

Underground Science*

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Why should one build a laboratory deep underground? To study the fundamental laws of physics, such as those governing the stability of the proton and the particle-antiparticle properties of the neutrino? To probe the interior of the sun? To record some of the most spectacular explosions in the universe in ways that complement optical and gravitational wave observations? To determine the nature of the dark matter that pervades the universe?

Underground science spans an astonishing range of disciplines. It addresses all of the questions listed in the previous paragraph and many more topics that fascinate physicists, astronomers, and cosmologists. Underground science also includes a vast range of both fundamental and practical subjects outside the pure physical sciences, including the behavior and evolution of life forms in exotic environments, the characteristics and stability of geologic structures, the evaluation of groundwater resources, the monitoring of nuclear weapons tests, and the vulnerability of microelectronics and other materials to cosmic radiation.

Why should one build a laboratory deep underground now? Over the past few years an intellectual revolution has begun at the intersection of astronomy, astrophysics, and cosmology with subatomic physics. Underground experiments—many of which embody

elements of both astronomical observation and conventional particle/nuclear physics—are playing a crucial role in this revolution. Extraordinary technical advances, driven in part by detector advances originating in nuclear and particle physics, are allowing observers to probe the universe in new ways and with vastly increased precision. We are now testing the structure of the universe a few hundred thousand years after the big bang and the nature of the dark matter and energy that govern the expansion of the universe, with prospects for understanding the implications for the underlying “theory of everything.”

The vitality of this intersection between accelerators, underground science, and the physics of the cosmos derives not only from the importance and breadth of the scientific questions being asked, but also from the rich crossfertilization of ideas and techniques. Two outstanding examples are neutrino physics and dark matter searches:

- Neutrino physics is among the fastest evolving scientific fields today. Neutrinos are fundamental, neutral, weakly interacting particles which come in three flavors: electron neutrinos, muon neutrinos and tau neutrinos. In the “standard model” of particle physics, neutrinos are massless and the three flavors are distinct particle states. In this theory, one neutrino flavor will not convert, or “oscillate” to another flavor with time. However, neutrino oscillations are expected from quantum mechanics if neutrino flavor eigenstates are mixtures of the mass eigenstates and if neutrinos have mass. Recently, experiments searching for “neutrino oscillations” have provided evidence for neutrino mass and mixing of flavor states in atmospheric and solar neutrino experiments. Now, at accelerators, a new generation of neutrino experiments is underway to further understand these beyond-the-standard-model neutrino properties. Taken as a whole, this group of experiments may give us our first clue as to what must be added to the surprisingly precise standard model of particle physics, as well as telling us whether neutrinos have sufficient mass to affect our models of the universe.
- As we try to understand the cosmology of the universe, one of the most vexing questions is: What is the dark matter that forms most of the matter of the universe? It

seems likely that the dark matter is made up of new particles which have not yet been produced in any laboratory. Nonaccelerator experiments have pursued this question over the last decade. These highly precise searches employ new detector technology in order to maximize sensitivity to interactions with the dark matter particles. Complimenting this work, recent accelerator experiments have indicated that new physics which could explain dark matter may be within reach of the next set of high energy experiments.

Neutrinos and dark matter represent only two subfields within the rich scientific program of a new underground laboratory.

Why should one build a deep laboratory in the U.S.? First, we have new possibilities for laboratories of great promise. Second, the European and Japanese facilities are highly subscribed. American scientists, whether they work on the frontier of nonproliferation activities or on fundamental research, have to locate their experiments in Italy or Japan, leading to added cost and complication. The U.S. now has an opportunity to lead underground science internationally by building the next-generation underground laboratory, one that will build on the European and Japanese experience and continue the emerging intellectual revolution in astro-particle and astro-nuclear physics.

We begin by describing in Section I the nature of the solar neutrino opportunity and then discuss in Section II the possibility of further constraining neutrino properties through observations of neutrinoless double beta-decay. Next we outline in Section III the role of underground experiments in detecting particle dark matter. We describe in Section IV the motivation and possibilities for a new generation of detectors testing nucleon stability. In Section V we discuss future possibilities for underground studies of atmospheric neutrinos and in Section VI consider the related question of future long baseline neutrino experiments. We describe in Section VII the special requirements of neutrino observatories for detecting neutrinos from Galactic supernovae. In Section VIII we discuss precision techniques for measuring fusion reactions at temperatures characteristic of stellar interiors, exploiting the

low-background environment of a deep laboratory. In the last three sections we describe the unique experiments that can be done underground in geoscience (Section IX), materials development and technology (Section X), monitoring nuclear weapons tests (Section XI), and microbiology (Section XII).

Each of these fields is on the frontier of science where the pace of new discoveries will be accelerated by the availability of a state-of-the-art underground laboratory.

I. SOLAR NEUTRINOS

The field of neutrino astrophysics began with the study of solar neutrinos. The history of this subject demonstrates the rapidly accelerating pace of technical innovation in underground science, the increasing breadth of the scientific issues, and the deepening connections with both conventional astrophysics and accelerator experiments.

Neutrinos that are created in the sun offer a unique opportunity to study both electroweak physics and nuclear fusion in the interior of our best known star. Within the sun, energy is generated by a chain of nuclear processes which is described by the “standard solar model.” Experimental tests of the standard solar model, including measurement of solar sound speeds, are in good agreement with the model. Therefore, we can use this model to predict the rate of production of electron neutrinos from the sun. These solar electron neutrinos have relatively low energy compared to accelerator-produced neutrinos, ranging from less than 1 MeV to about 20 MeV.

The “solar neutrino problem” is that experiments sensitive to electron neutrinos observe a lower rate than is predicted by the standard solar model. An elegant solution to the dilemma is that the neutrinos are converting, or “oscillating,” from electron neutrino flavor to some other neutrino flavor to which the detectors are insensitive.

The great distance, 10^8 km, between the nuclear accelerator in the solar interior combined with the relatively low energy of the neutrinos produced in the sun imply that squared neutrino mass differences as small as 10^{-12} eV² can be studied with solar neutrinos: solar

neutrino experiments are truly very long baseline oscillation experiments. Moreover, as the neutrinos pass through $> 10^{10}\text{gm cm}^{-2}$ of matter before exiting the sun, interaction with matter can affect their propagation, magnifying the consequences of neutrino mixing.

The first indication of the solar neutrino problem came from radiochemical experiments. These are experiments which integrate the rate of solar neutrinos over months and hence are called “passive” detectors. More recently, “active” detectors, which can reconstruct the kinematics of a solar neutrino interaction on an even-by-event basis, have confirmed the deficit of electron neutrinos from the sun.

The first solar neutrino experiment reported results in 1968, using data gathered in a newly excavated cavern within the Homestake gold mine in Lead, South Dakota. The passive Homestake detector, consisting of 615 metric tons of the cleaning fluid, perchloroethylene, produced over a three-decade period a precise constraint on the higher energy components of the solar neutrino flux, revealing a factor-of-three shortfall that gave rise to the solar neutrino problem. A decade ago, two similar radiochemical experiments, one conducted within a mountain in the Caucasus region of Russia (the Baksan Observatory) and the other in the Gran Sasso Underground National Laboratory in Italy, began taking data. Because these two experiments used a different material, gallium, in their detectors, they were sensitive to lower energy solar neutrinos than Homestake. These were also the first experiments to be tested with intense (\sim megacurie) laboratory neutrino sources, demonstrating that the systematic uncertainties in radiochemical experiments could be well-understood. As with the Homestake experiment, the gallium experiments also observed a deficit of electron neutrinos.

