# Neutrinos and Beyond: New Windows on Nature

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Neutrino Facilities Assessment Committee
Board on Physics and Astronomy

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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:

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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 Jonathon Katz (Washington University in St. Louis). Appointed by the National Research, 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.

# Preface

The President's FY2003 Budget Request for the National Science Foundation under the 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 Dr. 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 to provide scientific assessments of two possible future science initiatives: IceCube, a very large volume detector of high-energy neutrinos proposed for the South Pole; and a possible deep underground science facility to be developed in the US to pursue a broad range of fundamental questions in physics and astronomy. Fourteen persons were appointed to the commitee and the first meeting was held in June 2002, with delivery of the final report expected within six months.[1]

The committee interpreted its charge to be:

- 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 should address the unique capabilities of each class of new experiment and any possible redundancy between the two types of facility.

The fast-track time line required a very aggressive schedule and some limitations in the

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

breadth and depth of the committee's analyses. The committee directly assessed the primary science potential of both projects in a set of internal studies, but relied heavily on community-input for some of the broader issues included in the charge. The committee learned of other interesting potential applications of a deep underground laboratory (geology, national security, etc), but the committee had neither the expertise nor the time to study them in depth. Likewise, evaluation of project issues like technical readiness, costs, management, and so on, was outside the charge and we limited our study to only what was needed to be realistic about the assessments of the science. Finally, comparing IceCube and a US deep underground facility to other facilities where similar science might be addressed is a complicated issue. For IceCube, the comparison to be made is to three possible projects in the Mediterranean Sea. As stated in the report, these projects are well behind IceCube in technical development and therefore a direct comparison is difficult. For the water detectors, a site has not been selected or even the detailed technology or configuration of detectors. This awaits the completion of prototype phase that is now underway. Therefore, the committee was only able to compare these projects to IceCube in a more general way, for example the advantages of ice vs. water for a high-energy neutrino detector. As for a deep underground facility, the report discusses a broad array of potential experiments (some in the very long term) in the report. Some of these can and certainly will be undertaken elsewhere in the world. However, at this time, the actual experiments themselves are yet to be defined, as well as the actual programs in the major facilities elsewhere in the world. Therefore, the committee confined its study to determining the requirements for such experiments, (like size, depth, distance from accelerator facilities, etc) and from that the committee determined that some of the science planned for a deep underground laboratory in the US would have substantial advantages or uniqueness, while other science could and may well be undertaken elsewhere. For these reasons, the committee could only make limited conclusions with regard to what will be done elsewhere in the world. In fact, that will to no small extent depend on what is undertaken in the US.

In the case of the underground science facility, the committee did not address 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 these restrictions, the committee sought to identify the major classes of science problems that could be addressed with the general features of 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 finite budget prioritization exercises. This decision was influenced by the makeup of the committee, the fact that the physics experiments would be the primary factor in motivating this type of laboratory, 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 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 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.

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

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[2] The NeSS 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.

# Contents

# 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 unifies the forces and particles.

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

In this report, the science that requires instrumenting a very large volume of ice deep under the 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 the earth without absorption and can give insight into the production mechanisms at the source.

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 the earth have received more and more worldwide attention in nuclear physics, particle physics, cosmic ray physics, as well as astrophysics and cosmology. Such laboratories, shielded from cosmic rays, allow the study of rare phenomena, and provide a window toward unraveling 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, they have assessed the scientific potential for such a facility in a broader context.

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

## ICECUBE

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

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

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

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 R&D, prototyping and conceptual design phases. When the funding is approved, it is 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 provided the explanation with dramatic evidence that neutrinos oscillate from one type to another, implying that neutrinos have non-zero mass. With these discoveries and the emergence of this new field, it is now very timely to consider the possibility of building a new deep underground facility in the U.S. This recognizes both the large U.S. commitments being made to facilities abroad and the future science opportunities for such underground facilities. In fact, the development of a new underground laboratory with characteristics that are well matched to the needs of the future experiments could bring the U.S. back to a leadership position in this important area of science.

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

The proposals that are currently under consideration for a deep underground laboratory allow for the development of a flexible multipurpose infrastructure to support a full suite of experiments. The actual experiments will be proposed separately, peer reviewed and then funded to be done at the laboratory. Every effort should be made to closely integrate the actual development of a new laboratory with the experimental program that will be performed. A significant advantage of a central facility is in the sharing of common technical and equipment support among the various experiments. There are many other research uses for sufficiently shielded underground laboratory space including various geophysics and geobiology projects, but the committee did not have the expertise nor sufficient time to make additional evaluations.

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

**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 shedding 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 U.S. make the time ripe to build such a unique facility.*

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

## REDUNDANCY AND COMPLEMENTARITY

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

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

# 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, 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 the mass of the earth. Second, three proposals have been recently submitted to develop a deep underground laboratory in the U.S., which would host a variety of proposed or planned experiments requiring the extremely low background environment provided by the overburden of a deep subterranean location. There has been a 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 and National Science Foundation, and an NRC panel exploring science opportunities at the interface between physics and astronomy have all endorsed the development of such a facility. Proposals for a deep underground laboratory have included existing, closed mines, new excavation, and the use of operating mines or repositories. The magnitude and scope of these proposals provides both a significant opportunity and a serious challenge: they attest to the substantial excitement of the science potential of these major facilities, but demand a careful assessment of this potential in the face of the major long-term costs and responsibilities associated with these proposals.

The obvious commonality between the two scientific initiatives included in the charge to the committee, IceCube and a deep underground laboratory, is that they both explicitly involve neutrinos and both operate below the earth's surface. A more accurate characterization is that they both deal with research requiring the detection of extremely rare phenomena. However, although neutrinos (or other rare phenomena) play a prominent role in both projects, the origins of the neutrinos, their energy range, and the science IceCube and a deep underground laboratory address are very different. Furthermore, the initiatives included in the charge to the committee 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 detector for very high energy neutrinos from space. It addresses a variety of astrophysical problems and potential sources of high energy neutrinos. On the other hand, 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 located at a particular deep underground laboratory location have not been decided, but the scientific questions they would address are evident.

This report is largely organized along the lines suggested by the formal charge to the committee. First, some of the general science context common to both initiatives is outlined and some of the historical and international context for later discussions provided. Second, the major science potential of the IceCube project is identified and discussed in the context of other large-volume neutrino observatories. Third, the major science potential of a deep, underground national science laboratory is presented and discussed in the context of on-going international activities in these research areas. Finally, the conclusions of the committee regarding the scientific merit of this research, the unique opportunities and capabilities of these facilities, and the issue of possible redundancy between the two types of facility are described.

# 2

# Science Overview: Neutrinos and Beyond

## THE NEUTRINO: FROM BACKSTAGE TO CENTERSTAGE

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). In spite of the fact that trillions of neutrinos go through each of us every second, it took nearly thirty 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 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 explode to create the majority of the elements in the periodic table. But, recent discoveries have created special opportunities to use neutrinos in new ways to advance our knowledge of the Universe and the laws that govern it.

Some fifteen years after Reines established the existence of the neutrino, Ray Davis opened the neutrino window to the Universe by using 100,000 gallons of cleaning fluid 4000 ft 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 CERN in Europe and at Fermilab in the US 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.

One hundred-sixty thousand 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 US (the 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. While 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 the 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 unifies 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 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 SNO detector in the INCO Mine in Sudbury, Ontario brought clarity to the longstanding solar-neutrino problem. Beginning with Davis' 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 mu neutrinos, showed that the predicted number of neutrinos arrive at the earth, but 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. 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).

Satellites monitoring earth for nuclear explosions discovered gamma ray burst sources serendipitously. Only in the last five years were their locations pinpointed to galaxies at the edge of the observable universe. These most energetic explosions known, which put enormous energy in gamma rays over a few seconds, are thought to be associated with the collisions of neutron stars and black holes or the violent collapses 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.

## BEYOND NEUTRINOS

Some 50 years after Pauli's desperate proposal to save 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). This means that either our present understanding of gravity is incorrect or that there must be a non-luminous form of matter (now called dark matter), which 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 a factor of 7 short 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 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 comprise 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 accounts 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 that we are made of. 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 an approximate scale of 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 and if decays are not observed it will 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 both about the Universe and the deepest inner workings of the physical laws that govern it.

## Sidebar: 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 ...*

**by John Updike**

The mysterious neutrino entered the popular culture in John Updike's 1963 poem, Cosmic Gall. He stated their 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 only interact 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 such as are 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 center of the sun (see Figure 1).

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–comprise the basic building blocks of matter. 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 hopefully someday into the powerful 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 have even revealed physics beyond the Standard Model of particle physics. Studying and understanding neutrino mass and oscillation provides a unique view into the how the forces and particles are unified.

Because neutrinos are uncharged, it is possible that, like photons, they are their own anti-particles. 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 anti-matter. Were it not for the fact that a slight excess of matter over antimatter developed later, all matter and antimatter would have annihilated long ago. If neutrinos (of non-zero mass) are their own antiparticles (unlike quarks), additional pathways for matter-antimatter differences become possible, and thus they likely played a role in how the slight excess of matter arose in today's Universe.

