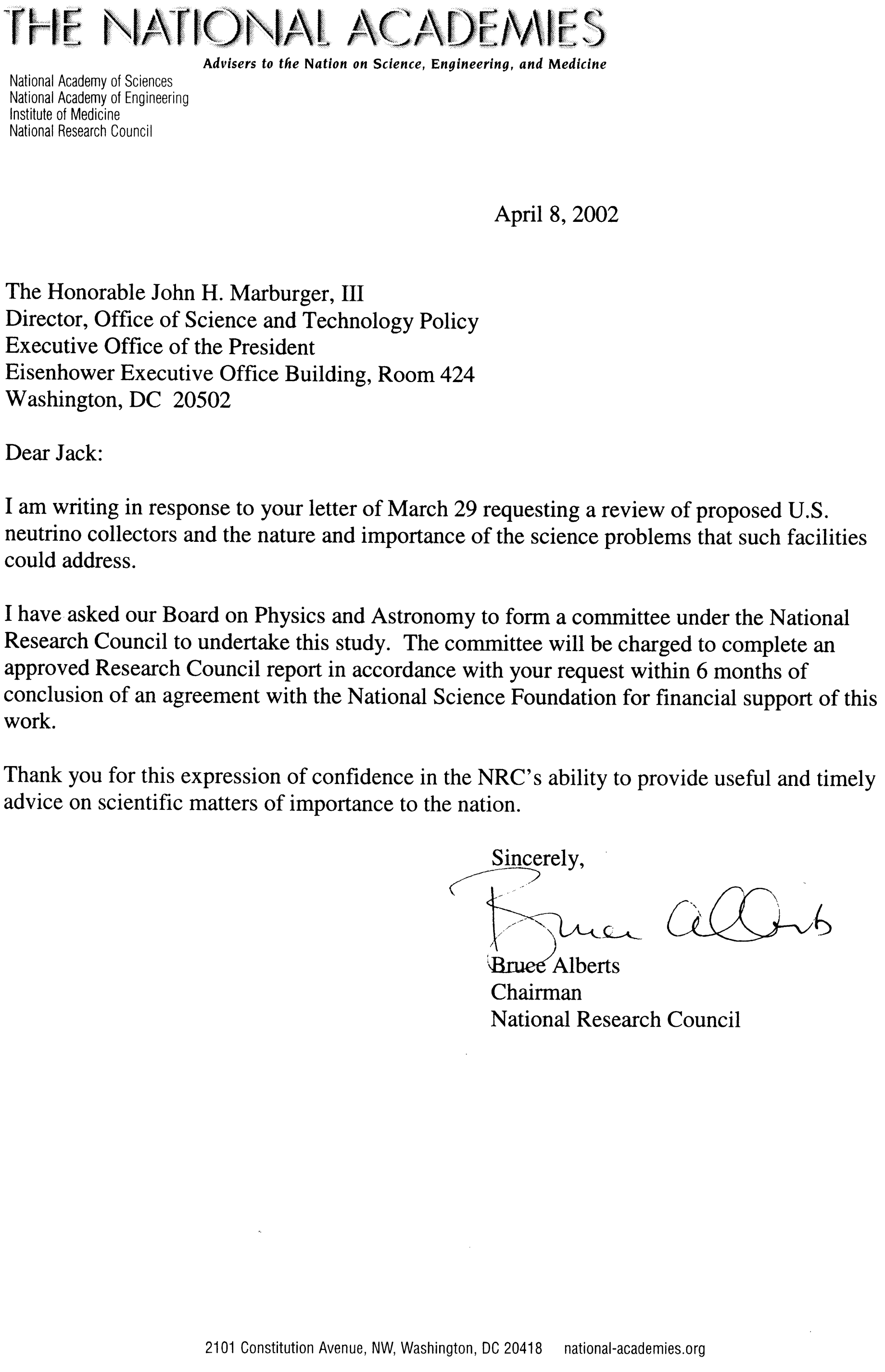
In addition, I request that this review assess the merits of neutrino detectors associated with deep underground research laboratories and large volume detectors, like IceCube. Specifically, the NRC should address the unique capabilities of each class of new experiments and any possible scientific redundancy between these two types of facilities. The review should also include:

- The identification of the major science problems that could be addressed with 1-km^3 class neutrino observatories.
- The identification of the major science problems that could be addressed with a deep underground science laboratory neutrino detector.
- An assessment of the scientific importance of these problems and the extent to which they can be addressed with existing, soon to be completed, or planned facilities around the world.

I am requesting that such a review be carried out under the sponsorship of NSF and completed by September 1, 2002.

Sincerely,

John H. Marburger, III
Director



THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine
National Academy of Sciences
National Academy of Engineering
Institute of Medicine
National Research Council

April 8, 2002

The Honorable John H. Marburger, III
Director, Office of Science and Technology Policy
Executive Office of the President
Eisenhower Executive Office Building, Room 424
Washington, DC 20502

Dear Jack:

I am writing in response to your letter of March 29 requesting a review of proposed U.S. neutrino collectors and the nature and importance of the science problems that such facilities could address.