The era of active solar neutrino detection began in 1987 with the Kamioka experiment: a water Cerenkov proton-decay detector located in the Mozumi Mine in the Japanese Alps. The Kamioka detector provided sensitivity to higher energy neutrino-electron scattering events. As in the previous cases, this experiment observed an overall deficit of solar neutrinos. As an important byproduct, the active detection allowed the historic first detection of neutrinos from a core-collapse supernova in 1987.

Concurrent with these pioneering experiments, developments in other areas enhanced the

significance of the observed deficit. In particular, advances in solar seismology led to precise determinations of the speed of sound as a function of solar radius, which is predicted by the standard solar model. These results confirmed the predictions to 0.1% rms, throughout the sun, and strongly disfavoring nonstandard solar models. Also, the theoretical discovery that solar matter could enhance oscillations produced new particle physics scenarios that are consistent with all the available measurements in particle physics and in astronomy. Finally, as discussed later in this paper, the discovery of atmospheric neutrino oscillations made oscillation-based explanations of the solar neutrino problem increasingly plausible.

Physicists studying solar neutrinos reached a consensus that the solar neutrino “problem” was really a unique opportunity to learn new electroweak physics. This prospect motivated three new detectors that are remarkable for their size and sophistication, and thus for the demands they make on underground technology. Super-Kamiokande is the successor to the Kamioka experiment, with almost 100 times the mass of the original Homestake experiment and a solar neutrino event rate of many thousands of events per year. The Super-Kamiokande experiment has produced important constraints on the spectrum of high-energy solar neutrinos and on the day-night effects associated with neutrino propagation through the earth. The Sudbury Neutrino Observatory (SNO) is using a 1000 tons of heavy water to distinguish electron-type neutrinos from other flavors generated by oscillations. This experiment is being conducted at great depth (6800 ft) in a nickel mine in Sudbury, Ontario, under unprecedented clean-room conditions, in order to minimize backgrounds. The results may tell us if a fourth, beyond-the-standard-model neutrino is contributing to solar neutrino oscillations. A third detector, BOREXINO, employs 1000 tons of organic scintillator. Under construction in the Gran Sasso National Underground Laboratory in Italy, BOREXINO is the first active detector designed to detect low-energy ${}^7\text{Be}$ solar neutrinos.

At present, active detectors for solar neutrinos have only measured recoil electron energies for the rare part of the solar neutrino flux produced by ${}^8\text{B}$ beta-decay. This is less than 10^{-4} of the total flux. More than 98% of the solar neutrino flux is predicted to have energies less than 1 MeV. To date, only passive detectors have been able to access these lower energies.

The fundamental $p - p$ neutrinos, which have energies less than 0.4 MeV, are predicted to constitute more than 90% of the total solar neutrino flux and it is important that the solar neutrinos in this range be studied in a variety of experiments with event-by-event reconstruction capability. The goals are to measure the total flux below 1 MeV in electron neutrinos and in (converted) μ and τ neutrinos and the energy spectra of these low energy neutrinos. The experiments require relatively high event rates since the predicted small seasonal and day-night time dependences can provide unique clues to the characteristics (masses and mixing) of the neutrinos.

Several innovative detectors, in advanced stages of development, have the potential to do this low energy physics. There are excellent prospects that such a complete program of neutrino spectroscopy could be completed within one to two decades. These low energy solar neutrino detectors could also be used for sensitive tests of other non-standard-model properties of neutrinos, such as magnetic moments.

The original goal of solar neutrino research was to use solar neutrinos to test the standard theory of how the sun shines. Precise tests of this theory will be possible once the propagation characteristics of neutrinos are known. The full resolution of the solar neutrino problem will also prepare us to study neutrino properties in new astrophysical environments, such as supernovae and the Big Bang, in which still higher matter densities and more complicated theoretical scenarios are encountered.

II. DOUBLE BETA DECAY

Fundamental particles have twins, called antiparticles, that have the same masses and spins, but opposite charges. For example the electron's antiparticle is the positron, a particle identical to the electron apart from its opposite (positive) charge. Clearly the electron and positron are distinct particles: the charges allow us to distinguish one from another. But what if there were a particle with no electric charge, and no charges of any other kind? What would distinguish particle from antiparticle?

The question of what distinguishes the neutrino and antineutrino has profound implications for particle physics. The possibility that the neutrino might be identical to the antineutrino allows the neutrino to have a special kind of mass—called a Majorana mass—that violates one of the important conservation laws of the standard model.

This question of the particle-antiparticle nature of the neutrino is associated, in turn, with a very rare phenomenon in nuclear physics. Certain nuclei exist which appear to be stable, but in fact decay on a timescale roughly a trillion times longer than the age of our universe. This process, double beta decay, involves a spontaneous change in the nuclear charge by two units, accompanied by the emission of two electrons and two antineutrinos. Following 30 years of effort, double beta was finally detected in the laboratory about a decade ago: it is the rarest process in nature that scientists have succeeded in measuring. Physicists are currently engaged in searches for a still rarer form of this process, one in which the two electrons are emitted without the accompanying antineutrinos. The existence of such “neutrinoless” double beta decay directly tests whether the neutrino is a Majorana particle.

The observation of neutrinoless double beta decay would have far reaching consequences for physics. Neutrinoless double beta decay probes not only very light neutrino masses—current limits rule out Majorana masses above ~ 1 eV—but also very heavy ones, up to a trillion eV. Interference effects between the various neutrino families (electron, muon, tau) can be studied with double beta decay and are not easily tested elsewhere. The existence of Majorana neutrinos is the basis for our best theory explaining why the familiar neutrinos are so light, relating these small masses to physics occurring at energy scales a trillion times beyond those accessible in our most powerful accelerators. The conservation law tested in neutrinoless double beta decay is connected, in many theoretical models, with the cosmological mechanism that produced a universe rich in nucleons (rather than antinucleons).

Recent experimental progress in this field has been rapid. Thirty years of effort was required before the standard-model-allowed process, two-neutrino double beta decay, was directly observed in 1987. Today accurate lifetimes and decay spectra are known for about

a dozen nuclei. The standard process is crucial to theory, providing important benchmarks for the nuclear physics matrix element calculations that are done to relate neutrinoless beta decay rates to the underlying neutrino mass.

Progress in neutrinoless double beta decay searches has been equally impressive. Extraordinary efforts to reduce backgrounds through ultrapure isotopically enriched materials, improved energy resolution, and shielding of cosmic rays and natural radioactivity has produced a “Moore’s law” for neutrinoless beta decay, a factor-of-two improvement in lifetime limits every two years over the past two decades. The bound from the nucleus ^{76}Ge , $\sim 2 \times 10^{25}$ years, corresponds to a Majorana mass limit of (0.4-1.0) eV, with the spread reflecting nuclear matrix element uncertainties.

A new generation of experiments is being proposed to probe Majorana masses in the range of 0.03-0.10 eV, a goal set in part by the squared mass difference, $\delta m^2 \sim (0.05 \text{ eV})^2$, deduced from Super-Kamiokande’s atmospheric neutrino deficit (described in a later section of this paper). These ultrasensitive experiments are confronting several new challenges. A new background—the tail of the two-neutrino process—can be avoided only in detectors with excellent energy resolution. Detector masses must be increased by two orders of magnitude: the counting rate is a fundamental limit at the current scale of ~ 10 kg detector masses. As the detector mass is increased, proportional progress must be made in further reducing backgrounds through some combination of active shielding, increased depth of the experiment, and purer materials.