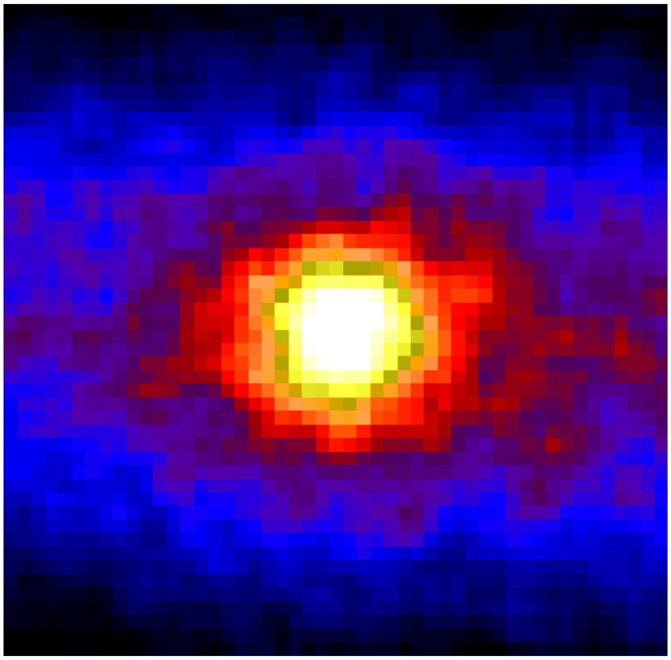


FIGURE 1: The Super-Kamiokande neutrino events created this false-color image of the center of the sun from events produced by the nuclear reactions deep in the center of the sun. Because neutrinos are so non-interactive, they can be used to probe deep inside of stellar objects to provide unique information on how they are powered. The angular resolution of neutrino astronomy is still poor compared with the performance of optical telescopes; in this figure, the visible light image of the Sun would be about the size of one pixel."

## Sidebar: 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 kilometers per hour for Mercury to 17,000 kilometers per hour 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% of the mass is concentrated at the center, the mass of a galaxy is spread out, extending far beyond its visible edge. Astonishingly, stars only account for 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 we can see it distort the images of distant galaxies beyond the cluster by its gravitational bending of their light (see Figure 2).

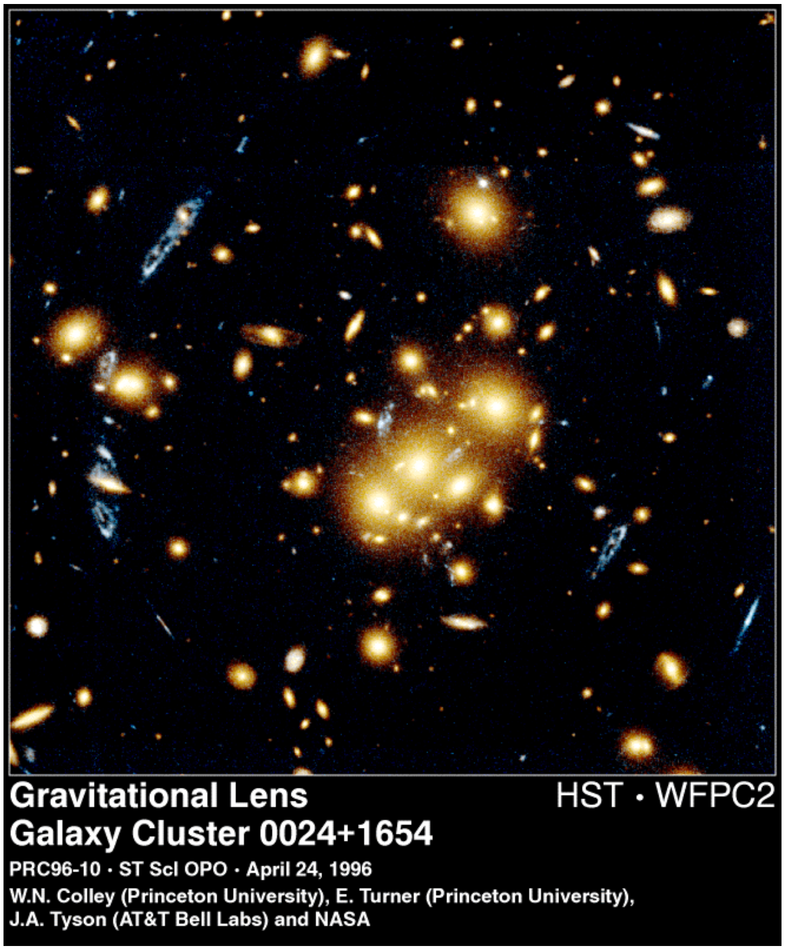


FIGURE 2: This Hubble Space Telescope image shows how the dark matter in the cluster of galaxies (seen as the yellow images) bends the light from more distant faint blue galaxies, creating multiple images of some galaxies and distorting the shapes of others. The use of "gravitational lensing" allows astronomers to map the dark matter in clusters of galaxies and to directly reveal the enormous amount of dark matter.

## Sidebar: Cosmic Rays and Cosmic Accelerators

Shortly after the discovery of radioactivity more than 100 years ago, physicists discovered that the 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 eV to more than a billion trillion eV. Cosmic rays colliding with the earth's atmosphere produce tremendous numbers of muons and neutrinos (which were used to show that neutrinos have mass). Our Sun, exploding stars within our galaxy and distant galaxies all produce cosmic rays. Not only do the cosmic rays provide samples of material from throughout the Universe, but also they 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 searching for rare events to deep underground.

The existence of high energy cosmic rays raises the question of both their origin and how they 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, 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 is more correct.

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

## 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:

- 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 is 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 (namely, it behaves as a Majorana particle). To observe and study these rare events requires laboratories shielded from the cosmic rays that bombard the earth (see sidebar).

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, far-away 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 3). 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 is 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 to the most energetic events in the Universe, from matter falling on to 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, we 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, there is a host of additional frontier experiments that requires 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.

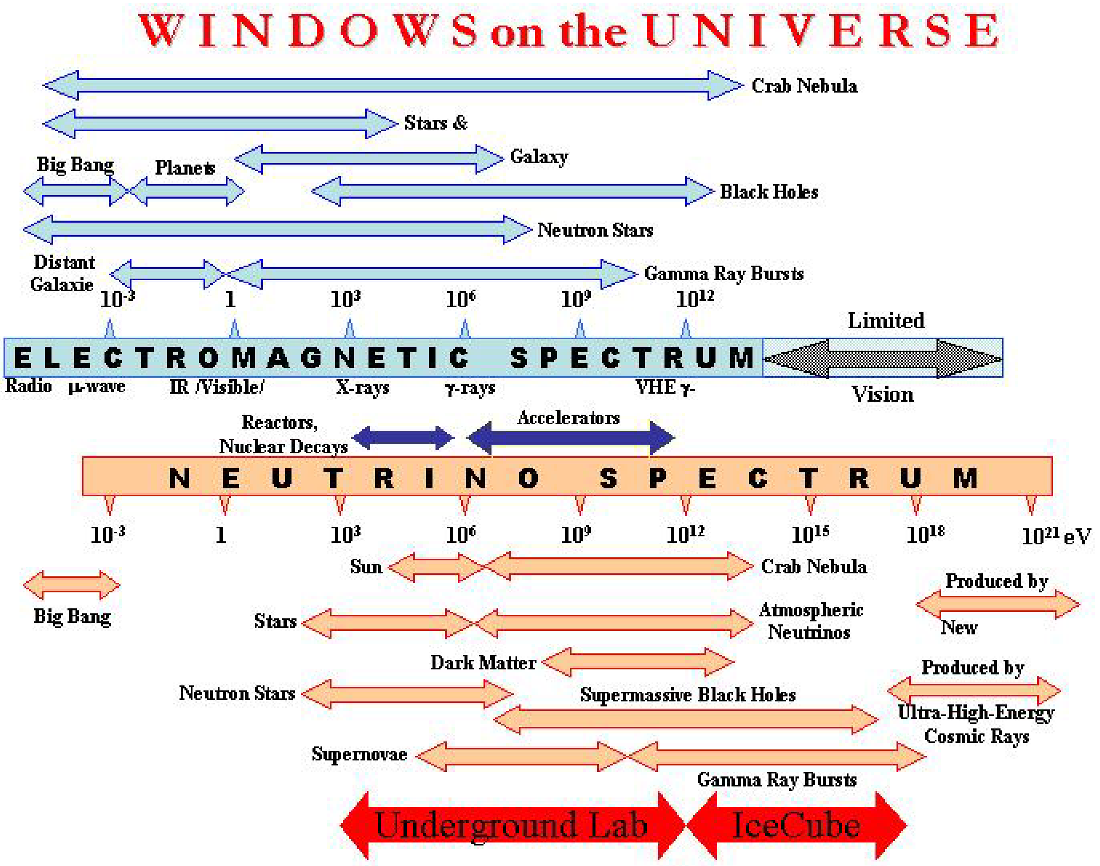


FIGURE 3: A comparison of the electromagnetic and neutrino windows on the universe, as both IceCube and the national underground lab will be sensitive to neutrinos. Astronomers view the universe with light of greatly different wavelengths and energies, from long-wavelength microwaves whose energies are ten thousand 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 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, have been revealed. 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. Between energies of about $10^{13}$ eV and $10^{19}$ eV photons can only reach us 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 offer the possibility of seeing into these processes for the first time. Detection of sources of astrophysical neutrinos will give us new windows on the Universe.

# 3

# Science Potential of IceCube

## INTRODUCTION

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 capabilities of neutrinos make possible the discovery of new astrophysical systems and new physical processes through the detection of neutrinos 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 several of the questions we posed in the last section:

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

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 a telescope—it may be that we won't see what we're looking for because there might not be any astrophysical neutrinos to discover from discrete sources. 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, one cannot say 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 over 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 ultra-compact 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. In order to achieve sufficient sensitivity to detect high energy neutrinos from distant sources, experiments on the scale of 1 km$^3$ or a billion tons of detector mass are required. Such experiments use the earth as a converter and detect neutrinos as they traverse the earth from below and interact near the experiment. Neutrino interactions produce upward-going muons that generate Cherenkov light in a suitably transparent medium such as water or ice 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 4 and 5 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 one thousand upward-going muons that are signatures of neutrinos produced in the atmosphere that lies below the horizon. IceCube will substantially improve upon AMANDA's capabilities, both through a larger detection volume and through the use of improved technology.