I have asked our Board on Physics and Astronomy to form a committee under the National Research Council to undertake this study. The committee will be charged to complete an approved Research Council report in accordance with your request within 6 months of conclusion of an agreement with the National Science Foundation for financial support of this work.

Thank you for this expression of confidence in the NRC's ability to provide useful and timely advice on scientific matters of importance to the nation.

Sincerely,

Bruce Alberts
Chairman
National Research Council

2101 Constitution Avenue, NW, Washington, DC 20418 national-academies.org

B

Charge to the Neutrino Facilities Assessment Committee

The Neutrino Facilities Assessment Committee will review and assess the scientific merit of IceCube and other proposed U.S. neutrino detectors—neutrino detectors associated with deep underground research laboratories and large volume detectors, such as IceCube—in the context of current and planned neutrino research capabilities throughout the world. Specifically, the study will address the unique capabilities of each class of new experiments and any possible redundancy between these two types of facilities. The review will also include: (1) the identification of the major science problems that could be addressed with cubic-kilometer-class neutrino observatories; (2) the identification of the major science problems that could be addressed with a deep underground science laboratory neutrino detector; and, (3) an assessment of the scientific importance of these problems and the extent to which they can be addressed with existing, soon to be completed, or planned facilities around the world.

C

Biographies of Committee Members and Key NRC Staff

COMMITTEE MEMBERS

BARRY C. BARISH, *Chair*, Linde Professor of Physics and director of the Laser Interferometer Gravitational-wave Observatory (LIGO), California Institute of Technology, is a member of the National Academy of Sciences and a fellow of the American Physical Society. He is a recipient of the Klopsteg award of the American Association of Physics Teachers. Dr. Barish received his doctorate from the University of California at Berkeley in 1962 and was a postdoctoral fellow there until moving to Caltech for good in 1963. An experimental high-energy and gravitational-wave physicist, he is leading the search for gravitational waves in LIGO and is involved in the Main Injector Neutrino Oscillation Search project, which is a long-baseline neutrino physics experiment between Fermilab and the Soudan Mine in Minnesota, as well as other major nonaccelerator experiments in both the United States and Italy. He is a former member of the 1991 Astronomy Survey Panel on Particle Astrophysics, the Briefing Panel on Scientific Frontiers and the Superconducting Super Collider for the 1986 physics survey, and the 2001 Astronomy Survey Panel on Particle, Nuclear, and Gravitational-wave Astrophysics. Dr. Barish co-chaired the Department of Energy (DOE)/National Science Foundation (NSF) High Energy Physics Advisory Panel's recent subpanel on long-range planning for the U.S. high-energy physics community. He is chair of the oversight committee for IceCube and a member of the agency review committee for the Sudbury Neutrino Observatory. Dr. Barish recently served as chair of the

International Union of Pure and Applied Physics (IUPAP) commission on particles and fields and is incoming chair of the U.S. Liaison Committee to IUPAP. He served as science coordinator of the DOE/NSF Scientific Assessment Group for Experiments in Non-Accelerator Physics (SAGENAP) review panel.

DANIEL S. AKERIB, associate professor of physics, Case Western Reserve University, received his doctorate from Princeton University in 1991. After fellowships at Caltech and the Center for Particle Astrophysics, he joined the faculty of Case Western Reserve University in 1995. His current research interests are in experimental particle astrophysics, dark-matter searches, low-temperature detectors, and accelerator-based particle physics. He is a member of the Cryogenic Dark Matter Search Collaboration (CDMS), located in the Soudan Mine in northern Minnesota. His group at Case Western is conducting experiments using a new generation of cryogenic detectors that have extremely good sensitivity to dark matter compared with conventional detectors, and it is also developing next-generation dark-matter particle detectors. He is deputy project manager for the CDMS II experiment and U.S. principle investigator on an ultralow-threshold detector grant from the Civilian Research and Development Fund for the Independent States of the Former Soviet Union. He was an NSF Faculty Early Career Development Program awardee in 1997.

STEVEN R. ELLIOTT, scientific staff member, Los Alamos National Laboratory, received his doctorate from the University of California at Irvine in 1987 and then did postdoctoral work at Los Alamos National Laboratory and Lawrence Livermore National Laboratory before joining the University of Washington as a research assistant professor in 1995. He returned to the Los Alamos National Laboratory in July 2002. His research expertise is in atomic, nuclear, and particle physics, and he is one of the world's experts in double beta decay physics. He is a member of the Sudbury Neutrino Observatory collaboration, the Russian-American gallium solar neutrino experiment, and the Majorana project to detect neutrinoless double beta decay. Dr. Elliott has been a member of several professional conference committees, a DOE review committee for the international Kamioka Liquid Scintillator Antineutrino Detector (KamLAND) neutrino experiment in Japan, and the program committee of the American Physical Society's (APS) Division of Nuclear Physics.