The current generation of experiments includes the Heidelberg-Moscow and IGEX ^{76}Ge detectors, the Caltech-Neuchatel effort on ^{136}Xe , and the ELEGANTS and NEMO-3 ^{100}Mo experiments. They have comparable goals (lifetime limits in excess of 10^{25} years) and comparable masses (~ 10 kg). The Heidelberg-Moscow experiment has acquired in excess of 35 kg-years of data and has established the stringent lifetime limit mentioned above (2×10^{25} years). All of these experiments are being conducted outside the U.S. because deep underground facilities are unavailable here, although several have U.S. collaborators.

The new experiments under consideration include enriched ^{76}Ge detectors, a cryogenic

detector using ^{130}Te , ^{100}Mo foils sandwiched between plates of plastic scintillator, a laser tagged time-projection-chamber using ^{136}Xe , and ^{116}Cd and ^{100}Mo in BOREXINO's Counting Test Facility. Some of these proposals are quite advanced, while others are in the research and development stage. The detector masses are typically ~ 1000 kg. Several proposed experiments depend on the availability of Russian enrichment facilities to produce the requisite quantities of the needed isotopes.

These experiments represent a crucial opportunity to advance the field of neutrino physics. The scale of neutrino masses is now being revealed in atmospheric and solar neutrino experiments, and will hopefully be confirmed in reactor and accelerator oscillation experiments like K2K, MINOS, and KamLAND. A new standard model incorporating massive neutrinos must include information on the Majorana contributions to the neutrino mass. The next generation of massive double beta decay experiments will begin to probe neutrino masses relevant to atmospheric and solar neutrino experiments, and thus might provide constraints necessary for understanding new physics.

III. DARK MATTER

The dark matter puzzle is a central problem of cosmology. Since the pioneering work of Zwicky in 1933, astronomers have suspected the existence of a dark component that dominates the universe's mass, clumps into large structures, but cannot be seen as it does not emit or absorb light. Over the last decade, the astronomy community has reached the consensus that dark matter is present at a variety of scales from spiral and elliptical galaxies to super clusters of galaxies. Moreover, it seems increasingly likely that this dark matter may be made of something different than ordinary baryonic matter. The mass density of dark matter may be ten times higher than that of the baryons inferred from the primordial abundance of light elements. The temperature fluctuations of the cosmic microwave background are two orders of magnitude below the values one would expect if the observed large-scale structure of our universe were attributed entirely to baryons.

One possible explanation is that baryons are hidden in condensed objects such as Massive Compact Halo Objects (MACHOs). Microlensing observations imply that MACHOs are unlikely to be abundant enough to form the halo of our galaxy.

A natural explanation for dark matter is that it is made of non-baryonic particles produced in the early hot universe. Underground facilities are essential for testing two of the best motivated candidates: light massive neutrinos and Weakly Interactive Massive Particles (WIMPs). Both of these particles were in thermal equilibrium with the rest of the universe at early times.

- Neutrinos of mass much smaller than $2 \text{ MeV}/c^2$ fall in the generic category of particles which decoupled when they were relativistic. Their current number density is roughly equal to that of the photons in the universe. The relic particle mass density is therefore proportional to the particle's mass (unless that mass is very small). The atmospheric neutrino oscillation results convincingly indicate the existence of at least one massive neutrino whose cosmological density is at least comparable to the mass density of stars. Although it is not possible to form galaxies with neutrinos alone, the general program of understanding the neutrino masses described in this report is essential to map the role that neutrinos play in cosmology.
- Another generic class of candidates are particles that thermally decoupled from the rest of the universe when they were non-relativistic. Their present density is inversely proportional to their annihilation rate. For these particles to be of the order of the critical density (e.g., one third of it), this annihilation rate has to be roughly the value expected from weak interactions, hence their name of Weakly Interactive Massive Particles. This may be a numerical coincidence, or a precious hint that physics at the W and Z scale is important for the problem of dark matter. Indeed, in spite of its phenomenological success, the standard model of particle physics is known to be incomplete. New physics near the W and Z^0 scale could lead to particles whose relic density is close to the critical density. For example, in order to stabilize the mass of

the vector intermediate bosons, one is led to postulate the existence of a new family of supersymmetric particles in the 100 GeV/c² mass range. The lightest supersymmetry particle is thus an outstanding dark matter candidate.

The WIMPs search is being carried out intensively with germanium detector arrays of unprecedented radiopurity and with very large NaI scintillation detectors. The field is at the forefront of the effort to develop novel cryogenic sensors providing excellent background discrimination. Current first-generation experiments have achieved a sensitivity significant to begin probing supersymmetry. Several second-generation experiments under development in the US and Europe have the potential to explore large regions of the supersymmetric parameter space.

The dark matter physics community is currently discussing a third generation of WIMP experiments for the second half of the decade. Two possible directions are envisioned. If the second-generation experiments discover a signal, the emphasis will probably shift to the detection of the recoil directionality, which would link the signal to the Galaxy and provide information on the Milky Way halo. The candidate technologies, e.g., photon detection in isotopically pure materials, low pressure time projection chambers, and extremely sensitive motion sensors detecting the scattering event, are particularly sophisticated and their development should be started as soon as possible. If the second-generation experiments fail to find a signal, it will be necessary to use photon-mediated or liquid xenon experiments with as much as 1 ton of detector material. The emphasis on the development would then be ultra-low radioactivity, very high rejection power, and large-scale production at low cost. This second route would become compelling if supersymmetry is discovered at the Tevatron or LHC.

A very deep site that is properly equipped (for instance with clean rooms and the possibility of handling cryogenic fluids) would be an important asset. Most of the sensitivity of the experiments currently under construction relies on the discrimination between nuclear recoils and electron recoils. The former might signal WIMP interactions while the latter

are generated by radioactivities within the detector. High energy neutrons, produced by cosmic muons in the apparatus or the cavity walls, are potentially problematic as they also produce nuclear recoils, mimicking WIMPs. The rates are unfortunately poorly known. Although the second generation of experiments may be done at 2000 m.w.e. with little neutron shielding, the third generation will likely require deeper sites. Underground material refining facilities (e.g., for the detector supports) could also prove important in reducing ambient backgrounds.

Although the field of dark matter research is still young, there are strong suggestions that the underlying physics is profound. Maps of the cosmic microwave background and tests of the Hubble expansion using supernovae as standard candles suggest that the universe is flat, currently balanced by a combination of dark matter and dark energy. These cosmological results hint at deep connections between the dark matter associated with new particle physics and the laws that govern the large-scale evolution of our universe.

IV. NUCLEON DECAY

A great many species of elementary particles have been discovered in the century since Thompson's discovery of the electron. With a very few exceptions, all known elementary particles spontaneously disintegrate into other particles. For instance, some forms of natural beta radioactivity arise when a neutron within an atomic nucleus decays into a proton, an electron and an antineutrino. The average time before a decay occurs—called the particle's lifetime—is characteristic of the species of decaying particle.

For modern physicists it is the particle which does NOT decay which requires an explanation. This explanation usually looks for a conserved quantity whose value must be the same for the parent particle and for all of the daughters in the event that a decay takes place. For instance, electric charge is conserved in the neutron decay mentioned above, because the charge (zero) of the initial neutron equals the sum of charges of its daughters: proton (+1) plus electron (−1) plus antineutrino (zero). Since energy conservation requires particles to

decay into daughter particles with a smaller mass, the lightest particle carrying a conserved charge must be stable. The electron is the lightest electrically charged particle, and this is our understanding of why the electron does not decay.

So far as we know ordinary matter does not decay, and this implies the proton must be extraordinarily stable. If the ambient radioactivity found in ordinary matter were due to decaying protons (it isn't) then the proton lifetime would have to be more than 10^{16} years, or a million times longer than the age of the universe. This limit can be raised even further if known sources of radioactivity are removed, as was first demonstrated by Reines and collaborators in 1954, who established a limit of about 10^{22} years.