In the global perspective, IceCube is the only km$^3$-scale neutrino experiment ready for construction now. There are efforts in Europe, notably ANTARES, NESTOR, and NEMO, to build detectors that use the Mediterranean Sea as the detecting medium. These groups are presently building smaller-sized detectors and plan to propose one km$^3$-scale experiments in the near future with approval and construction starting within the decade. The experiments planned for the South Pole and for the Mediterranean are largely complementary in nature, both in terms of their observational targets and in terms of their capabilities. By detecting upward-going muons, IceCube is sensitive to astrophysical sources in the northern celestial hemisphere, whereas a Mediterranean experiment studies 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 one 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, we should mention 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 strongly motivated as a follow up to well-established signals from an experiment like IceCube that can be done with present-day expertise.

## 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 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 ultra-high energy neutrinos. Based on these high energy cosmic ray and gamma ray studies, the detector scale of IceCube (1 $km^3$) is the minimal size for which one has 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. Galactic sources, 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 ten neutrino events per year in a $km^3$ detector. Some AGN can maintain such high luminosities for relatively long periods of time (i.e. weeks, months). Transient objects, such as GRBs can reach much higher peak power levels (factor of 100,000 higher), 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. Blazars are thought to be AGN where a relativistic jet powered by matter falling onto a black hole (with about a billion times the mass of the sun) is nearly aligned with the direction to the 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 comparable power to that of the observed gamma rays, then detectable fluxes of neutrinos would be produced in the jet through pion production by nuclear and photo-hadronic 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 EGRET satellite experiment detected almost one hundred AGN at gamma ray energies up to $10^{10}$ eV, while ground-based telescopes such as Whipple detected five AGN up to energies of $10^{13}$ 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%) 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 (GRBs) 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 due to 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 explained by the 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 ten neutrino events per year at $10^{14}$ eV energies in IceCube, detected from an ensemble of GRBs in the northern celestial hemisphere. GRBs produced in the collapse of massive stellar progenitors could lead to about ten neutrino events per individual burst, detected a few times a year at $10^{12}$ eV energies in IceCube. These events would be correlated in position and in time with the gamma ray bursts themselves, and thus 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 gamma ray bursts by testing the gamma ray emission model and the shock acceleration physics.

Although AGN and GRBs are the likeliest high energy neutrino source candidates, there are a variety of other astrophysical objects that are possible neutrino sources. As a very wide-field telescope, IceCube can search for neutrino emission from most of the northern celestial hemisphere. Among potential sources, young pulsars, which are highly magnetized fast 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 they are sites of hadronic acceleration. Microquasar jets are associated with accreting stellar-mass black holes or neutron stars. Finally, supernovae, the very bright explosion 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 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. 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. However, another potential source of background 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 ultra-high 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 ultra-high energy astrophysical accelerators, proposed to explain the origin of the highest energy cosmic rays, could be detectable by IceCube. Optically thin sources of > $10^{19}$ eV protons 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 ultra high energy cosmic rays, they are likely to produce a flux of high energy neutrinos. In addition, the ultra-high 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 interaction between the CMB and protons with energies of $10^{20}$ eV and above, produce pions, which subsequently decay generating neutrinos. The flux of these photo-pion neutrinos rises around $10^{17}$ eV where it is marginally accessible to IceCube at the level of 1 event/yr. In the ultra-high energy range, IceCube is complementary to cosmic ray experiments such as the Auger Project whose 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 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 through their annihilations in the sun by high energy neutrino telescopes (e.g. IceCube). 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 it 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 on heavy nuclei. Therefore, the two types of experiments are sensitive to different part 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 relative 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 get severely depleted when propagating across the universe while neutrinos do 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 and beyond $10^{12}$ eV scales, which are 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 megaton 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 serves as a better detector- and signal-transmission medium. (Detectors in ice suffer from higher scattering losses than underwater, but ice is generally more transparent and possesses lower backgrounds (i.e. from radioactive potassium-40 and bioluminescent marine life.)) An expert panel of the international scientific body IUPAP recently endorsed an underwater cubic-kilometer scale followup to the NESTOR Mediterranean project, but no concrete proposals have been submitted as there is significant remaining R&D to determine the best design. As such, then, IceCube is unique in its stage of development, in its employment of ice as the detector volume, 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 towards a km$^3$ volume, over a five to six year period. Unlike many large-scale experiments, IceCube will be operational during the construction period as it grows. Currently, IceCube has a head start on its competitors, and so timely deployment of the detector will give it a lead in the exploration of this new window of astrophysics.

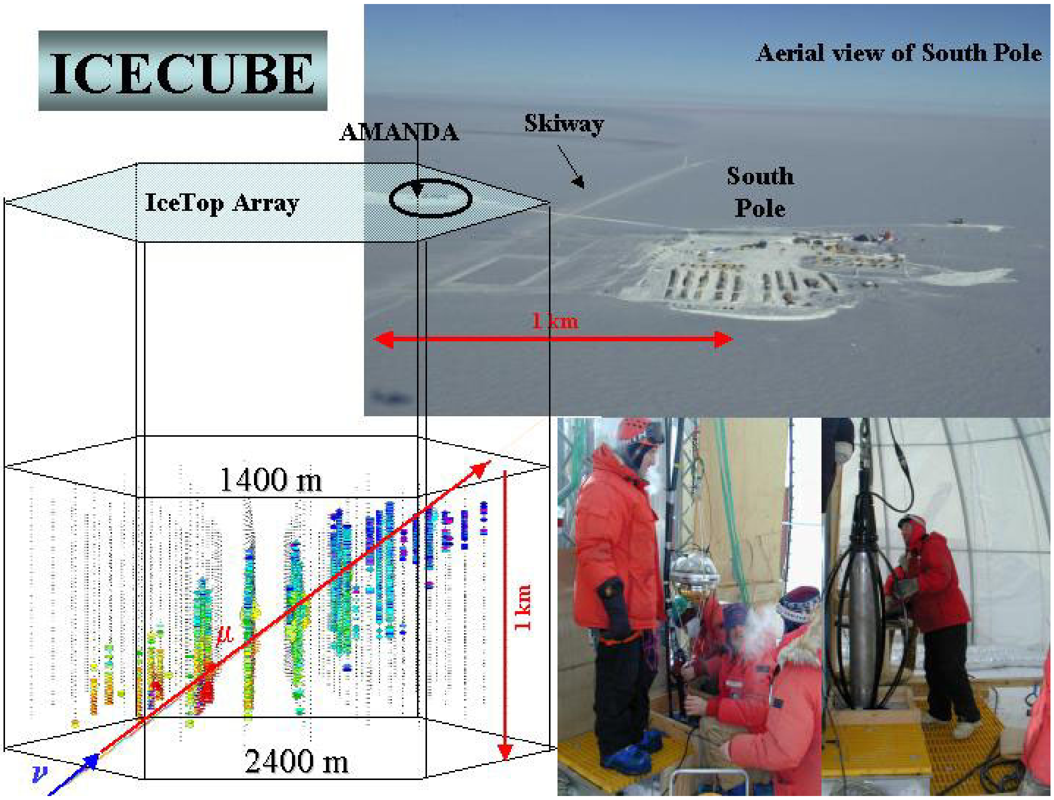


FIGURE 4: The IceCube detector is shown in the left side of this figure. The upper right shows the landing strip for airplanes (Skyway) and the region on the surface above the AMANDA experiment. The

lower right shows light sensor strings being lowered deep into the ice using a hot water drill.  IceCube will have 80 strings with 60 light sensors per string for a total of 4,800 sensors.

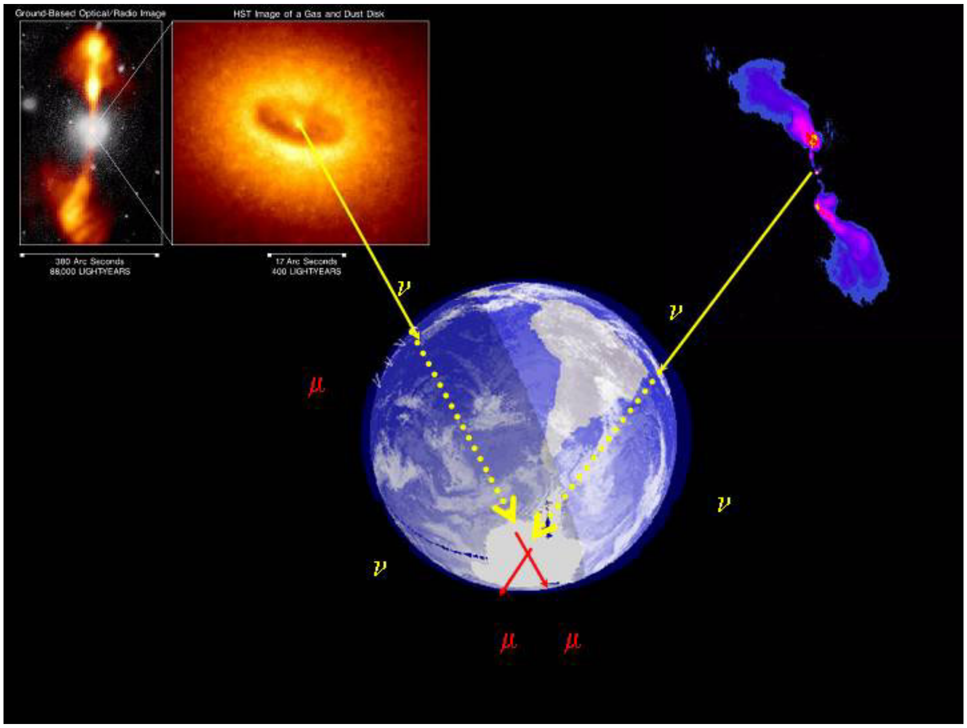


FIGURE 5: IceCube will detect muons generated by cosmic neutrinos as they traverse and interact in the earth.