PATRICK D. GALLAGHER, physicist, National Institute of Standards and Technology (NIST). received his Ph.D. in physics at the University of Pittsburgh in 1991. Dr. Gallagher is currently leader of the Research Facilities Operations Group and Beam Experiment coordinator at the NIST Center for Neutron Research. Dr. Gallagher's group at NIST designed, installed, and operates the liquid hydrogen cold neutron source, the neutron guide network, and the instruments in the Cold Neutron Research Facility and reactor and coordinates experimental facilities. Dr.

Gallagher's research interests include neutron and x-ray diffraction of nanoscale structures, especially in soft condensed matter systems such as liquids, polymers, and gels, as well as the experimental study of nonequilibrium structure and processes in complex condensed matter systems. Dr. Gallagher is a member of the American Physical Society (Polymer Physics) and the Materials Research Society (MRS). In 2000 Dr. Gallagher was a NIST agency representative at the National Science and Technology Council (NSTC) and Office of Science and Technology Policy (OSTP), where he had responsibility for major science facilities (especially the Spallation Neutron Project and the National Ignition Facility), science funding, the government-university research partnership, radioactive waste management, radiation protection regulations, science and security at DOE national labs, and laboratory reform. He is the chair of the OSTP's Neutron Sciences Interagency Working Group; a past member of the Proposal Evaluation Committee for the Los Alamos Spectrometer Development Project and of the DOE's Review Committee on the Technical, Cost, Management Review of the Los Alamos Neutron Science Center Short Pulse Spallation Source (LANSCE SPSS) Enhancement Project; and a former member of the Targets and Instruments Advisory Committee for the Spallation Neutron Source at Oak Ridge. He is currently a member of the National Research Council's Solid State Sciences Committee.

ROBERT E. LANOU, JR., professor of physics, Brown University, is an elementary particle physicist specializing in experimental studies at high-energy accelerators and in the development of new detector technology for low-energy neutrino detectors. Dr. Lanou received his doctorate from Yale University. A member of the Brown faculty since 1959 and chair of the physics department from 1986 to 1992, Dr. Lanou is a fellow of the American Physical Society (APS) and the American Association for the Advancement of Science (AAAS). He was previously on the staff of the University of California at Berkeley, and was a visiting fellow in the Italian National Universities at Padua and Bari and at the Fermi National Accelerator Laboratory, Osaka University, Japan, and the Center for Particle Astrophysics at Berkeley. He has served on the High Energy Physics Program Advisory Committee of several national laboratories, as well as on the Executive Committee of the American Physical Society's Division of Particles and Fields. Dr. Lanou was a member of the NRC's Panel on Neutrino Astrophysics. He was science coordinator for the DOE/NSF Scientific Assessment Group for Non-Accelerator Physics when that group reviewed, and approved for further development, the IceCube project, and he was a member of an NSF peer-review panel for the Homestake National Underground Science Lab proposal.

PETER MÉSZÁROS, Distinguished Professor of Physics and Astronomy and Astrophysics and head of the Department of Astronomy and Astrophysics, Pennsylvania State University, received his doctorate from the University of California at Berkeley in 1972. The author of 130 refereed journal articles, he has research interests in theoretical astrophysics and specifically in high-energy astrophysics, gamma-ray bursts, cosmology, and neutron stars. His recent work has centered on the formulation and development of the cosmological fireball shock scenario of gamma-ray bursts, and he serves as the science/theory lead of the SWIFT consortium, a multi-institution National Aeronautics and Space Administration (NASA) satellite to study gamma-ray-burst afterglows, that is currently under construction and scheduled for launch in 2003. He also has interests in the production of ultrahigh-energy neutrinos and photons from gamma-ray bursts, in preparation for experiments such as NASA's Gamma-ray Large Area Survey Telescope (GLAST) and the IceCube/AMANDA projects. He is involved with the NSF Physics Frontier Center for Gravitational Wave Physics and the Center for Gravitational Physics and Geometry, both at Penn State. Dr. Meszaros was a joint recipient of the Rossi Prize from the High Energy Astrophysics Division of the American Astronomical Society in 2000, and he was a John Simon Guggenheim Memorial Foundation Fellow in 1999–2000. He is a fellow of the American Physical Society, and he was a National Academy of Sciences International Research and Exchange Fellow in 1986. In additional to numerous ad hoc review panels at NASA and the NSF, he is a member of the gamma-ray burst panel for NASA's Constellation-X Facility Science Team and a board member of the Hobby-Eberly Spectroscopic Survey Telescope.