The remarkable stability of the proton is explained in modern particle theory (the Standard Model) by proposing that it is also the lightest particle to carry a conserved charge. Whereas electric charge conservation keeps the electron stable, for the proton the relevant conserved charge is called baryon number. Its conservation was first proposed by Stueckelberg in 1938 and by Wigner in 1949.

Until the 1970s there were no compelling theoretical arguments for violation of baryon number conservation. This situation changed with the success of efforts to unify the weak and electromagnetic forces and with the development of quantum chromodynamics as the theory of the strong interaction. Theoretical efforts to construct grand unification theories which would further unify these three forces led naturally to interactions which violated baryon number conservation, and so predicted the proton should decay. Since these new baryon-number violating interactions were very weak, the proton lifetime was predicted to be extremely long. The simplest and most popular of these theories, based on the symmetry group $SU(5)$, predicted a proton lifetime in the range of 10^{28-30} years and specified the dominant decay product to be a positron and a neutral pion ($p \rightarrow e^+\pi^0$).

These predictions stimulated ambitious new proton decay searches with massive underground detectors—including the Frejus, IMB, Kamiokande, Kolar and NUSEX experiments—in the 1980s. In its initial report in 1983, the largest of these detectors, IMB, set a lower limit of 6.5×10^{31} years for the lifetime for the decay $p \rightarrow e^+\pi^0$, effectively

ruling out the minimal SU(5) grand-unified theory. With additional data collected over the remainder of the decade, the lower limit on the lifetime was increased to 8.5×10^{32} years.

Further improvement of these limits requires large, higher-sensitivity detectors: to test lifetimes of 10^{33} years would require about 10^{33} protons or neutrons, or a ten kiloton mass. This was the primary motivation for building the Super-Kamiokande experiment in Japan. The 50 kiloton Super-Kamiokande detector began taking data in 1996.

Although larger detectors could produce larger proton decay signals, they also produce more background events, where an ordinary reaction is mistaken for proton decay. Backgrounds for proton decay arise when cosmic rays interact in the upper atmosphere producing muons and neutrinos which can penetrate and interact within the detector. The number of muons reaching the detector can be reduced by locating the detectors underground, but neutrinos cannot be avoided so simply because they can pass through the entire earth unscathed. Although the vast majority of these atmospheric neutrino interactions bear little resemblance to proton decay, a small fraction are indistinguishable based on the measured topology and kinematics of the events. Recently obtained data from a scaled-down version of Super-Kamiokande installed in the neutrino beamline at the KEK accelerator in Japan will help experimentalists to improve their estimates of the rates of such background events. More sophisticated simulations of neutrino production in the atmosphere, coupled with new measurements of the primary cosmic ray fluxes and the secondary particles produced, will likewise refine our understanding of the atmospheric neutrino fluxes themselves in the near future.

While the data from Super-Kamiokande have yet to reveal evidence for proton decay, the motivation for still more sensitive searches is strong. Baryon number differs from electric charge in that there is no fundamental reason why it should be conserved. Recent theoretical papers have stressed the relevance of Super-Kamiokande's discovery of neutrino oscillations to the mechanism for proton stability. One effort to incorporate oscillations within a grand unified model predicts the proton lifetime to lie in the range of 10^{34} years, with decays into kaons and antineutrinos ($p \rightarrow \bar{\nu}K^+$) being predicted as the dominant decay mode.

Such decays could be revealed by new experiments that improve on the Super-Kamiokande sensitivity by a factor of five or ten.

By producing important atmospheric and solar neutrino results in addition to new limits on baryon number violation, Super-Kamiokande illustrates the strong intellectual and practical connections between proton decay experiments and other kinds of underground science. Furthermore, the theoretical motivations are strong. There is evidence that our fundamental approach to unification is sound, and although models can predict a broad range of proton lifetimes, the range immediately beyond current experiments is exceedingly interesting. Proton decay remains one of the very few opportunities for directly testing grand unified theories with experimental data.

V. ATMOSPHERIC NEUTRINOS

When primary cosmic-ray protons and nuclei enter the atmosphere, their interactions produce secondary, “atmospheric” cosmic rays including all the hadrons and their decay products. The spectrum of these secondaries peaks in the GeV range, but extends to high energy with approximately a power-law spectrum. Because they are affected only by the weak force, atmospheric neutrinos rarely interact in the earth. Thus a single underground detector can use the atmospheric neutrino beam simultaneously in a short-baseline and a long-baseline mode to search for neutrino oscillations over a range of pathlengths from 10 to 10,000 kilometers, with sensitivity to mass-squared differences down to less than $\sim 10^{-4}$ eV².

Because they are weakly interacting, neutrinos were the last component of the secondary cosmic radiation to be studied. With the advent of very large, deep underground detectors, whose construction was originally motivated by the search for proton decay, there are now extensive measurements of the flux of atmospheric neutrinos. What is emerging from recent studies is a discovery which is likely to have an impact comparable to that of the original discoveries made with atmospheric cosmic rays half a century ago, including existence of the pion, the kaon and the muon. The 50-kiloton Super-Kamiokande experiment, with a

20-kiloton fiducial volume, has now accumulated sufficient statistics to see clearly that the flux of muon-neutrinos depends not only on the rate at which they are produced in the atmosphere, but also on the pathlength they travel to the detector. There is a deficit of upward muon-neutrinos relative to downward neutrinos measured in the same detector, the response of the detector being up-down symmetric.

The most likely cause of this pathlength dependence is neutrino oscillations, in which neutrinos produced as muon-type, after passing a certain distance (which depends on energy), manifest themselves with a different “flavor,” in this case as τ -neutrinos. This behavior suggests that the neutrinos possess a small but non-zero mass. If so, this would be the first evidence for physics beyond the standard model of particle physics. This possibility has stimulated intense activity to find the implications for particle theory, and to relate this manifestation of neutrino physics to the long-standing solar neutrino problem (or the “solar neutrino opportunity” as it is described elsewhere in this essay).

The first evidence that atmospheric neutrinos were not behaving as expected came from the observation by IMB that the fraction of neutrino interactions with stopping muons was lower than expected. Then Kamioka reported that the ratio of muon-like to electron-like neutrino interactions was lower than expected. The Frejus experiment, however, reported a ratio consistent with expectation. These detectors had fiducial volumes ranging from a fraction to a few kilotons. As statistics accumulated from the water detectors (IMB and Kamioka) and first results were reported from Soudan, evidence for the “atmospheric neutrino anomaly” increased. Then, the Kamioka experiment published the first evidence for a pathlength dependence characteristic of neutrino oscillations. An important aspect of both ν_μ/ν_e and upward/downward is that, as ratios, both are insensitive to uncertainties in the calculations of what is expected in the absence of oscillations. The $\nu_\mu \leftrightarrow \nu_\tau$ oscillation interpretation that is emerging from the data is also consistent with deviations from the expected angular distributions of neutrino-induced upward muons measured in MACRO and Super-Kamiokande. This event sample probes a higher range of neutrino energies than the neutrino interactions inside the detector.

The identifying characteristic of neutrino oscillations, the rise and fall of neutrino intensity as a function of energy, cannot be observed at present with Super-Kamiokande. This is a consequence of the limited energy and angular resolution of the experiment coupled with the fact that, with the estimated value of the mass of the heavier neutrino, the first dip occurs for paths in which neutrinos are coming from near the horizon. The pathlength changes rapidly with zenith angle near the horizon. This consideration also limits the accuracy with which neutrino mass can be determined with the atmospheric neutrino beam.