# 4

# Science Potential of a Deep Underground Laboratory

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

- 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 is 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 in 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 two miles of rock to absorb the most energetic of the muons created by cosmic ray protons striking the 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 ten 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 tolerate less stringent conditions either because the process being sought has a higher rate, or because some special experimental tag can be used to identify the important events even in the presence of backgrounds. 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.

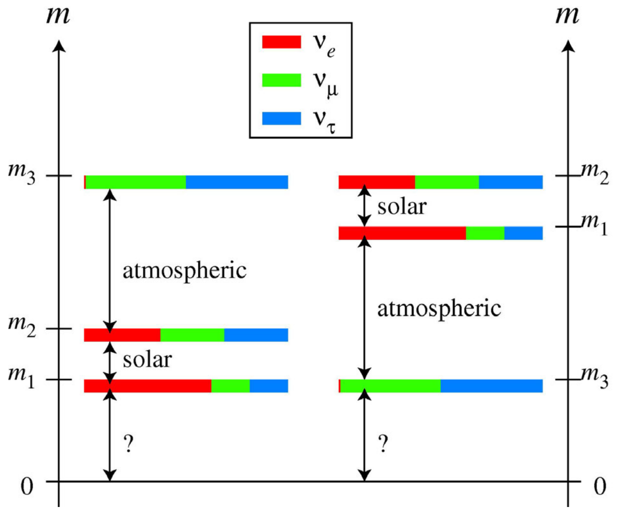
Among the scientific objectives discussed in this chapter, solar neutrinos, double beta decay, and dark matter experiments are poised to develop next generation detectors that require low-background, and need an underground facility for technology development in the next few years in a field of science of intense international interest. 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 over the next 5 years to lead to the synthesis necessary for the long baseline program. A long baseline target detector is likely to serve also as a proton decay experiment, supernova neutrino study, and many other purposes.

## NEUTRINO PROPERTIES

The neutrino has had a very rich history. As described in the Science Overview, 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 interacting very weakly 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 there is not one but there are three distinct types of neutrinos, an electron, mu, 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 mass of 511,000 eV. The Standard Model of particle physics, therefore, has been built with the key assumption that neutrinos were massless.

This tidy picture was dramatically changed by the recent experimental discoveries. Both in atmospheric and solar neutrinos, there is now strong evidence that neutrinos change from one type to another (oscillate) as they travel through space. Because particles with no mass such as photons do not sense time according to Einstein's theory of relativity, any change in their character signals that neutrinos experience time and hence must have a mass, thus challenging one of the assertions of the Standard Model. The 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 inferred mass-squared differences from the data are very tiny, tenths of eV and less. This is very small compared to the typical masses of quarks and other leptons; and is more than ten orders of magnitude lighter than the top quark. Why are the neutrino masses so tiny? Another new puzzle since these discoveries is that the compositions of neutrinos with definite mass values are highly mixed up, as shown in Figure 6, with large fractions of electron, muon, and tau types in a given neutrino. This must be compared to the situation among quarks, where the amount of mixture is very small, 0.01–5%. The aim of the next generation experiments is to, first of all, establish the new emerging picture of neutrinos, and determine yet unknown parameters in the neutrinos, and then 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° the maximum admixture of a second flavor. With three flavors, there are three angles, $\theta_{12}$, $\theta_{23}$, and $\theta_{13}$. The mixture of the electron-type in the 3rd neutrino which is related to $\theta_{13}$, is known to be small, but we do not know how small. There may be additional neutrinos species (sterile) beyond those we currently know. If so, how many are there?

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



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

FIGURE 6: Two possible patterns of masses and admixtures of three neutrinos that explain current solar and atmospheric neutrino data are shown. Different colors represent the admixture of the electron, mu and tau neutrinos in each mass value. We do not yet know which pattern is correct. The differences in masses and the admixtures are known only crudely. The absolute scale of neutrino masses is largely unknown, but 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 the crucial information on the absolute scale. The potential differences between neutrinos and antineutrinos are also unknown.

As will be 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 crucial roles 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, for which work Raymond Davis, Jr. received the 2002 Nobel Prize in physics. 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 Sudbury Neutrino Observatory 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, mu and tau neutrinos. Strong indications of this conversion were already apparent when data from the Super-Kamiokande, SAGE, Gallex, and Homestake solar neutrino experiments were considered together. A new solar neutrino experiment, Borexino, and a reactor antineutrino experiment, KamLAND, are now being commissioned 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%. 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.

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 from electrons (the ES reaction). Taken together, these measurements provide model-independent determinations of the electron and non-electron neutrino flux components at each energy, and solar-model-dependent determinations of the sterile components. Because the electron and non-electron 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 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. Good ideas exist for both types of experiment. They are currently in an R&D phase, some of which will call forunderground space for tests soon, and some which are already taking place (i.e. the 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 site 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 is to compare the rate of solar neutrino interactions to 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 3000 mwe. Since no tag exists for the ES experiments (other than that the scattered electron tends to point away from the sun) a substantial margin of signal over background is desirable, which would emerge at depths of 6000 mwe. The

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

CC experiments expect rates 10 to 100 times smaller (for unenriched isotopic material), but in most cases proposed have a tag that helps with background rejection. The signal rate equals the transmutation rate at a depth of about 6900 mwe.

Although current generation solar neutrino observatories could promise to significantly advance the state of the science, there is still much to learn, especially in terms of low background, high-precision physics. It cannot be said that these difficult experiments would become impossible at depths shallower than 6000 mwe, but it is clear that at such depths a major background source is under control, whereas at lesser depths it remains uncertain. A laboratory sited at 6000 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 of future solar neutrino experiments which address measurements not accessible to accelerator experiments. Protons from accelerators produce an almost pure beam of muon neutrinos, while solar neutrinos are purely electron neutrinos. With such beams we may even observe CP violation, a possible subtle difference in properties between neutrinos and anti-neutrinos that may be fundamentally related to matter/anti-matter 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 of neutrinos. When cosmic rays hit the earth's atmosphere, neutrinos are created that enter underground experiments. Even those created on the other side of the earth easily penetrate the 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 the earth. However for quantitative measurements of neutrino mass and mixing parameters, accelerator-based neutrino oscillation experiments are crucial. With particle accelerators, we 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 K2K in Japan, ICARUS/OPERA in Europe (temporarily on hold), and NuMI/MINOS in the U.S, 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 to be primarily mixing between the muon and tau types by these experiments. However, the remaining critical mixing parameter, known as $\theta_{13}$, will be poorly determined at best. This parameter is different from zero if each of the three neutrino types (electron, muon, and tau) mix with all the others. The value of $\theta_{13}$ , now known to be less than 10 degrees, will only be measurable by presently planned experiments 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 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 $\theta_{13}$ will be the critical goal and the gateway to exciting new issues, like CP-violations and establishing the neutrino family mass hierarchy (see Figure 7). Both can be addressed if the value of $\theta_{13}$ is large enough. Sensitivity to all these questions depends on many factors but mostly on (1) the neutrino energy, (2) the distance between production and observation, (3) the neutrino source flux, and (4) the detector mass and sensitivity.

The most likely route to determining $\theta_{13}$ 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 1GeV, the optimal distances are longer than about 500 km, depending on the exact value of the mass splitting determined in the next few years. Since the oscillation probability 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 $\theta_{13}$ 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 need to be more substantial. It has been shown that it is not easy to disentangle effects of $\theta_{13}$, different mass hierarchies, and CP violation, because all of them affect the oscillation probabilities simultaneously. We will need at least two different baselines and/or energies to resolve each of them separately. In Japan and Europe, the baselines presently envisaged are relatively short. Therefore it makes sense to develop plans for experiments with baselines longer than 1000km in the U.S. in the context of the international program. Indeed, distances from the two major proton laboratories (Fermilab and Brookhaven) range from 1200 to 2600 km for the several proposed underground sites.

Already planned long baseline experiments involve neutrino energies of order GeV, beam powers of ~100 kilowatts, detectors of 5–50 ktons, and distances of 200 to 700 kilometers. 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 (~2000 km). An important issue to be resolved for such experiments is the high power source, whether it is more intense, a “super beam”, or supplies a storage ring serving as a “neutrino factory”. Super beams are being considered in many parts of the world. The neutrino factory concept is undergoing substantial accelerator R&D and will need time to demonstrate feasibility.

The timing for such experiments in the U.S. is probably still a few years away. It may be wisest to finalize plans after the mixing parameters are better known. More importantly, the neutrino source needs careful planning and needs to be coordinated with optimization of a large, well-instrumented, detector. The existence of an adequate underground laboratory would facilitate this planning. Also, laboratory infrastructure and staff would greatly expedite the installation, commissioning and operation of large detectors. Even 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 necessity for great depth to reduce 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 issue 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 U.S. has important (and somewhat unique) historical, scientific, and geographical advantages. If the U.S. 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 finalize in about five years. Such plans are likely to be much more reliable if an underground facility were 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 non-zero *differences* between the squares of the masses of different kinds of neutrinos, and therefore prove that neutrinos must have a finite mass. However, the absolute value of the mass and whether the neutrino is distinct from its anti-particle are still completely open questions. If the neutrino is distinct from its anti-particle 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 anti-particle 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 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 where 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 $\Delta m_{atm}^2 \sim 3x10^{-3}$ 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 anti-particle 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 man made) 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 U and Th chains are radioactive with large enough decay energies to pollute the peak region. Since the half-lives of the parent U and Th isotopes ($\sim 10^{10}$ years) are much shorter than that of double beta decay, very low U and Th 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. Thus the capabilities to purify, fabricate, and assemble parts underground is needed to mitigate this problem. 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 4000 mwe or deeper to mitigate the cosmic ray-related background.