HITOSHI MURAYAMA, a professor of physics at the University of California at Berkeley, received his doctorate from the University of Tokyo in 1991. After postdoctoral work at Tohoku University and Lawrence Berkeley National Laboratory, he joined the physics department at the University of California at Berkeley in 1995 and was promoted to full professor by 2000. His research interests are in theoretical particle physics, specifically supersymmetry phenomenology, particle cosmology, electron-positron linear collider physics, supersymmetric field theories, and neutrino physics. He received the 2002 Yukawa Memorial Prize in Theoretical Physics for his work. Dr. Murayama was a member of the DOE/NSF High Energy Physics Advisory Panel's recent subpanel on long-range planning for the U.S. high-energy physics community and served on the organizing committee for that community's Snowmass summer study in 2001. He is a member of the KamLAND collaboration, a new neutrino experiment in Japan. He was a Sloan Foundation fellow from 1996 to 1999 and is a member of the Particle Data Group, an international collaboration that reviews particle physics and related areas of astrophysics and compiles/analyzes data on particle properties.

ANGELA V. OLINTO, associate professor of astronomy and astrophysics at the Enrico Fermi Institute of the University of Chicago, received her doctorate from the Massachusetts Institute of Technology in 1987 before moving to postdoctoral and research positions at Fermilab and the University of Chicago, where she joined the faculty in 1996. Her research interests are in theoretical astrophysics, nuclear and particle astrophysics, and cosmology. She is the team leader for the High-Energy Particles from Space group at the new NSF Center for Cosmological Physics located at the University of Chicago. Dr. Olinto was an organizer of the 2002 Aspen Winter Workshop on ultrahigh-energy cosmic rays and high-energy neutrinos. She is a collaboration member of the Pierre Auger Observatory project in Argentina and a fellow of the American Physical Society, is a member and corporate secretary of the Aspen Center for Physics, and was a member of the DOE's Nuclear Science Advisory Committee.

RENE A. ONG, professor of physics and astronomy, University of California at Los Angeles, received his doctorate from Stanford University in 1987. He was a Robert McCormick Fellow of the Enrico Fermi Institute at the University of Chicago and then an assistant professor and associate professor in the Department of Physics at the University of Chicago. He moved to the University of California at Los Angeles in 2001. His research interests are in particle astrophysics, with recent work focused on the astrophysics of the high-energy universe, as revealed by gamma rays, neutrinos, and cosmic rays. Prof. Ong is U.S. principle investigator for the Solar Tower Atmospheric Cerenkov Effect Experiment (STACEE) ground-based gamma-ray telescope located in New Mexico and is a member of the Very Energetic Radiation Imaging Telescope Array System (VERITAS) collaboration building an array of gamma-ray telescopes in Arizona. He is an associate member of the Gamma Ray Large Area Space Telescope (GLAST). Dr. Ong served on the 2001 Astronomy Decadal Survey's Panel on Particle, Nuclear, and Gravitational-wave Astrophysics and the Panel on High Energy Astrophysics from Space. He was a member of the recent subpanel on long-range planning for the DOE/NSF High Energy Physics Advisory Panel (HEPAP) and the High-Energy and Nuclear Physics Advisory Panel of the Particle and Nuclear Astrophysics and Gravitation International Committee (PANAGIC). He is currently a member of HEPAP and the Scientific Assessment Group for Experiments in Non-Accelerator Physics (SAGENAP).

R.G. HAMISH ROBERTSON, professor of physics and scientific director of the Center for Experimental Nuclear Physics and Astrophysics, University of Washington, is U.S. co-principal investigator on the Sudbury Neutrino Observatory (SNO). His specialty is neutrino physics, including neutrino mass and solar neutrinos, and his past research interests have spanned weak interactions, atomic beam magnetic resonance, nuclear astrophysics, isobaric multiplets, and nuclei far from stability. In addition to SNO, he is a collaborator on the Karlsruhe Tritium Neutrino (KATRIN), Majorana, and Molybdenum Observatory of Neutrinos (MOON) experiments that probe neutrino mass, double beta decay, and solar neutrinos. He received his Ph.D. in nuclear physics in 1971 from McMaster University. Before joining the Physics Department at the University of Washington, Dr. Robertson was a fellow of the Los Alamos National Laboratory. Before that, he was a professor of physics at Michigan State University, a research associate at Princeton University, an Alfred P. Sloan Fellow, and a visiting scientist at the Chalk River Nuclear Labs and Argonne National Laboratory. He is a fellow of the British Institute of Physics, a member of the Canadian Association of Physicists, and a fellow of the American Physical Society. In 1997 he received the APS Tom W. Bonner Prize. He has chaired the Nuclear Science Advisory Committee and the Division of Nuclear Physics (DNP) of the APS. A past member of the Board on Physics and Astronomy of the National Research Council, he has also served on previous NRC nuclear physics and neutrino astrophysics panels, the APS-DNP Executive Committee and Program Committee, the APS Bonner Prize Committee, the National Science and Engineering Research Council (Canada) Grant Selection Committee, review committees for the Lawrence Berkeley Laboratory Nuclear Science Division and Caltech's Physics, Mathematics and Astronomy Division, the editorial boards of *Physical Review D* and *Annual Reviews of Nuclear and Particle Physics*, the Scientific Assessment Group for Experiments in Non-Accelerator Physics, and review panels for the National Science Foundation and the Department of Energy.