Assuming a next-generation nucleon decay detector in a dedicated underground laboratory, it is natural to ask what would be the prospects for atmospheric neutrino physics. Assuming the detector would have an order-of-magnitude larger sensitive volume, several possibilities could be explored. These might include:

- Larger statistics for more precise determination of the mixing angle;
- Possible observation of ν_τ appearance;
- Better sensitivity to oscillations by containing higher energy events which have naturally better angular resolution. The goal would be to resolve the first oscillation dip, which would allow a more precise determination of neutrino mass;
- More statistics on neutral current events;
- Study of \sim GeV neutrino interactions in nuclei.

VI. LONG BASELINE NEUTRINO OSCILLATION EXPERIMENTS

The data on atmospheric neutrinos probably provides the strongest evidence today for the existence of neutrino oscillations and hence a non-zero neutrino mass. If indeed the effect seen by the Super-Kamiokande experiment (and supported by IMB, Kamioka, Soudan2 and MACRO) is due to neutrino oscillations then the most important characteristics of the phenomenon are:

- Large mixing angle ($\sin^2(\theta) > 0.88$ at 90% CL);
- $1.5 < \delta m^2 < 5 \times 10^{-3} \text{ eV}^2$ at 90% CL;
- Dominant mode of $\nu_\mu \rightarrow \nu_\tau$.

The characteristics of these parameters are such that the phenomenon can be investigated very well by the terrestrial long-baseline accelerator experiments. The dominant neutrino flavor produced by the accelerators is ν_μ , from π or K decays. The energies at which copious neutrino beams are available (few GeV), and feasible accelerator-detector distances (few hundred or few thousand km) provide L/E ratios well matched to the suggested δm^2 . Finally, the large mixing angle for the dominant modes allows precise studies of the parameters.

At the present time, three different long-baseline accelerator oscillation programs are either scheduled or already running. The K2K experiment, in Japan, utilizes a neutrino beam from the KEK PS and Super-Kamiokande as the detector. The mean neutrino energy is about 1 GeV and the baseline is 250 km. The experiment started taking data in the middle of 1999 and has already seen events in the detector which are about 2 sigma away from the no-oscillation hypothesis. The MINOS experiment, in the US, utilizes the beam from the Main Injector accelerator at Fermilab (120 GeV protons) and a magnetized iron scintillator spectrometer in a former iron mine in northern Minnesota. The baseline is 730 km, and the energy is variable from a mean energy of 3 GeV to about 15 GeV. The experiment should commence data taking at the end of 2003, and, depending on the energy of the beam used, detect a few thousand to a few tens of thousands of events per year. The CERN neutrino program, Geneva, Switzerland, utilizes a neutrino beam from the CERN SPS directed towards Gran Sasso Laboratory in Italy, about 730 km away. The experimental program emphasizes detection of τ neutrinos and thus the mean beam energy is about 20 GeV. A hybrid emulsion detector, OPERA, has been approved and a liquid argon TPC, ICARUS, is a strong possibility for the second detector. The data taking is scheduled to start in May, 2005.

FIG. 1. The distances of different underground sites from Fermi Laboratory



These experiments will try to elucidate the nature of the atmospheric neutrino effect. Specifically, some of the experimental goals are: a) confirmation of the existence of neutrino oscillations by verification of neutrino disappearance and a change in the energy spectrum between the near and far detectors; b) precise measurement of the oscillation parameters obtained mainly from the detailed study of the energy spectra for ν_μ interactions; c) verification that the $\nu_\mu \rightarrow \nu_\tau$ mode is the dominant oscillation mode, by either observing τ s directly or by seeing a change in the NC/CC ratio; d) observation (or improvement of limits) on subdominant oscillation modes, e.g., $\nu_\mu \rightarrow \nu_e$ or $\nu_\mu \rightarrow \nu_{\text{sterile}}$; and e) investigation of the possible presence of more exotic phenomena like neutrino decays (possibly in conjunction with oscillations) or presence of extra dimensions.

All three of the experiments mentioned above rely on underground laboratories for their principal (i.e., far) detector. We can ask to what extent an underground location is essential for long baseline accelerator experiments. The correct answer is probably that it is not as essential as for some of the other physics programs discussed above in other sections but it greatly facilitates a number of measurements and allows one to expand the scope of the experimental program. Some of the more important reasons for choosing an underground location are as follows:

The far detectors need to be massive and thus cover a large area leading to a significant number of cosmic rays passing through or interacting in a surface detector. The cosmic ray background constrains the trigger and forces some *a priori* decisions as to which categories of events will be detected. This background might also necessitate an extensive cosmic ray veto shield.

One way to reduce the problems discussed above is to use a very short beam-on time in the accelerator, so as to reduce the cosmic ray problem by selecting events only in a narrow time window. The problem with the short on-time solution is that it can create serious pileup problems in the near detector, where the event rate will be a million times or so greater. This may well constrain the accelerator intensities that one can use. For some machines, for example, neutrino factories based on muon storage rings, the very nature of the machine precludes very short beam-on times.

Use of a hybrid emulsion detector is seriously compromised in a ground-level detector. Such detectors require a very high percentage of good trigger events so as to minimize the required emulsion use, development, and scanning. Clean event selection, without a great deal of auxiliary tracking information, is much easier to accomplish if the cosmic ray flux is suppressed. In addition, because of the long memory of emulsions, the exposed emulsions will be much cleaner, that is, freer of background, if they are exposed in an underground detector.

For lower energies, and for studies of neutral current events or charged current events for non- ν_μ modes, interactions of neutrons from cosmic rays could simulate neutrino interactions of interest. This background would be suppressed for underground detectors.

In summary, underground laboratories provide significant advantages for long-baseline neutrino oscillation experiments. These advantages may become even more important for the next generation of experiments; these experiments will have higher statistical precision and thus the minimization of systematics will become even more important.

VII. SUPERNOVA NEUTRINOS

A core-collapse supernova is one of the most striking events occurring in the cosmos. The neutrinos that are emitted represent 99% of the $\sim 10^{53}$ ergs released by the collapse. Supernova neutrinos carry detailed information about the collapse mechanism and about new neutrino physics at very high matter densities and within strong magnetic fields. They may allow neutrino observers to distinguish the formation of a neutron star from the formation of a black hole, complementing information learned from gravitational wave detectors and from optical observations. The long time behavior of the neutrino luminosity probes the neutrino opacity deep within the protoneutron star, where high density nuclear matter may exist in exotic states. In the current best model of core collapse supernovae, neutrinos play an essential role in the explosion mechanism itself, helping to revive the stalled hydrodynamic shock wave by heating the nucleon soup left in the shock's wake. Neutrinos also play an important role in the synthesis of heavy elements in supernovae. Thus the detection of supernova neutrinos would provide a wealth of information on topics ranging from flavor mixing to the evolution of Galactic metals.

The available data on supernova neutrinos are limited to the ~ 20 events from Supernova 1987A, recorded in the Kamiokande and IMB detectors. All of these events may have been produced by electron antineutrinos interacting with the protons within these water Cherenkov detectors. The neutrino events from SN1987A provided a qualitative confirmation of theoretical ideas about core collapse (for example, the neutrino cooling time and the total energy release), and demonstrated the potential for supernova neutrinos to constrain neutrino masses kinematically. Yet, because we lacked the requisite detectors at the time of SN1987A, much information was lost because of the small number of recorded events and the inability to separately detect electron neutrino, electron antineutrino, and heavy-flavor neutrino events.

