Underground Science and Laboratories E 6.4

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1. Introduction and Charge to the Working Group

In this summary of the experimental working group E6.4, we will be presenting the science, accomplishments, and future research endeavors related to underground science. Specifically, the advances and prospects in double beta decay experiments, solar neutrino and low energy solar neutrino experiments, supernovae searches, and possible sites for a national underground scientific laboratory are summarized. The science of proton decay, long baseline experiments and dark matter searches are presented elsewhere. However, there exist many similarities and synergism with these fields and references to these fields are made.

These sessions comprising Underground Science specifically addressed the following questions and topics presented to the workgroup in its charge:

- Review the current status of the experimentation and the science for these fields.
- Define the generic detector capabilities needed to advance the program into the next decade.

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- Quantify the major facilities and technological advancements that are needed and that are proposed.
- On the topic of a National Underground facility, what are the infrastructure requirements for such a facility? Does the US need such a facility? What are the advantages and disadvantages to a single site or multiple sites? What are the main scientific motivations for such a facility?
- How can the R&D and siting of future experiments be better coordinated within the US?

The progress made on all fronts of underground science during the past decade is astounding. In the field of solar neutrinos we have witnessed the exceptional work from Super-K and SNO. Together they have provided very strong evidence for neutrino oscillations between active flavors. SNO has confirmed the Standard Solar Model predictions for active neutrino fluxes. The work by Super-K, IMB, and Soudan has firmly established neutrino oscillations for atmospheric neutrinos. These results coupled with LSND's intriguing results provide the first hints of sterile neutrinos. Neutrinos have been observed from supernovae explosions providing unique information on supernovae mechanisms. Two-neutrino double beta decay has been observed. The background levels in next-generation double beta decay experiments have achieved such low levels that the searches for neutrino-less double beta decay are probing effective neutrino masses of the order of those suggested by atmospheric neutrino oscillation experiments ($\sim$10 millielectron volts). If observed neutrinoless double beta decay would answer the question of the Dirac or Majorana nature of neutrinos. In addition the absolute mass scale may be established by these measurements. Underground science has opened the door to the first new physics beyond the Standard Model. We have many topics and open questions remaining in neutrino physics: the exact nature of the neutrino, is it Dirac or Majorana; the mixing parameters for neutrinos and the precise understanding of the MNS-matrix parameters; the existence of sterile neutrino families; the unitary of the MNS matrix, is there CP violation in the neutrino sector; the important issues of proton-decay; a more complete understanding of stellar and supernovae mechanisms. All these intriguing issues share a common need to suspress backgrounds, predominately by going underground. In several cases the next generation experiments will require extreme shielding to permit the experiments to succeed.

2. Double beta decay

The exact nature of 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 observable only with a very rare phenomenon in nuclear physics. 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 decay was finally detected in the laboratory about a decade ago: it is the rarest process in nature that scientists have succeeded in directly measuring. We 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) which are not easily tested elsewhere can be studied with double beta decay. 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 double 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 $\sim$ 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 ($\sim$ 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 detector using ^{130}Te, ^{100}Mo foils sandwiched between plates of plastic scintillator or liquid scintillator based detectors, a laser tagged time-projection-chamber using ^{136}Xe, and ^{116}Cd and ^{100}Mo in BOREXINO's Counting Test Facility. The detector masses are typically $\sim$ 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.

Some of these proposals are quite advanced, while others are in the research and development stage. It is conceivable that complete proposals for construction of these next generation experiments could be completed in the next 2 to 3 years with scaled construction beginning immediately. A majority of these proposals for new experiments require extreme depths to shield cosmic ray background and cosmic ray–induced activities. All experiments would benefit from reduced backgrounds. Some of the experiments may require fabrication and construction facilities at moderate depth to ensure ultra-low levels of activity in the detector materials.

3. Solar neutrinos

The field of neutrino astrophysics began with the study of solar neutrinos. And very recently solar neutrinos provided additional evidence that the Standard Model of electro-weak physics requires expansion to account for neutrino oscillations from all families of neutrinos. The history of this subject well 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 electro-weak 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. This has recently been confirmed by combining the Super-K and SNO data, thus resolving this nearly 30 year-old problem.

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} eV^2 can be studied with solar neutrinos: solar neutrino experiments are truly very long baseline oscillation experiments. Moreover, as the neutrinos pass through $> 10^{10}$gm cm^{-2} of matter before exiting the sun, interaction with matter can affect their propagation, magnifying the consequences of neutrino mixing. This situation provides the current, and importantly future, solar neutrino experiments unique abilities to refine the oscillation parameters and extract important MNS-matrix elements.

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 (~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.