There are several proposals in the U.S. and around the world for next-generation double beta decay experiments with sensitivity to 50 meV. The EXO, Majorana, and MOON proposals have US participation and will very likely be carried out in the US if acceptable underground sites can be found. These three and the GENIUS and CUORE proposals are the most advanced efforts, in our opinion, for reaching the 50-meV target. There are a large number of experienced double beta decay experts in the US and an even greater number of low background experts. The forming US collaborations have many of these experts involved. These collaborations are presently active in expanding their manpower, and performing research and development measurements. Furthermore, these groups have obtained seed money and proposals are being written. Two of these experiments (EXO and Majorana) will be looking for an underground site for initial detector systems in the coming year. There are also US collaborators on the CUORE project that is being assembled in Europe. All in all, the US is in a strong position to make a significant contribution to this next generation of experiments. Deep underground lab space is essential to the success of these efforts; the national underground facility is a natural way to meet their common needs. Because these experiments require underground space soon for R&D efforts, the need is urgent.

## 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. The case for a new form of elementary particle as the resolution of the dark-matter problem has become very strong, 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, which we focus on here, since it is mostly in 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.[*]

In the mid-1980's, 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 natural radioactivity and cosmic rays compared to this rate. The general methods to defeat 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

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

or seasonal modulation.

At this time, no conclusive evidence exists for WIMPs. Early WIMP detection experiments in the late 1980's 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 one ton will be needed to fully explore the range of currently favored models. Internationally, groups with strong US 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 also recoil from nuclei. Most sources of neutrons, e.g., from natural radioactivity in rock, are relatively low-energy and can be effectively shielded. A troublesome source is 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 underway in the US and worldwide to detect the dark matter. The leading efforts include the French Edelweiss experiment in Frejus and the US Cryogenic Dark Matter Search at the Soudan Mine, both using low-temperature detectors; the Italian experiment DAMA in the Gran Sasso Laboratory using a large array of sodium iodide detectors; and the UK/US Zeplin experiment using liquid xenon in the Boulby Mine in the UK. The challenge for these collaborations is to avoid claims of a false signal by fully understanding their systematic effects. The other experiments mentioned, along with a range of other approaches, including gas detectors with directional sensitivity (the US-led DRIFT experiment), a competing liquid xenon experiment (the US-led XENON collaboration), ultra-pure germanium diode detectors (the US-led Majorana and German-led GENIUS efforts) and superheated droplet detectors (US-led SIMPLE and Canadian-led Picasso efforts), are in various stages of progress. Each of the different approaches attack the electromagnetic backgrounds with a variety of methods, with a common aspect being that some suppression and screening of radioactive contamination is 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 warrant a scale up to 1-ton of detector mass. While 1-10 kilogram-scale experiments get underway, 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 2-4 year timescale 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.

Improvements in detector technology or assaying and screening of detector components can reduce the level of electromagnetic backgrounds without much regard to 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 question depends on the relative immunity to electromagnetic versus neutron backgrounds and is therefore experiment specific. In general, we anticipate reduction of electromagnetic backgrounds by further technological improvements that are independent of depth. Such improvements will only increase the overall sensitivity to WIMPs if there is a concordant reduction in the neutron background. With only modest reduction in electromagnetic backgrounds – which looks achievable in the coming decade -- siting at less than 4500 mwe could leave neutrons as the dominant source of background. By siting these next-generation ton-scale experiments at depths of 4500 mwe or greater, the risk of being background limited by neutrons will be considerably reduced. A depth of 6000 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 this field. With kilogram-scale experiments already underway, work on the underground lab must begin as rapidly as possible to allow the R&D for ton-scale experiments to get started in a timely way. The creation of a unique well-equipped deep underground lab will maximize the chance for the US 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 not involve 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, so-called baryon number is conserved. The proton that makes up atomic nuclei is the lightest particle with non-zero baryon number, and hence is absolutely stable. However, in most extensions of the Standard Model, baryon number is not conserved and hence the proton is predicted to decay. Ultimately all known forms of matter would decay, albeit with lifetime many orders of magnitude longer than the age of Universe. The discovery of proton decay would have enormous impact on the understanding of nature.

There are many arguments for why the proton should decay. An obvious point is that our Universe consists of only matter, and no anti-matter. When the Universe was born, both matter and anti-matter were created in equal amounts. If it stayed that way, all matter and anti-matter must 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 anti-matter (one part in ten billion) has transmuted to matter. This implies that baryon number is not conserved, in turn implying that the proton must decay.

Einstein dreamed that there is a simplicity underlying 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 proton) and leptons (such as electron 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 sometime 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 microscopic world, quantum mechanics, and 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 conservation law 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, we 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 to the shortest distance scales available to us, with a possible exception of the neutrino mass. Past experiments have already set the limit that the proton lifetime is beyond $10^{32}$ 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 had been 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 and look for them to decay. The most recent experiment, Super-Kamiokande, houses 50 kt of water. By watching carefully for a proton to decay in this tank of water over many years, they have set the best lower limits on proton lifetime so far, $1.6\times10^{33}$years for $p\rightarrow e^+\pi^0$ and $6.7\times10^{32}$years for $p\rightarrow\nu K^+$. These lifetimes may be compared to the age of Universe, which is about $1.4\times10^{10}$ years. This very important result has excluded the simplest models of non-supersymmetric and supersymmetric grand unified models.

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

The proposed proton decay experiments require modest depth. Shielding from the bulk of cosmic rays is necessary, requiring the depth of about 2000mwe or greater. However, detection of some modes of nucelon decay (e.g., proton to a lepton and two neutrinos, or even neutron decay into three neutrinos) may 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. IMB and Kamiokande have detected neutrinos from a supernova in the Large Magellanic Cloud (SN1987A), and 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 collision of cosmic rays, and saw the first hint of neutrino oscillations and hence finite neutrino mass. This observation was later established by a bigger proton-decay experiment Super-Kamiokande, also corroborated by Soudan-II and MACRO experiments. Kamiokande and Super-Kamiokande have demonstrated that neutrinos come from the sun, confirming its power in 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 experiment using the neutrino beam produced at KEK a distance of 275 km.

The increasing cost and size needed for the next generation proton decay experiments make it important that such an experiment would serve multiple purposes. As such, a proton decay experiment that is capable of acting as a target detector for an accelerator-based long-baseline neutrino oscillation experiment seems particularly attractive. The technology for building a detector 20-40 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 the readiness 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. Because neutrinos can escape an enormous density of material, they carry direct information on the interiors of stars and gas that cannot be studied by optical telescopes. There are a number of potential measurements to 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 are not accessible to direct optical observation because they occur in the interior of the sun — and what can be measured well is the total thermal energy radiated from the solar surface. Neutrinos provide a direct window on these processes.

The solar neutrino detectors using water Cherenkov 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 the understanding of the sun’s operation, some questions do remain. In addition to the main cycle of hydrogen converting into helium, there is a second cycle of thermonuclear reactions that can occur, in which the elements carbon, nitrogen, and oxygen serve as nuclear catalysts for converting hydrogen to helium. Only about 2 percent of the sun’s energy is believed to come from this CNO cycle, but the result depends on the presolar abundances of these elements relative to hydrogen and helium. Additionally, the probable 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 for which a sufficiently deep underground facility would provide an ideal environment.

The processes in the sun are typical of similar stars that are too far away for their neutrinos to be detected on earth. To give a detectable signal from distant stars requires extreme conditions and by far the most likely is the occurrence of 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% of the energy is released in the form of neutrinos. It is only in such very hot environments that the elements heavier than oxygen can be released — the heavier elements in the solar system, such as iron, gold, 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 re-energize the explosive shock wave that is otherwise stalled by infalling matter, and 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 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 the detection of many more (thousands) of neutrinos from a single supernova and measuring flux of the emitted neutrinos, the energy spectrum, the time distribution (the pulse lasts a few seconds), and their distributions among the different flavors, neutrinos and antineutrinos.

The best signals will come from nearby supernovae,but the times of their occurrence are not predictable. The existing detectors such as LVD, Super-Kamiokande, SNO, and KamLAND, as well as planned future detectors, would primarily detect electron-anti-neutrinos, 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 base-line 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 inner workings of the supernova explosion, by studying the spectrum of the muon and tau neutrinos. New designs have been proposed for this purpose.

Coordination of the timing 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 on supernovae and will provide a better window on how the elements heavier than oxygen essential to our life had come to exist on the 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 that we did not assess. Others range over a wide variety of interesting possibilities, which were beyond the charge and expertise of this committee, from geologic processes to subterranean life forms, as well as to other uses of such environments with ultra-low backgrounds, including possible applications related to national security.

## UNDERGROUND SCIENCE IN AN INTERNATIONAL CONTEXT

Underground science is a burgeoning field 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 U.S. has priority in underground physics because of the pioneering Homestake and IMB (precursor to the Japanese Kamioka experiment, in fact) experiments which gave the US a tradition of excellence and discovery. The major current labs are summarized in Figure 7, which plots the depth of the laboratory against the cosmic-ray muon flux at that depth. The "depth" is not the actual depth, but 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 (4700 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 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.