NICHOLAS P. SAMIOS, Distinguished Senior Scientist and director emeritus, Brookhaven National Laboratory, is a member of the National Academy of Sciences and a fellow of the American Academy of Arts and Sciences and the American Physical Society. An experimental high-energy physicist, he spent 15 years as the director of Brookhaven. Dr. Samios led the experiment at Brookhaven that discovered the charmed baryon in 1975, and as director he led the effort to construct the Relativistic Heavy Ion Collider—the world's newest facility for nuclear physics research. He has won DOE's E.O. Lawrence Memorial Award and the New York Academy of Science Award in Physical and Mathematical Sciences, and he received the W.K.H. Panofsky Prize from the American Physical Society in 1993 in recognition of his participation in the omega-minus particle discovery. He was the 2001 recipient of the prestigious international Bruno Pontecorvo Prize by the Joint Institute for Nuclear Research in Russia for his contributions both as a researcher in elementary particle physics, particularly neutrino physics, and as a scientific administrator. He is a former member of the NRC's Commission on Physical Sciences, Mathematics, and Applications and of the NRC's Supercollider Site Evaluation Committee.

JOHN P. SCHIFFER, senior physicist, Argonne National Laboratory, and professor of physics emeritus, University of Chicago, is a member of the National Academy of Sciences and a fellow of the American Physical Society, the American

Association for the Advancement of Science, and the American Academy of Arts and Sciences, and he is a foreign member of the Royal Danish Academy of Sciences. He has expertise in a broad range of experimental nuclear physics and related fields. He has served on a number of advisory and review committees and was chair of the Nuclear Science Advisory Committee (NSAC) from 1983 to 1985, during which time the 1983 Long Range Plan for the field was prepared and the first committee to look at new solar neutrino experiments was formed. He has been chair of the Division of Nuclear Physics of the American Physical Society, served on its Executive Committee, was its divisional councilor, and has been chair of the Physics Section of the AAAS. He is a recipient of the American Physical Society's Tom W. Bonner Prize for his work in nuclear structure and of Yale's Wilbur Lucius Cross Medal. Dr. Schiffer served on numerous NRC committees and was chair of the Committee on Nuclear Physics while it undertook the decadal study, published in 1999, *Nuclear Physics—the Core of Matter, the Fuel of Stars.*

FRANK J. SCIULLI is the Pupin Professor of Physics at Columbia University. His research interests include weak interactions of elementary particles, particularly K-meson decays and neutrino interactions. He received his Ph.D. in experimental high-energy particle physics in 1965 from the University of Pennsylvania. Before going to Columbia University, he was a research associate in particle physics at the University of Pennsylvania and a research fellow and professor in particle physics at the California Institute of Technology. He led a series of experiments at Fermilab on neutrino interactions between 1970 and 1990. Dr. Sciulli's research is now primarily concerned with the scattering of high-energy electrons and protons at the Deutsche Elektronen Synchrotron (DESY) Laboratory in Germany. The experimental program uses the Hadron Electron Ring Accelerator (HERA) colliding beam accelerator and the ZEUS detector. Dr. Sciulli is a member of the American Association for the Advancement of Science and Sigma Xi and is a fellow of the American Physical Society. He was also a member of the recent NRC Committee on the Physics of the Universe. He chaired the DOE High Energy Physics Advisory Panel's Subpanel on Accelerator-based Neutrino Oscillation Experiments in 1995 that recommended the MINOS long-baseline experiment between Fermilab and the Soudan Mine.

MICHAEL S. TURNER is the Bruce V. and Diana M. Rauner Distinguished Service Professor and chair of the Department of Astronomy and Astrophysics at the University of Chicago. He also holds appointments in the Department of Physics and Enrico Fermi Institute at Chicago and is a member of the scientific staff at the Fermi National Accelerator Laboratory. Prof. Turner is a member of the National Academy of Sciences and a fellow of the American Physical Society and the American Academy of Arts and Sciences. His research interests are in theoretical astrophysics, cosmology, and elementary particle physics. Prof. Turner is a leader in the application of particle and nuclear physics to astrophysics and cosmology and has made important contributions to the theory of big-bang nucleosynthesis, big-bang baryogenesis, the inflationary universe, and the nature of dark matter and its role in the formation of structure in the universe. He has been a Sloan Foundation Fellow and is a recipient of the Helen B. Warner Prize from the American Astronomical Society, the Julius Edgar Lilienfeld Prize from the American Physical Society, the Quantrell Award for excellence in undergraduate teaching at the University of Chicago, and the Halley Lectureship at Oxford University. Prof. Turner was chair of the NRC's Committee on the Physics of the Universe. He has also been a member of other NRC committees, including the 2001 Astronomy and Astrophysics Survey Committee.