The solar neutrino "problem" provides us with 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}Be solar neutrinos.

At present, active detectors for solar neutrinos have only measured recoil electron energies for Charged Current and Elastic Scattering for the rare part of the solar neutrino flux produced by ^{8}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 *pp* 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 are proceeding know that we understand that neutrinos are oscillating between active species. 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. The current experiments have yielded us an extremely well calibrated source of neutrinos, the sun, with uncertainties in the *pp* flux of less than 1%. The next generation of low energy solar neutrino experiments can use this flux to probe for solar neutrinos and refining the MNS-matrix parameters.

The study of *pp* neutrinos will require tremendous shielding from backgrounds, both cosmic rays and intrinsic radioactivity. Most of these experiments are in early R&D phases and are 3 to 5 years from the proposal phase.

4. Underground Laboratories

The planning for a national underground science laboratory was begun as part of the long range planning process for the nuclear physics community. The underground laboratory was discussed at preparatory workshops, at town meetings and at the Nuclear Science Advisory committee (NSAC). Consistently through this planning process the idea of a dedicated deep underground laboratory found strong broad-based support from the Nuclear Community. An independent multidisciplinary panel (the Bahcall Committee) was established to probe the science, the sites and the advantages of a deep laboratory. A proposal has been developed and presented to NSF. It is in the process of receiving both mail-reviews and a full review committee. A brief summary of these steps is presented here along with the conclusions of the Bahcall committee.

At a pre-town meeting (September 2000) hosted in Seattle the neutrino community held a workshop to consider options and experiments for the future. From the underground science working group three conclusions were reached.

- Near term experimental needs can be mostly met at WIPP—this will permit us to continue excellent research and critical R&D. Encourage the agencies to provide support for essential infrastructure at WIPP to ensure that those programs can succeed.

- Many longer-term needs and anticipated requirements in the future require that we "go deep." Now is our chance to plan for this. The community must have a hard look and evaluate the options and develop a plan for a deep national facility.

- We should establish a "standing committee" to perform these evaluations. From this recommendation the Bahcall committee was established.

From the entire town meeting the highest priority was, "To satisfy the background requirements of new solar/supernova neutrino and double beta decay experiments, the nuclear physics community should spearhead an effort to create a deep underground multipurpose laboratory. Because this national facility could also serve the needs of dark matter and nucleon decay experiments, it is important to involve colleagues from particle and astrophysics."

The entire nuclear physics community then met in a series of town meetings organized around the sub-fields of nuclear physics. Two of these meetings took place in Oakland, California in November, 2000. The overlap of these meetings was planned to take advantage of the large overlapping interest in astrophysics and cosmology shared by several of the sub-fields within nuclear physics. The highest priority from the Neutrinos, Astrophysics, and Fundamental Symmetries town meeting was: "Nuclear physics must build on its successes with low-energy neutrinos by initiating work on the next generation of neutrino experiments. These efforts are not only key to understanding the nuclear physics of stars and supernovae, but could profoundly influence cosmology, astrophysics and particle physics. Our community must spearhead an effort to create a deep underground multipurpose laboratory that could accommodate the essential new solar-neutrino and double-beta-decay experiments, as well as others of interest to the broader scientific community."

Finally, the full Nuclear Physics community presented and discussed the recommendations of the full field and all the town meetings in March 2001. The third priority from NSAC, following support of existing programs, and pursuing RIA if funds could be secured, was the support of the National Underground Laboratory. "We strongly recommend immediate construction of the world's deepest underground science laboratory. This laboratory will provide a compelling opportunity for nuclear scientists to explore fundamental questions in neutrino physics and astrophysics."

The Bahcall committee was a multidisciplinary committee with nuclear physics, astrophysics and high energy physics, representation. The committee was established following the Seattle meeting and completed its work prior to the March meeting of NSAC.

The charge to the committee was:

- To evaluate the scientific justification for a national facility for deep underground science.

- Identify the experiments such a facility might host and the attributes of the underground laboratory (depth, access, infrastructure impact, support, ...).

- Evaluate suitability of suggested sites (Homestake, San Jacinto, WIPP, Soudan, Greenfield sites) and recommend how to formulate the strongest proposal for an outstanding site or sites.