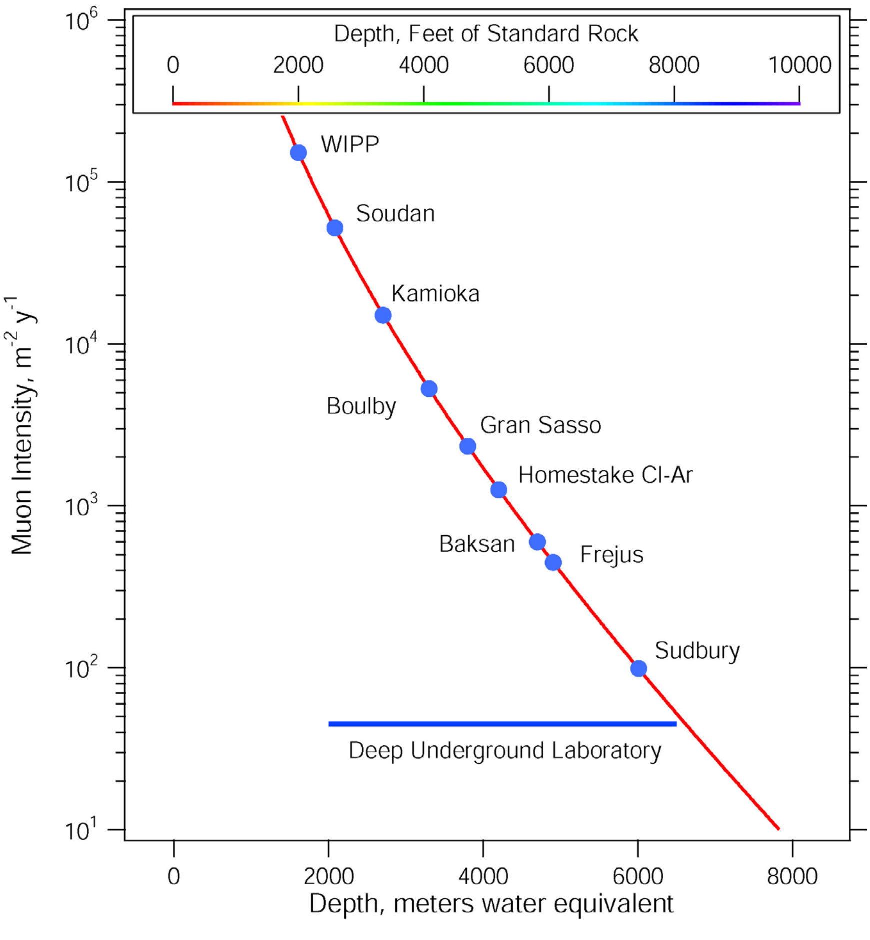


FIGURE 7: Variation of the flux of cosmic-ray muons with overburden. "Standard Rock" has a density of 2.650 g cm^-2, but actual rock density depends significantly on location. The horizontal bar indicates the range of depths that would be available for experiments in a multipurpose underground laboratory. 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.

In Europe several small laboratories have been built contiguous to road tunnels (LSC (Canfranc), LSM (Fréjus-Modane), Gotthard, Mont Blanc), as well as a large multipurpose installation, the Gran Sasso National Laboratory in Italy. While some are no longer in use, Fréjus (4900 mwe) is in demand, and Canfranc (2450 mwe) and Gran Sasso (3800 mwe) are being expanded. The Gran Sasso Laboratory hosts the GNO gallium experiment, Borexino ( a liquid scintillator detector for solar neutrinos), and two long-baseline experiments to detect neutrinos from CERN. A 1000-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 18000 m$^2$ of laboratory space is being expanded with the addition of two new halls and an independent access tunnel for safety. Fréjus, with 3400 m$^2$ of space at one of the deepest locations, is home to two double beta decay experiments (NEMO-3 and 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 2092 m (6000 mwe), SNO is presently 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 15000-m$^3$ cavity at the 2092-m level and a 2000-m$^2$ laboratory building, respectively. The first of the new experiments is PICASSO, a supercooled droplet detector for dark matter WIMPs. A CdTe 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 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 10000 - m$^3$ cavity would also become available for new research.

In Finland, scientific work is being carried out on the 90, 210, 400, 660, and 900 m levels of the Pyhäsala mine in Pyhäjärvi (CUPP), and a maximum current depth of 1440 m (4050 mwe) is available for new caverns. There is access by both a vehicle ramp and a single-shaft hoist. Experiments currently underway are measuring cosmic-ray interactions and the fast neutron background from radioisotopes in the rock. Proposals exist to search for multi-muon events, and a large long-baseline experiment with a beam from CERN, 2288 km away.

The Boulby potash mine (3350 mwe) in the United Kingdom is operated by the UK Dark Matter Collaboration and contains dark matter detectors using Xe and NaI. It is being augmented with new surface facilities in preparation for the next generation of ton-scale dark matter 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 (2700 mwe), and the other in a disused rail tunnel near Oto (1400 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 Cherenkov 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 1000-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 2-flavor mixing. KamLAND may also be a detector of low-energy solar neutrinos (from $^7$Be) but at the depth of 2700 mwe, the cosmic-ray production of $^{11}$C is a serious background.

Other new experiments at Kamioka include a small LiF dark matter experiment, a gravitational wave detector, and a 100-kg prototype liquid Xe detector for dark matter, low-energy solar neutrinos, and double beta decay. The Xe project (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 Cherenkov detector, "Hyper-K," is under consideration for both a proton-decay search and for long-baseline precision studies of neutrino oscillations and CP violation.

Within the US, there are two operating underground laboratories, the Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM (1600 mwe), and the Soudan mine in Minnesota (2080 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 (7000 mwe or more) and existing infrastructure. Other sites in the U.S. 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 6500 mwe and accessible by vehicle via a level tunnel. Deeper depths would be possible with a sloping tunnel. The other is at WIPP, which is presently used as an active safe repository for low level nuclear waste, and which could be expanded to accommodate an experimental physics program.

The scientific community in the US has played a very significant role in the accomplishments in underground science in the past 30 years. For instance, the U.S. experiments 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 the only two experiments on Earth to observe the neutrino flux from supernova 1987A (the other experiment being the Japanese Kamioka project). US 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 US, and would such a facility then be unique?

In the case of the megaton-scale detectors, no underground cavity of this scale presently 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 background, but, to illustrate, at the depth of the Homestake Cl-Ar experiment, 4200 mwe, cosmic-ray activation was a source of background with an attendant experimental uncertainty, whereas in the SNO experiment at 6000 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% 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 more quickly than the pace at which a US 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 in a sufficiently advanced state of development that underground sites are 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 US 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 US 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 the understanding of 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 multi-prong approach with experiments deep underground, on land and in space. This close coupling of the science at the largest scales known to man, to the science at the smallest scales imaginable to man, 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 probing some of today's most compelling questions in elementary particle physics, astrophysics and cosmology.

Our scientific evaluation of the IceCube and deep underground initiatives presented in this report need to be viewed in the context of the broader planning for future projects in physics and astronomy. In particular, the NRC report "*Connecting Quarks and the Cosmos: Eleven Science Questions for the New Century*," addresses a set of important questions at the interface of astronomy and physics, several of which would be addressed by these projects. In particular, the report addresses the goals to "determine the neutrino masses, the constituents of the dark matter and the lifetime of the proton". 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."

By their nature, these two projects 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." It gives a new deep underground laboratory its 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 of these initiatives, although it places them below the highest scientific priority of the field, participation in the worldwide efforts toward a linear collider. Regarding the scientific goals of IceCube, it says it is an "example of a mutually beneficial cross-disciplinary effort between astrophysics and particle physics," and it comments that experiments deep underground "will make important contributions to particle physics for at least the next twenty years, and should be supported by the high energy physics community."

Our own assessments of the scientific opportunities presented by IceCube and a new deep underground laboratory are quite consistent with these reports. For both, we find that the total scientific opportunities in the areas of astrophysics, nuclear physics, particle physics and their intersections make for impressive and exciting research programs. We believe both are well worthy of 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 ultrahigh 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 both important consequences in our understanding of the universe, and also in our understanding of the physics involving the basic constituents of nature.

IceCube is an exploratory experiment in a new area of science involving the detection of high energy neutrino 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 for these, as well as for new and unexpected types of sources.

Neutrinos traverse the Universe almost unimpeded making them a powerful new probe, but because of the small interaction cross sections a very large detector is needed to make detections possible. In order to achieve sufficient sensitivity, experiments on the scale of 1 km$^3$ or a billion tons of detector mass are required. The scheme in IceCube and underwater detectors is to use the material of the 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. The IceCube sensors are deployed by lowering strings of photomultiplier tubes into melted ice and allowing the strings to be frozen in place.

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; both through a larger detection volume and through the use of improved technology. Ice Cube 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 six-year period. We note that a prompt start of construction will lead to IceCube becoming the first detector to embark on these high energy neutrino observations, an important feature 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 their work; furthermore, initial results could even be available 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 state where they have demonstrated that a full-scale detector for Ice Cube can be constructed that meets the performance requirements of the experiment. Before construction can begin the project will need to install appropriate management, make final technical and design decisions, and strengthen the collaboration to leverage the experiment to its full potential. The underwater detector efforts in Europe are at an earlier state of development and are not yet ready for a large-scale installation.

To summarize, our 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 provide the possibility of studying rare forms of penetrating radiation in a low background environment (e.g. neutrinos and dark matter); and they also provide a low background environment to study rare processes (e.g. double beta decay, proton decay, etc). A variety of physics areas have been examined in some detail, with respect to the requirements to address the critical and exciting scientific questions that have recently emerged and were enunciated in the section on future opportunities. These topics include solar neutrinos, double beta decay, dark matter, long baseline neutrinos, proton decay, and stellar processes. In all cases numerous new experiments are being devised, proposed and discussed that would greatly increase our knowledge of these complex physics phenomena. They vary in size and complexity.

We find 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 4500 meters water-equivalent (mwe) or more. There are a few experiments that because of special detector features may be done with 2000 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 as depths of 2,000 mwe are deemed adequate. But both of these share a need for large, massive detectors and hence a sufficiently large site for the underground lab. However, even in these latter cases one can envision instances where greater depth would be an asset in accomplishing the physics goals. Of course these studies have been undertaken with our present knowledge. Historically, it has always been prudent to anticipate unexpected backgrounds, more stringent requirements or new physics that need greater sensitivity. These trends argue for greater depths to leverage the science, but 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 at a distance greater than 1000 km from existing, high intensity proton accelerators. The United States has an advantage in this siting requirement due to the large size of the North American continent and the proven and expandable capability to produce intense neutrino beams at Brookhaven National Laboratory and at Fermilab.