NRC STAFF

DONALD C. SHAPERO received a B.S degree from the Massachusetts Institute of Technology in 1964 and a Ph.D. from MIT in 1970. His thesis addressed the asymptotic behavior of relativistic quantum field theories. After receiving the Ph.D., he became a Thomas J. Watson Postdoctoral Fellow at IBM. He subsequently became an assistant professor at American University, later moving to Catholic University and then joining the staff of the National Research Council in 1975. He took a leave of absence from the NRC in 1978 to serve as the first executive director of the Energy Research Advisory Board at the Department of Energy. He returned to the NRC in 1979 to serve as special assistant to the president of the National Academy of Sciences. In 1982, he started the NRC's Board on Physics and Astronomy (BPA). As BPA director, he has played a key role in many NRC studies, including the two most recent surveys of physics and the two most recent surveys of astronomy and astrophysics. He is a member of the American Physical Society, the American Astronomical Society, and the International Astronomical Union. He has published research articles in refereed journals in high-energy physics, condensed-matter physics, and environmental science.

TIMOTHY I. MEYER is a program associate at the NRC's Board on Physics and Astronomy. Dr. Meyer joined the NRC staff in 2002 after earning his Ph.D. in experimental particle physics from Stanford University. His thesis concerned the time evolution of the *B* meson in the BaBar experiment at the Stanford Linear Accelerator Center. His work also focused on radiation monitoring and protection of silicon-based particle detectors. During his time at Stanford, Dr. Meyer received both the Paul Kirkpatrick and Centennial Teaching awards for his work as an instructor of undergraduates. He is a member of the American Physical Society, the American Association for the Advancement of Science, Phi Beta Kappa, and the Union of Concerned Scientists.

D

Meeting Agendas

FIRST MEETING
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C.

Monday, June 24, 2002

Closed Session

8:00 am	Convene; introductions; review charge and discuss goals for the meeting Committee composition and balance discussion —Barry Barish, Chair —Don Shapero, Director, Board on Physics and Astronomy

Open Session

9:30 am	Welcome; public introductions, and study plan —Barry Barish

Background and Charge

9:45 am Office of Science and Technology Policy views
—Patrick Looney, Assistant Director, Physical Sciences and Engineering, Office of Science and Technology Policy

10:15 am Break

10:30 am Department of Energy plans for neutrino physics
—Peter Rosen, Associate Director, DOE Office of High Energy and Nuclear Physics

Opportunities with U.S. Underground Neutrino Facilities

11:00 am Scientific merits of proposed large U.S. underground neutrino facilities
Underground Science, Homestake, and an Introduction to San Jacinto
—Wick Haxton, University of Washington

12:15 pm Lunch

1:00 pm National Science Foundation views on the study and charge
—Joseph Bordogna, Deputy Director, National Science Foundation

1:45 pm Scientific merits of proposed large U.S. underground neutrino facilities (continued)
–Waste Isolation Pilot Plant, Carlsbad, NM
—Todd Haines, Los Alamos National Laboratory

Major Underground Neutrino Physics Topics

2:15 pm Double beta decay
—Steve Elliott, University of Washington/Los Alamos National Laboratory

3:15 pm Break

3:30 pm Solar neutrinos
—Andrew Hime, Los Alamos National Laboratory

4:30 pm Long-baseline neutrino oscillations
—Stanley Wojcicki, Stanford University

5:00 pm Off-axis neutrino beam research and the Soudan experiment
—Earl Peterson, University of Minnesota

5:30 pm General discussion of the scientific opportunities

6:00 pm Adjourn for the day

Tuesday, June 25, 2002

Open Session

8:00 am Reconvene
—Barry Barish

Opportunities with Foreign Underground Neutrino Facilities

8:00 am Large international underground neutrino physics efforts
—Yoichiro Suzuki, Kamioka Observatory, Japan
—Alessandro Bettini, Laboratori Nazionali del Gran Sasso, Europe
—David Sinclair, Sudbury Neutrino Observatory and Carleton University, Canada

9:30 am Break

Opportunities in High-Energy Neutrino Astrophysics

9:45 am Neutrino astrophysics and IceCube
—Per Olof Hulth, University of Stockholm
—Francis Halzen, University of Wisconsin
—Christian Spiering, Deutsche Elektronen-Synchrotron (DESY)
—David Nygren, Lawrence Berkeley National Laboratory

11:15 am International high-energy neutrino astrophysics: ANTARES and NESTOR
—John Carr, Centre de Physique des Particules de Marseille
—Leonidas Resvanis, NESTOR Institute for Deep Sea Research, Technology, and Neutrino Astroparticle Physics

12:15 pm Working Lunch

Closed Session

1:15 pm Committee deliberations
—Barry Barish
5:00 pm Adjourn

SECOND MEETING
HILTON CHICAGO O'HARE AIRPORT
CHICAGO, ILLINOIS

Thursday, July 25, 2002

Open Session

9:00 am Convene
—Barry Barish, Chair

9:00 am Dark-Matter Searches
—Rick Gaitskell, Brown University

10:00 am Proton Decay: Theory and Experiment
—Hitoshi Murayama, University of California, Berkeley
—Chang Kee Jung, State University of New York, Stony Brook
—Robert Svoboda, Louisiana State University