The next Galactic supernova should generate thousands of events in underground neutrino observatories that either exist now or will be operating in the near future, such as

Super-Kamiokande, SNO, LVD, and KamLAND.

The predicted mean energies of the different neutrino flavors are: 11 MeV (ν_e), 16 MeV ($\bar{\nu}_e$), and 25 MeV ($\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$). This temperature hierarchy is determined by basic features of neutrino-matter interactions and is relatively insensitive to model assumptions. Distinctive oscillation signals, such as an inversion of the electron and heavy flavor neutrino temperatures, may be observable. Matter enhanced oscillations could occur for densities up to ten orders of magnitude larger than the densities probed by solar neutrinos. Neutrino mixing angles as small as 10^{-5} could lead to complete $\nu_e - \nu_\tau$ conversion.

Observation of the $\bar{\nu}_e$ is relatively easy; they interact via the charged-current interaction, transferring essentially all their energy to a positron that can be detected in a water Cerenkov detector. However, the $\nu_\mu, \bar{\nu}_\mu, \nu_\tau,$ and $\bar{\nu}_\tau$ at supernova energies interact only through the neutral-current interactions; they transfer only part of their energy to the detector. Thus the energy distributions of $\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$ must be sampled by observing them with multiple detectors having different detection thresholds. Suitable detectors include the oxygen nuclei in the water Cerenkov detectors, deuterium (in SNO), carbon in organic scintillators (excitation of the 15.11 MeV state), and lead and iron (proposed as targets in future detectors). If many events are observed in detectors with separate sensitivities to $\nu_e, \bar{\nu}_e,$ and heavy flavor neutrinos, then this information may be used to test oscillation hypotheses and to learn about the dynamics of core collapse and neutron star cooling.

The time profiles of the neutrinos could be used to infer their masses from their time-of-flight differences, provided good statistics are achieved. The mass, or an upper limit to the mass, of the heaviest neutrino could be determined down to about 30 eV, a six-order-of-magnitude improvement over the present limits. Discrimination between the different types of events could be achieved from the differences in their signatures in water Cerenkov detectors or from the mean energies of the different flavor neutrinos in a detector that observes only neutral current events. If sharp temporal features exist in supernova neutrino spectra, lower mass bounds might be obtainable.

Much of the information carried by supernova neutrinos is important to other endeavors

in physics and astrophysics. The supernova mechanism is one of the outstanding terascale computing challenges in numerical astrophysics: detailed temporal and spectral information on the neutrino flux would place stringent constraints on modeling efforts. If neutrinos can be used to diagnose aspects of the collapse, such as the possibility of delayed collapse into a black hole, constraints might be placed on the resulting gravitational wave form, aiding gravity wave experimentalists in their attempts to identify a signal. The intimate connection between neutrinos and supernova nucleosynthesis opens up an interesting intersection with optical astronomy: rapid strides are being made in determining r-process and other abundances in early, metal-poor stars.

Finally, as rare events, supernovae present special challenges to neutrino experimentalists. Estimates of the Galactic supernova rate range from one to ten per century. Thus one must think in terms of long-term observatories rather than short-term experiments. The long time between supernova events argues for supernova observatories that are either inexpensive and easy to maintain, or have multiple purposes.

VIII. NUCLEAR ASTROPHYSICS

Experimental nuclear astrophysics is concerned with the study and measurement of nuclear processes that drive both the steady evolution and the explosion of stellar systems. In the Precision Era of nuclear physics, simulating stellar conditions in the laboratory is a crucial link for interpreting the wealth of observational elemental and isotopic abundances data from satellite-based observatories through complex computer simulation of stellar evolution and stellar explosion. Two major goals have crystallized over the last decade. The first centers on the understanding of nuclear processes far off stability in the rapid rp- and r-processes, which characterize nucleosynthesis in novae, X-ray bursts, and supernovae. The second goal focuses on understanding hydrostatic nuclear burning through the different phases of stellar evolution, determining the lifespans of the stars and the onset conditions of stellar explosions. They also determine the elemental and isotopic abundances observed

in stellar atmospheres and in the meteoritic inclusions that have condensed in stellar winds.

The laboratory measurement of nuclear processes in stellar explosions requires the development of a new generation of radioactive beam facilities both to produce the exotic, shortlived nuclear species and to observe reactions that occur on the split-second timescales of stellar explosions. Different techniques are needed for the study of reactions that characterize the long-lasting, quiescent periods of stellar evolution. A new generation of high intensity, low-energy accelerators for stable beams must be built to simulate within human timescales the processes that occur in nature over stellar lifetimes. To obtain empirical information regarding the effects of the stellar plasma on fusion rates, one must go to very low energies in the laboratory where the effects of atomic electrons become most important.

While more than thirty years of intense experimental study have allowed us to define the major features of nuclear burning during hydrostatic stellar evolution, so far only two fusion reactions have been studied at the actual stellar energy range. Many other rates crucial to stellar modeling have been deduced indirectly from extrapolations of higher energy laboratory data. These extrapolations can be off by orders of magnitude in cases where the underlying nuclear structure is poorly constrained. The resulting uncertainties complicate the modeling of important phases of stellar evolution, such as the CNO reactions within massive main sequence stars and the later stages of nuclear burning where reactions on heavier species dominate. Descriptions of the red giant and the asymptotic giant helium and carbon burning phases, which are the sites for the s-process responsible for the origin of more than half of the known elements, are also limited by nuclear physics uncertainties. The fusion of ${}^4\text{He} + {}^{12}\text{C}$ is, for example, an important reaction occurring in the initial stage of a supernova in which the above-ground laboratories have difficulties making low energy measurements because of cosmic ray backgrounds. A more detailed knowledge of nuclear rates is necessary to interpret and understand the rapid convection processes that link the nucleosynthesis site deep inside the star with the stellar atmosphere.

While the motivation for improving our knowledge of stellar reaction rates is clear, experimental studies of reactions for the hydrogen-, helium-, and carbon-burning phases are

often frustrated by the combination of extremely small cross sections (at the sub-pico-barn level) and high backgrounds induced by cosmic ray interactions at the accelerator sites. The cosmic ray-induced counting rate in ground-level detectors exceeds the signal by many orders of magnitude at energies corresponding to stellar temperatures.

A low-energy accelerator facility LUNA has been installed at the Italian Gran Sasso Underground National Laboratory to study nuclear reactions of importance for the pp-chain, which supplies almost all of the sun's energy. The enormous reduction of cosmic ray background by almost a mile of rock shielding led to the first successful measurement of the ${}^3\text{He}({}^3\text{He},2\text{p}){}^4\text{He}$ reaction at energies characteristic of solar fusion (~ 16 keV). This measurement eliminated a highly speculative but long-standing uncertainty in the solar neutrino problem, the possibility of a low energy resonance in the ${}^3\text{He}-{}^3\text{He}$ system. A similar effort on two other reactions important to the pp-chain, ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$ and ${}^7\text{Be}(\text{p}, \gamma){}^8\text{B}$, could help sharpen standard solar model predictions of the ${}^7\text{Be}$ and ${}^8\text{B}$ solar neutrino fluxes.