A new laboratory should have the potential to host a broad spectrum of experiments. As mentioned, this will require both significant depth and sufficient underground space to realize the full range of opportunities. This will result in economies coming from shared resources, as well as developing a stimulating scientific center. The survey of science experiments that could utilize a deep underground laboratory finds a compelling collection of experiments that are, or soon will be, feasible in the near term and that address some of the most fundamental questions in particle physics and cosmology. The committee finds that the science motivation for mounting large-scale experiments underground has increased markedly in the recent past. The committee also concluded 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 both initiating and implementing many of the important subterranean experiments. In recent years, some of the most important new experiments have been sited outside of the United States, not because there is a lack of U.S. participation, but because the major facilities for underground experiments are located in other countries.

The breadth and quality of the potential future experimental program requiring an underground location suggests that there is a major opportunity for the United States if it can soon develop a large new underground facility with the ability 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 the detailed strategy for developing an experimental program.

In summary, our assessment is that a deep underground laboratory in the US. 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 shedding light on the nature of the dark matter that holds the Universe together. Recent discoveries about neutrinos, as well as 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

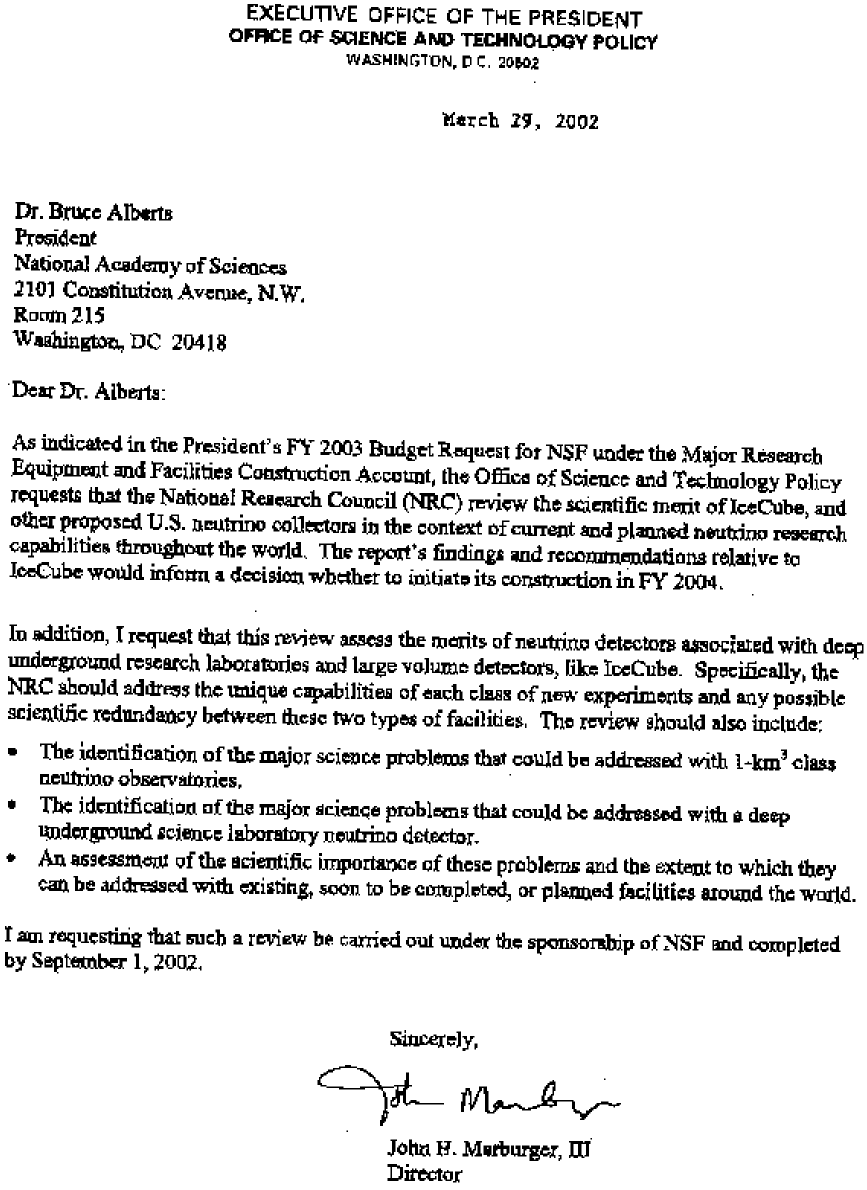
The two scientific initiatives assessed in this report (IceCube and a deep underground laboratory) have largely distinct science goals. Although neutrinos play a prominent role in both projects, the origins of the neutrinos, their energies, and the science they address is very different. IceCube takes advantage of the very clear ice available at the South Pole, in order to develop an observatory for ultrahigh energy neutrinos that might be produced by energetic sources in the Universe. IceCube has secondary goals involving the detection of neutrinos from supernovae, and to look 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, proton decay, solar neutrino studies and experiments on neutrino oscillations. Direct dark matter experiments at an underground laboratory are different and complementary to searches that might use the IceCube detector, as they are suited to different mass ranges and different types of interaction of dark matter particles on nuclei. In this way, although some of the science may overlap between the two projects, they are both critical investments that address the science questions.

Similarly, the large detectors for proton decay and long base-line neutrino oscillation studies deep underground could also serve as a detector for supernovae. Otherwise, we find essentially no overlap or redundancy in the primary science goals and capabilities of IceCube and that of a deep underground laboratory. Finally, we find 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 megaton-sized detectors, and will take advantage of the opportunity for high energy neutrino detection. The national underground lab offers the United States some vital scientific opportunities that will impact 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



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.

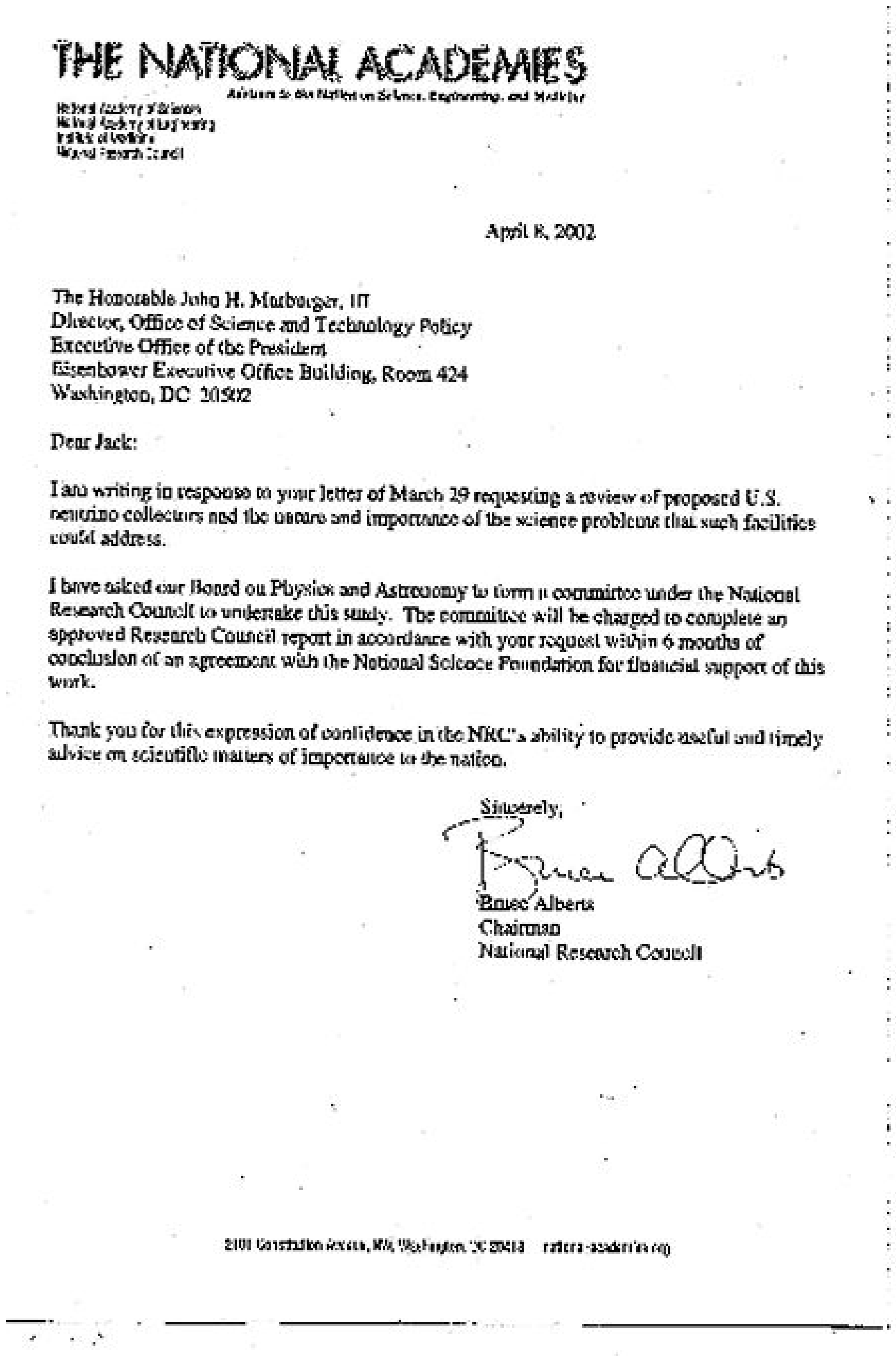
In addition, I request that this review assess the merits of neutrino detectors associated with deep underground research laboratories and large volume detectors, like IceCube. Specifically, the NRC should address the unique capabilities of each class of new experiments and any possible scientific redundancy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

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, Director of the Laser Interferometer Gravitational-wave Observatory, California Institute of Technology. He 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 AAPT.  Prof. Barish received his doctorate from the University of California at Berkeley in 1962. He was a postdoctoral fellow there until moving to Caltech for good in 1963. Dr. Barish is an experimental high energy and gravitational wave physicist. He is leading the search for gravitational waves in LIGO and is involved in the MINOS project; a long baseline neutrino physics experiment between Fermilab and the Soudan Mine in Minnesota, as well as other major non-accelerator experiments both in the U.S. 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 DOE/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.  Prof. Barish recently served as chair of the IUPAP commission on particles and fields and is incoming chair of the U.S. Liason Committee to IUPAP.  He served as science coordinator of the DOE/NSF SAGENAP review panel for non-accelerator physics.