11:30 am Lunch

12:30 pm Scientific Potential of Long Baseline Neutrino Experiments
—William Marciano, Brookhaven National Laboratory

1:00 pm Scientific Potential of Bright Neutrino Beams for Underground Physics
—Thomas Roser, Brookhaven National Laboratory
—Deborah Harris, Fermi National Accelerator Laboratory

2:00 pm Scientific Potential of a Neutrino Factory for Underground Physics
—Dan Kaplan, Illinois Institute of Technology

2:30 pm Alternate Development Plans for a National Underground Laboratory
—Alfred Mann, University of Pennsylvania

2:45 pm Break

Closed Session
3:00 pm Committee deliberations
—Barry Barish

5:00 pm Additional primer on high-energy sources
—Angela Olinto, University of Chicago
—Rene Ong, University of California, Los Angeles

6:30 pm Adjourn for the day

Friday, July 26, 2002

Closed Session

8:00 am Reconvene
Committee deliberations
—Barry Barish

4:00 pm Adjourn

THIRD MEETING
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

Monday, September 30, 2002

Open Session

8:30 am Convene
—Barry Barish, Chair

8:30 am Office of Science and Technology Policy views
—Patrick Looney, Assistant Director, Physical Sciences and Engineering, Office of Science and Technology Policy

Closed Session

9:00 am Committee deliberations and report drafting
—Barry Barish

6:00 pm Adjourn for the day

Tuesday, October 1, 2002

Closed Session

8:30 am Reconvene
Committee deliberations and report drafting
—Barry Barish

Noon Adjourn

E

Glossary and Acronyms

Active galactic nuclei (AGN): Bright centers of some galaxies; they are thought to have huge black holes at the center. Very distant ones are called quasars.

Background: False events or unwanted particles traversing the device, preventing useful data taking.

Baseline: Typically the distance between the neutrino source and detector. Neutrino oscillation experiments are usually categorized as short or long baseline.

Beta decay: In this context, the radioactive decay of a nucleus whereby a neutron is converted into an electron and a proton while emitting a neutrino. Double beta decay is a much rarer process with two electrons emitted either with or without two neutrinos.

Big bang: The model of the initial phase of the universe in which all matter and energy were concentrated with high density and temperature 15 billion years ago. The present universe expanded from that epoch and is still expanding.

Bottom: The second-heaviest quark. It has negative electric charge one-third that of the electron.

Charged-current: Interaction between a neutrino and another particle involving the exchange of charged electroweak force carrier, the W particle.

Charm: The third-heaviest quark. It carries positive electric charge two-thirds that of electron.

CNO cycle: The carbon-nitrogen-oxygen cycle of stellar fusion that uses the heavier elements carbon, nitrogen, and oxygen to effectively convert hydrogen into helium.

Cosmic microwave background (CMB) radiation: The residual light from the big bang.

Cosmic rays: Protons, nuclei of heavy atoms, and possibly other particles that have been accelerated to high energies by astrophysical process and then impinge upon Earth.

CP violation: The mechanism by which matter and antimatter evolve in time differently. The C and P, standing for charge conjugation and parity, refer to so-called symmetry operations in quantum physics.

Dark energy: An as-yet-unknown form of energy that pervades the universe. Its presence is inferred from the discovery recently that the expansion of the universe is accelerating.

Dark matter: Matter that does not emit or absorb enough light or other radiation to be observed directly.

Dirac-like: A theoretical framework for the introduction of particles with mass into a modern quantum field theory (named for Paul A.M. Dirac). A key feature of this framework is that the particle is distinct from its antiparticle.

Down: A low-mass quark of negative charge one-third that of the electron. The down quark is one of the two quarks that occur in everyday matter (neutrons, protons).

Elastic scattering (interaction): In this context, the scattering of neutrinos by electrons via the electroweak interaction. The probability with which an electron neutrino scatters differs from that for the muon or tau neutrino.

Electron-volt (eV): A measure of energy equal to that gained by an electron passing through a potential difference of 1 volt. Einstein's relation between mass and energy ($E = mc^2$) is often used to define a unit of particle mass when divided by the speed of light (c) squared. The electron volt, with its internationally recognized multipliers for milli, kilo, and mega (meV, keV, MeV), respectively, is a useful unit for discussing the variety of particle masses.

Equivalence principle: A fundamental principle of Einstein's theory of general relativity of which one consequence is that all objects (and light) behave in a gravitational field in the same way independent of the velocity, internal structure, or other properties.

Gamma-ray burst (GRB): High-intensity burst of gamma rays from cosmic sources first observed by detectors on satellites. Most of the gamma-ray bursts come from objects at cosmological distances. Gamma-ray bursts are also visible in other parts of the electromagnetic spectrum.

Gravitational lensing: A consequence of Einstein's theory of general relativity in which the path of light can be bent by the presence of matter, giving rise to effects similar to those of light traveling through an optical lens.