Underground facilities provide generic opportunities for studying nuclear reactions at stellar energies because of the massive passive shielding of cosmic rays. However, while passive shielding is essential, at low energies beam-induced background requiring active shielding also arises. Here there are great opportunities for improving underground measurements of stellar reactions. In this regard the LUNA accelerator, which operates with high intensity dc-mode proton and alpha beams, offers only limited options. A high-intensity low-energy (≤ 1 MeV/amu) heavy-ion accelerator in ac-mode could provide better conditions through inverse kinematics measurements. This includes higher effective efficiencies and event identification techniques through timing and particle identification with a recoil separator system, and a beam rejection power of better than 10^{-20} of the total system. Such a facility requires extensive R&D studies on the accelerator aspects, gas-target techniques, and recoil separator improvements. The need for beam intensities of ≥ 1 mA for achieving a rate of a few events per month will define extremely stringent requirements for the experimental equipment. The availability of suitable underground sites would motivate many in the nuclear reactions community to study what might be achievable.

IX. GEOSCIENCE

Geoscience research is of critical importance for groundwater resource evaluation, energy resource extraction, environment remediation, and nuclear waste isolation. One of the most challenging aspects of subsurface evaluation is the heterogeneity of characteristics, fractures, faults, and interfaces, controlling localized (channeled) flow and transport paths, as well as rock deformation and failure. Traditional geoscience research activities are based primarily on coring and logging along boreholes from the ground surface and laboratory measurements of small rock and fluid samples collected from different stratigraphic layers. The geoscience community recognizes the limitations of stratigraphy-based models in capturing the heterogeneous nature of subsurface features, events, and processes and emphasizes the importance of using underground tunnels for direct access to deep geological formations for observation, characterization, and testing.

Many recent advances in geosciences are associated with nuclear waste repository studies in fractured tuff at Yucca Mountain, Nevada, and in salt bed at Carlsbad, New Mexico. Seepage evaluation along tunnels, geochemical and isotopic signals of old flow paths, fracture opening and rock deformation induced by stress releases, geophysical imaging of fluid movement and structure changes, and the heater tests for coupled process evaluation are among the highlights from tunnel studies. Numerical models have been used successfully to represent the flow and transport fields at different scales, with parameters calibrated against data collected in both boreholes and tunnel test beds.

An urgent need exists to continue the momentum for geoscience research that builds upon the experience of tunnel studies and expands the scope for experiments over time periods longer than the duration available in underground facilities before operations begin. The next generation of underground tests, the systematic evaluation of processes over different spatial scales, and the development of advanced techniques for long-term monitoring over great distances are logical activities for new underground laboratories currently under consideration. Such a laboratory would offer a unique opportunity for geoscience to join

other physical sciences in developing a sharply focused understanding of subsurface physical characteristics and environmental conditions. As in other physical sciences, new understanding and new geoscience can evolve from analyses of large data sets collected over long time periods and over ranges of relevant scales. There is no substitute for an *in situ* program of measurement and observation.

Deep underground laboratories can be used to investigate subsurface multiphase flow and reactive chemical transport processes, characterize physical and chemical properties of weak and fractured rocks, and investigate model predictions through large-scale, long-term controlled experiments. Geoscience studies depend sensitively on site and formation characteristics.

Some of the important subjects to be investigated include the following geohydrological processes: seepage into and drainage out of tunnels, the heterogeneity of rock formations, and the multiphase transfers and coupled processes. Geochemistry studies are also important, especially mineral assemblages and alterations, pore water composition and tracer distribution, and age determination and isotopic measurements. Geomechanics can be investigated using strength and deformation measurements of fractured rocks, *in situ* stress measurements, and fracture behavior and propagation measurement, while geophysics can be studied using imaging, rock failure and damage monitoring, and long-baseline, low-frequency investigation of rock-masses.

An integrated geoscience test bed may require multilevel, multitunnel configurations over the spatial scales of 10 to 100 m in each spatial dimensions. The experiments may last over decades to test slow processes such as heat transfer. The largest Yucca Mountain heater test at a single drift is scheduled for four years of heating and four years of cooling. If the rock mass between two drifts is the key area of study, the tests may require decades of heating and cooling. For large-scale flow and transfer tests with reactive and conservative tracers, the plume quantification may require periodic drilling and sampling. "Mine-back" observations are required to validate the plume images based on borehole network monitoring. Unique equipment required for the geoscience test beds would include:

- Electrical power to run the heaters in megawatt range;
- Drilling equipment operated under above-boiling conditions in heated block or below-freezing conditions for geochemical sampling to preserve fluid;
- Mechanical excavation equipment for mine-back operation.

X. MATERIALS DEVELOPMENT AND TECHNOLOGY

The field of underground particle physics and astrophysics, and solar neutrino research in particular, has created a unique opportunity to extend and exploit our understanding of ultra-low background materials, counting techniques, and ultra-pure chemical methods. The 2 to 3 orders of magnitude improvement in the ability to detect natural and man-made phenomena over what is achievable using non-underground technologies, suggests a bright future for new applications in materials analysis.

Since the first solar neutrino experiment established the recording at the few atom level of the rare gas ^{37}Ar produced by neutrinos from the sun, underground science has set new records in the detection of specific isotopes at very low levels. These low-event-rate measurements are based principally on three key areas of technology: material background reduction, ultra-low level counting techniques, and ultra-pure materials. The three areas are related, and a summary of the current status is provided here.

In the radiochemical solar neutrino detectors, newly developed ultra-low level gas proportional counters have achieved backgrounds in selected energy windows at the levels of a few events per year. These counters have since been used to detect not only ^{37}Ar and ^{71}Ge at the single atom level but also at similar levels, isotopes such as ^{133}Xe and ^{135}Xe that are produced in nuclear reactors. In the GALLEX project, it was demonstrated that a few atoms of ^{133}Xe could be collected and counted in less than a day from a volume of about 150 m^3 . To extend this capability requires the use of material with ultra-low natural radiation background for shielding; for example, low radioactivity lead from Roman times,

collected from sunken naval vessels off the Italian coast. Also the Xe atoms have to be chemically manipulated through synthesis and purification steps. The purification steps involve separation of Xe atoms from a few ^{222}Rn atoms. Also the counting gas is prepared from pre-nuclear-age xenon and tritium-free water used in the gas preparation is collected from sources under the Dead Sea in Israel.

With low radioactive shielding, combined with ultra-pure scintillators, (the Borexino Counting Test Facility (CTF) achieves 10^{-16} g/g removal of Th and U isotopes), one can achieve detection systems for Xe isotopes at the few atom level and corresponding orders of magnitude improvement in sensitivities. At such levels, the traditional terminology “ $\mu\text{Bq}/\text{m}^3$ ” is not representative and one refers to counting atoms per hundreds of cubic meters. In this illustration, the application to fission isotopes or nuclear activities is clear. The magnitude of the improvement in sensitivity opens new horizons—shorter collection times, smaller sample sizes, longer transport times, and much improved sensitivity to short-lived isotopes.

In addition to the proportional counter case illustrated above, ultra-low background research is achieving world record detections in liquid scintillators at the few event level. For example, ^{14}C has been detected for the first time from crude oil in the CTF and ^{85}Kr has been detected from atmospheric samples as small as one liter. Low-level cryogenic x-ray detectors are used at the Gallium Neutrino Observatory for the detection of chemically separated ^{71}Ge ; the new very low background germanium detectors of the Max Planck Institute fur Kernphysik achieves detections at the level of a few background events per month per gamma ray line. Such new capabilities provide for considerable extensions in the ability to perform analyses of trace elements.

The development for underground experiments of the low-level detector techniques, the ultra-pure chemical manipulation of small amounts of materials, and the collection of low background materials, some quite exotic, is an important research area. The PIsCES (Precision Isotope Counting Experimental Setups) program was formulated by the Space Science Division of the Naval Research Laboratory, in collaboration with U.S. and European

partners, to provide a mechanism to extend these techniques and explore the analysis of exceedingly small amounts of materials. Combined with neutron activation of stable isotopes and accelerator mass spectroscopy the sensitivities to trace analysis in small material sample sizes is further expanded.