**DANIEL S. AKERIB**, Associate Professor of Physics, Case Western Reserve University. Dr. Akerib 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 CDMS Collaboration (Cryogenic Dark Matter Search), 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 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 ultra-low threshold detector grant from the Civilian Research and Development Fund for the Independent States of the Former Soviet Union. He was an NSF CAREER awardee in 1997.

**PATRICK D. GALLAGHER**, Physicist, National Institute of Standards and Technology. Dr Gallagher 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, 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, and the experimental study of non-equilibrium structure and processes in complex condensed matter systems. Dr. Gallagher is a member of the APS (Polymer Physics) and the MRS. In 2000 Dr. Gallagher was a NIST agency representative at the NSTC and 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 Los Alamos Spectrometer Development Project, the DOE's Review Committee on the Technical, Cost, Management Review of the 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 NRC's Solid State Sciences Committee.

**STEVEN R. ELLIOTT**, Scientific Staff Member, Los Alamos National Laboratory. Dr. Elliott received his doctorate from the University of California at Irvine in 1987, and then went on to postdocs 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 atomic, nuclear, and particle physics and 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 a several professional conference committees, a DOE review committee for the international KamLAND neutrino experiment in Japan, and the program committee of the American Physical Society’s Division of Nuclear Physics.

**ROBERT E. LANOU, JR.**, Professor of Physics, Brown University. He 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, Prof. Lanou is a fellow of the American Physical Society and the American Association for the Advancement of Science. He was previously on the staff of the University of California, Berkeley, a Visiting Fellow in the Italian National Universities at Padua and Bari, 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 the Executive Committee of the American Physical Society’s Division of Particles and Fields. Prof. Lanou was a member of the NRC’s Panel of 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 was member of an NSF peer-review panel for the Homestake National Underground Science Lab proposal.

**PETER MÉSZÁROS**, Distinguished Professor of Physics and Astronomy & Astrophysics, Head, Department of Astronomy and Astrophysics, Pennsylvania State University. Prof. Meszaros received his doctorate from the University of California at Berkeley in 1972. The author of 130 refereed journal articles, his research interests are in theoretical astrophysics and specifically 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, which is a multi-institution NASA satellite to study gamma ray burst afterglows, currently under construction and scheduled for launch in 2003. He also has interests in the production of ultra-high energy neutrinos and photons from gamma ray bursts, in preparation for experiments such as NASA’s Gamma ray Large Area Survey Telescope 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 an NAS IREX 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**, Professor of Physics, University of California at Berkeley, California. Prof. Murayama received his doctorate from the University of Tokyo in 1991. After postdoctoral work at Tohoku University and Lawrence Berkeley Laboratory, he joined the physics department at the University of California at Berkeley in 1995, and was quickly 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 1996-1999, and is a member of the Particle Data Group, which is 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 and the Enrico Fermi Institute, University of Chicago. Prof. Olinto 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 ultra-high energy cosmic rays and high energy neutrinos. She is a collaboration member of the Pierre Auger Observatory project in Argentina. She is a fellow of the American Physical Society, 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, Los Angeles. Prof. Ong 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, 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 STACEE ground-based gamma-ray telescope located in New Mexico and is a member of the 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 HENAP 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. He is U.S. Co-Principal Investigator on the Sudbury Neutrino Observatory. 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 KATRIN, Majorana, and 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, Prof. Robertson was a Fellow of the Los Alamos National Labs. Previous to that, he was 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 of the APS. A past member of the Board of 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 NSERC (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. Dr. Samios 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. He is an experimental high energy physicist, and 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 to 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 the NRC's Supercollider Site Evaluation Committee.

**JOHN P. SCHIFFER** Senior Physicist, Argonne National Laboratory and Professor of Physics emeritus, University of Chicago. Dr. Schiffer is a member of the National Academy of Sciences, Fellow of the American Physical Society, the American Association for the Advancement of Science, and the American Academy of Arts and Sciences, and 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 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, and 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**, Pupin Professor of Physics, 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 DESY Laboratory in Germany. The experimental program uses the HERA colliding beam accelerator and the ZEUS detector. Prof. Sciulli is a member of the American Association for the Advancement of Science and Sigma Xi, a Fellow of the American Physical Society, and 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, and 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

**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 studied 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.

**JOEL R. PARRIOTT** is a senior program officer at the NRC's Board on Physics and Astronomy. Dr. Parriott came to the NRC in 1998 after receiving his Ph.D. in astronomy and astrophysics from the University of Michigan. His research, for which he received the Ralph B. Baldwin Prize from the University of Michigan, involved gas dynamics in elliptical galaxies and high-performance parallel computing. In addition to serving as the study director for this report, Dr. Parriott has directed several important NRC study committees including the most recent Astronomy and Astrophysics Survey Committee, the Committee on the Organization and Management of Research in Astronomy and Astrophysics, the Committee on the Physics of the Universe. He is a member of the American Physical Society, the American Astronomical Society, and the American Association for the Advancement of Science.

**DONALD C. SHAPERO** received the B.S degree from the Massachusetts Institute of Technology in 1964 and the 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. 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.

# D

# MEETING AGENDAS

## FIRST MEETING

**June 24–25, 2002**
**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,

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| | 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***

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| 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***

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| 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**

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| 8:00 am | Reconvene<br>—Barry Barish |

***Opportunities with foreign underground neutrino facilities***

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| 8:00 am | Large international underground neutrino physics efforts<br>—Yoichiro Suzuki, Kamioka Observatory, Japan<br>—Alessandro Bettini, Laboratori Nazionali del Gran Sasso, Europe<br>—David Sinclair, Sudbury Neutrino Observatory & Carleton University, Canada |
| 9:30 am | Break |

***Opportunities in high energy neutrino astrophysics***

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| 9:45 am | Neutrino astrophysics and IceCube<br>—Per Olof Hulth, University of Stockholm<br>—Francis Halzen, University of Wisconsin<br>—Christian Spiering, Deutsche Elektronen-Synchrotron (DESY)<br>—David Nygren, Lawrence Berkeley National Laboratory |
| 11:15 am | International high energy neutrino astrophysics: ANTARES & NESTOR<br>—John Carr, Centre de Physique des Particules de Marseille<br>—Leonidas Resvanis, NESTOR Institute for Deep Sea Research, Technology, and Neutrino Astroparticle Physics |
| 12:15 pm | Working Lunch |

**Closed Session**

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| 1:15 pm | Committee deliberations<br>—Barry Barish |
| 5:00 pm | Adjourn |

## SECOND MEETING

**July 25–26, 2002**
**Hilton Chicago O'Hare Airport**
**Chicago, Illinois**

### Thursday, July 25, 2002

**Open Session**

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| 9:00 am | Convene |
| | —Barry Barish, Chair |
| 9:00 am | Dark Matter Searches |
| | —Rick Gaitskell, Brown University |
| 10:00 am | Proton Decay: Theory & 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**

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| 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

### September 30–October 1, 2002
### 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**

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| 9:00 am | Committee deliberations and report drafting<br>—Barry Barish |
| 6:00 pm | Adjourn for the day |

### Tuesday, October 1, 2002

**Closed Session**

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| 8:30 am | Reconvene<br>Committee deliberations and report drafting<br>—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 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 was concentrated with high density and temperature 15 billions years ago. The present Universe expanded from that epoch and is still expanding.

**Bottom:** the second heaviest quark. It has negative electric charge 1/3 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 2/3 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 radiation (CMB):** 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 1/3 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 electron neutrino scatters with a different probability than the muon and tau neutrinos.

**Electron volt (eV):** a measure of energy equal to that gained by an electron passing through a potential difference of one 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 eV is a useful unit to discuss the variety of particle masses when prefixed by the international conventions such meV, keV, MeV for milli-, kilo- Mega- electron volts, respectively.

**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. GRBs are also visible in other parts of the electromagnetic spectrum.

**Gravitational lensing:** a consequence of Einstein's Theory of General Relativity where the path of light can be bent by the presence of matter, giving rise to effects similar to ordinary optics.

**Gravitational wave:** a ripple in the geometry of spacetime propagating as a wave according to 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):** 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).

**m.w.e.:** a designation of radiation shielding depth in meters-water-equivalent. Typically, 1 meter of rock is approximately 3 m.w.e.

**Majorana-like:** refers to that property of neutrino mass description in which the neutrino and its anti-particle 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 which 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.

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

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

**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 proton 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 which carry charge can decay into muons and neutrinos (or their anti-particles).

**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 neutrons, 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 two theories of relativity, the General (gravity) and Special theories.

**Relic:** in this context, particles created in and remaining presently from the Big Bang or other astrophysical events.

**Shock, shockwave:** 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.

**Strange:** the fourth heaviest quark. It carries a negative charge 1/3 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).

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

**$\theta_{13}$, $\theta_{12}$ :** The mixing angles for neutrino oscillations which measure the content of the electron neutrino into two of the mass states (see Fig. 7).

**Top:** the heaviest of the six quarks. It carries a positive charge 2/3 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 2/3 that of the electron**.**

**Water Cherenkov detector:** 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:** for Weakly Interacting Massive Particle. A leading particle candidate for dark matter.