Gravitational wave: A ripple in the geometry of space-time propagating as a wave according to the theory of general relativity.

Hadron: A particle such as a proton, neutron, or pi meson (pion) that can interact via the strong force, as well as the electroweak force.

Jet (astrophysical): A stream of fast-moving material ejected outward from an object such as a young star or a massive black hole in the center of a galaxy.

Large Magellanic Cloud: A dwarf galaxy, proximate to and orbiting our own Milky Way Galaxy.

Left-handed, right-handed: A particle condition describing the relative orientation of its direction of motion and the sense in which its angular momentum is rotating ("spinning"). A right-handed particle has its rotation sense aligned with respect to its direction of motion as in the advance of a right-handed screw. Left-handed implies the opposite orientation. Left- and right-handed neutrinos have different interactions.

Lepton: Any one of a group of six fundamental particles having electroweak interactions assigned in three families (the charged electron, muon, and tau, each with its associated neutrino).

Majorana-like: Refers to that property of neutrino mass description in which the neutrino and its antiparticle are identical (named for E. Majorana).

Mixing: In neutrino oscillations, refers to the possibility that a neutrino created as purely one type can at a later time or position be composed of a mixture with the other two types.

Mixing angle: A parameter that gives a measure of the amount of mixing between any pair of neutrino types.

Muon: The second-lightest lepton particle in the Standard Model. The muon is produced copiously in cosmic-ray interactions in the atmosphere and is deeply penetrating in matter.

mwe: A designation of radiation-shielding depth in meters of water equivalent. Typically, 1 meter of rock is approximately 3 mwe.

Neutral current: The interaction between a neutrino and another particle involving the exchange of a neutral electroweak force carrier, the Z particle.

Neutralino: The term ascribed to the lightest supersymmetric particle, which is neutral and is expected to have the longest lifetime of all supersymmetric particles as there are no other supersymmetric partner particles into which it can decay.

Neutrino oscillation: A process whereby neutrinos of one type change into those of another type (and even back again) if one or more of the types has mass. (See also *mixing*.)

Neutron star: A star with such high density and pressure that its constituents have been completely crushed by gravity until most of the electrons have been squeezed into protons forming neutron-rich material.

Nucleosynthesis: The process by which protons and neutrons fuse together to form the nuclei of the chemical elements. Big-bang nucleosynthesis refers to the time period 3 minutes after the big bang when the lightest elements (hydrogen, deuterium, helium, etc.) were formed.

Pi mesons, pion: One of the many strongly interacting but unstable particles. Those that carry charge can decay into muons and neutrinos (or their antiparticles).

pp reactions: In this context, refers to the principal, initiating fusion reaction in the Sun in which electron-type neutrinos are created.

Quantum gravity: A modern theory for gravity attempting an appropriate description of physical processes that occur at very small length scales or over very short times. The Einstein theory of general relativity, as a classical theory, is inconsistent with the principles of quantum theory.

Quark: The elementary constituents of matter, such as the proton and neutron, but also of the unstable particles created in very energetic interactions. There are six types of quarks in the Standard Model (up, down, charm, strange, top, and bottom).

Relativity: A theoretical framework proposed by Einstein in the early part of the 20th century. There are two theories of relativity, the general (gravity) and special theories.

Relic: In this context, particles created in and remaining currently from the big bang or other astrophysical events.

Shock, shock wave: A very narrow region of high pressure and temperature formed in a fluid when the fluid flows supersonically over a stationary object or when a projectile flies supersonically through a fluid.

Spin: An intrinsic property of particles. Defines a measure of the angular momentum they carry.

Standard Model: The theory summarizing the current picture of elementary particle physics. It includes three families of quarks and leptons, the electroweak theory of the weak and electromagnetic forces, and the quantum chromodynamic theory of the strong force.

Standard solar model: The modern theory of how the Sun produces energy from fusion, including a detailed description of the nuclear processes, abundances, and reaction rates.

Strange: The fourth-heaviest quark. It carries a negative charge one-third that of the electron.

Supernova: A powerful explosion of a star. Depending on the type of explosion, supernovae are categorized as Type Ia or Type II (more cataclysmic).

θ_{13}, θ_{12}: The mixing angles for neutrino oscillations that measure the content of the electron neutrino into two of the mass states (see Figure 4.1).

Tau: The heaviest and last-discovered charged lepton particle of the Standard Model.

Top: The heaviest of the six quarks. It carries a positive charge two-thirds that of the electron.

Unified theory, grand: A class of modern theories attempting to go beyond the current Standard Model of particle physics and account for the unification of all the forces of nature.

Up: One of the lightest of the six quarks. It carries a positive charge two-thirds that of the electron.

Water Cerenkov detection: A technique in which large volumes of water are instrumented with photon sensors (photomultiplier tubes). The photons are created when a charged particle's speed exceeds the velocity of light in water.

WIMP: Weakly interacting massive particle: a leading particle candidate for dark matter.