Although the Gran Sasso Underground National Laboratory provides a small facility that can accommodate some of their low counting rate capability for materials applications and detector development, a facility is needed in the U.S. to house dedicated detectors with a larger research scope. The larger detectors at the Gran Sasso Underground National Laboratory have a high priority for use with ongoing solar neutrino projects and are rarely available otherwise. For this reason the PIsCES collaboration has sought the creation of a U.S. underground facility.

XI. MONITORING NUCLEAR TESTS

All nuclear explosions produce large quantities of fission products and their daughters. Important among these radioisotopes are ^{133}Xe and ^{135}Xe . The monitoring of radioactive noble gases is, indeed, one of the techniques enumerated in the Comprehensive Test Ban Treaty (CTBT) for verifying compliance with the accord. The amount of radioxenon reaching the surface after an underground detonation and subsequently mixing with the atmosphere is a function of the permeability of the rock, the depth of burial, and the fission yield of the device, often complicating radiochemical monitoring efforts.

In principle the detection of ^{133}Xe (half-life 5.3 days) alone would suffice to confirm that a nuclear explosion has occurred. In fact, however, small but fluctuating amounts of ^{133}Xe are present in the air as a result of emissions from normally operating nuclear reactors. As a result, it may be necessary to detect the ratio of ^{135}Xe (half life 9.2 hours) to ^{133}Xe in order to confirm that a nuclear detonation, as opposed to reactor emissions, has been observed.

The short half lives of both isotopes, combined with severe dilution of the radioactive gases in the atmosphere and the comparatively long time that may be required to get an air

sample, place a premium on the ability to detect both in small quantities. Also, attempts to evade the CTBT, which bans all nuclear test explosions of whatever yield, may employ small tests, where the yield of the nuclear event is tons rather than kilotons. As a result, a very-low-background counting facility such as has been proposed by the PIsCES collaboration for testing at the Gran Sasso Underground National Laboratory is a necessity. PIsCES combined with appropriate sampling techniques would likely lower the yield threshold for the detection of nuclear explosions by radiochemical means by 1 to 3 orders of magnitude below today's best capabilities. Such thresholds are probably well below the level at which any testing state could hope to gain information useful for improving its nuclear stockpile.

Sensitive radiochemical detection of nuclear explosions is particularly important when other possible cheating scenarios are taken into account. The most commonly cited method of evasive testing is to detonate the test device in a very large underground cavity. In theory, at least, the shock wave and seismic signal from the explosion can be reduced by a factor approaching 100. This would make a 1-kiloton explosion seem to seismographers to be only a 10-ton detonation, and hence far harder to detect by seismic means alone. However, a 1-kiloton fission explosion produces the same amount of radioxenon, regardless of whether it has been seismically decoupled or was fully tamped in hard rock. Indeed, cavity decoupling acts to release additional radioactive gases in two ways. A fully coupled blast causes a collapse "chimney" to form, sealing in much of the radioactive debris; a decoupled test does not result in such a self-sealing effect. In addition, the large surface area of the decoupling cavity provides more channels through which radioactive gases can reach the surface.

The possibility that another country could improve its nuclear weapons by evasive testing when the U.S. was effectively prevented from any type of testing by the openness of our society played a role in the October, 1999 rejection of the CTBT in the Senate. An underground laboratory with sensitive equipment would address this concern. The facility could contribute significantly to U.S. knowledge of the testing programs of other nations. An underground laboratory in the U.S. to which samples could be brought quickly, and under U.S. control, would be an important addition to efforts to deter nuclear proliferation

around the world.

XII. MICROBIOLOGY

Due to the expense and contamination associated with coring from the surface, few microbial samples have been collected from depths greater than 0.5 kilometers. These few samples nevertheless have demonstrated that microbial communities do extend down to 2.8 kilometers below the surface. The extreme conditions there, including extremes of temperature, pressure, salinity, pH, and ambient radiation, and the low availability of energy sources and liquid H₂O, approach the limits for life and novel “extremophiles” have been isolated. The paucity of high quality samples, however, has greatly hindered efforts to determine the size, structure, and metabolic activities of the deep subsurface microbial communities and the biogeochemical processes that support them. Recent investigations in the ultradeep gold mines of South Africa indicate that deep underground excavations provide unique “windows” into the subsurface continental biosphere. The depths and pressures of Homestake Mine approaches those at ocean ridges and the temperatures of the mined formations lie within the zone for microbial thermophilicity (45°–65°C).

The microbial communities encountered in these mines are composed of a mixture of contaminating (allochthonous) and indigenous (autochthonous) microorganisms. To distinguish autochthonous from allochthonous microorganisms requires sample collection and processing techniques that quantify and minimize the allochthonous microbial contaminants in the mine water and rock core samples. This permits evaluation of the relationship between the indigenous microbial communities and large-scale hydrogeochemical facies of water as well as small-scale geochemical heterogeneity of rock and pore water.

With long term access to an underground facility with instrumented boreholes and a small field laboratory, scientists can address many fundamental questions regarding the relationship between subsurface microbial community dynamics and biogeochemical and hydrological processes:

- Does primary production of organic substrates by autotrophic microorganisms dominate in certain subsurface terrestrial environments over heterotrophic utilization of organic substrates originally produced by surface-based photosynthesis? This question has been hotly contested in the recent literature and directly impacts the search for life on planets within our solar system.
- What are the abiotic mechanisms and rates for H₂ and CH₄ production in the subsurface and are they sufficient to support chemolithotrophic microbial communities? Radiolytic reactions have been proposed as a source of H₂ and abiotic redox reactions involving water, inorganic C, and mineral-bound Fe(II) have been proposed as sources of H₂, CH₄, and light hydrocarbons.
- Are *in situ* microbial activities so low as to only support average doubling times on the order of centuries? This has been proposed on the basis of geochemical modeling, which yielded rates that were 10³–10⁶ lower than laboratory measurements. *In situ* measurements at high temperature and pressure analogous to those performed at deep-sea vents have not been undertaken. If this hypothesis is correct, have subsurface microorganisms evolved special agents to guard against the deleterious environmental effects, such as ambient radiation?
- A fracture flow hydrogeological regime dominates most terrestrial deep subsurface settings. Are the deep subsurface microbial communities present in fluid-filled fractures distinct from those embedded in the rock strata? Are they responsible for the precipitation of fracture-filling minerals? Because coring such environments from the surface utilizes high pressure drilling fluids, which invariably contaminate the fracture surfaces and adjacent rock matrix, these questions have not been appropriately addressed. Expensive packer systems are also required to isolate discrete fracture zones for fluid sampling to avoid mixing and contamination. Microbial colonization of the deep subsurface occurs primarily by microbial transport through fractures, particularly when

topographically- or hydrothermally-driven meteoric water flow and fracture-generated permeability is enhanced by tectonics. With an underground facility, however, low fluid pressure coring and inexpensive packers can be employed enabling us to delineate the differences between fracture and rock matrix microbial communities.

These questions will never be resolved with the collection of one core from a single site or a single set of rock or water samples. Rather, the distribution, diversity and activity of microbial communities in a subsurface environment must be examined in terms of a hydrogeologically and geochemically well-characterized location by a sustained effort over several years. Such a research program would provide greater insights into how microorganisms can function and survive in extreme deep terrestrial environments, how their activity produces distinctive geochemical or molecular signatures, and how we may better culture and study such organisms in the laboratory. New technologies designed to detect life on other planets or quantify microbial activity at high temperature and pressure require ready access to well-characterized subsurface sites for field testing.