In considering the science justification for an underground laboratory the committee considered the following scientific fields and topics:

- Nuclear Physics—double beta decay, solar neutrino experiments, dark matter detection, nuclear astrophysics experiments (facility)

- High Energy Physics—long baseline neutrino experiments, atmospheric neutrino, double beta decay, dark matter detection, proton decay experiments

- Low Background Counting and Detector and Material R&D

- Geophysics, Rock Mechanics, Seismology, and Biophysics

In the process of evaluating potential sites the committee and technical subcommittee considered the following criteria:

- Construction Costs—access, underground halls, outfitting mechanical/electrical systems, installing detectors
- Facility Operating Costs
- Risk—environmental/permitting, rock/salt structural integrity, seismic, mechanical systems
- Management—scientific, site operations, ownership/sharing
- Depth and Backgrounds
- Neutrino Beam
- Time to Detector Installation
- Outreach Possibilities
- Local Awareness and Support
- Laboratory Context—cost of living, climate, travel to laboratory area, commuting to laboratory, local universities, ease of access, local industrial infrastructure, scientific environment
- Suitability for Detectors—ultra-low background, flammables and cryogens, "ultra-K" large water Cerenkov detector

The Technical subcommittee specifically addressed issues for four prototype experiments.

- Detector A: modest-sized, ultra-low-background detector of the type that might be used for a double beta decay or cold dark matter experiment
- Detector B: large inventory ($\sim$ 1 kiloton) of flammable liquid scintillator, similar to a super-Borexino or a super-KamLAND
- Detector C: larger inventory of a liquid cryogen, for example, 5 kilotons of argon
- Detector D: ultra-K detector, containing $\sim$ 0.5 megaton of water

The technical subcommittee of the Bahcall committee visited the following sites in drafting their report and forming their conclusions.

- WIPP, NM: 1600 – 2300 mwe
- Homestake, SD: up to 7200 mwe
- San Jacinto, CA: 5400 – 6300 mwe
- Soudan, MN: 2200 mwe
- Various Greenfield Sites, CA and NV: 5000 to 8000 mwe
- Grand Sasso (visited for reference): 3900 mwe
- Kamioka (visited for reference): 2800 mwe

The recommendations of the Bahcall committee were:

- The Committee unanimously recommends the establishment of a deep premier national underground scientific laboratory to enable US leadership and synergism in a broad array of scientific fields in the coming decades (See subsequent talk).
- The Committee endorses a single primary site as the most effective method of realizing the anticipated scientific program.

- The Committee believes that there are two excellent sites for a premier deep underground science laboratory: Homestake and San Jacinto. We judged that Homestake and San Jacinto are very similar in their technical suitability for underground experiments. Although the committee is not charged with making a formal site selection, time is of the essence, and the agencies need to be aware of the time-sensitive nature of the site selection. We strongly encourage interagency cooperation to help realize this exciting opportunity for science.
- At the time of this meeting the Committee favors the Homestake site for the following reasons: 1) faster time scale to produce important scientific results, 2) less initial capital outlay to produce world-class science, 3) greater positive impact on the local population, and 4) lower inherent uncertainties.
- The San Jacinto site is also judged to have great potential for several reasons including horizontal access allowing simple and cost effective access and operation, lower operating costs, and the close proximity of strong scientific research universities.
- Homestake—needs to solve indemnification.
- San Jacinto—needs to resolve environmental impact issues.
- Additional deep sites (Greenfields) exist if the first two should encounter serious impediments to achieving a Deep National Facility.

The Bahcall committee specifically addressed the benefits of a single underground facility and strongly recommended a single deep site be pursued. The reasons for this centralized facility included:

- Sharing of common infrastructure including access, machine shops, administrative support, computing, and telecommunications;
- Provision for a common safety support that must oversee equipment and procedures for dangerous components such as flammable and cryogenic materials;
- Synergistic interactions among scientists doing different experiments in an environment where they can easily exchange ideas;
- Establishment of common facilities that can be used by different groups interested in, for example, low radioactivity materials or low level counting measurements;
- Creation of a support organization that can make possible the testing and implementation of new ideas;
- Providing a critical mass for outreach to the local population, especially K–14, and to the public at large;
- Provide a research center that would be a base for international collaborations to maintain scientific and technical staff for developing and carrying out large scale projects;
- Provide a nurturing and exciting scientific environment for students and young scientists;
- Provides a center for international scientific meetings.

The support for a national underground facility by the nuclear community is well established and documented. There are great benefits in cooperation between the fields on this endeavor and cooperation between high energy physics, nuclear physics and other fields has been sought and encouraged from the start of this process. There is a proposal in to the National Science Foundation for the conversion of the Homestake Mine into a premier deep underground facility. This proposal is modeled on Gran Sasso in Italy and has planned from the beginning to provide both the spectrum of deep and shallow sites to pursue underground science for the coming decades. The proposal is begin reviewed in the usual NSF fashion with both mail and panel reviews. At the time of SNOWMASS the results of these reviews were not known. The concept of a deep national laboratory was also the focus of an independent committee formed by NSF and DOE to consider the science, the sites, and the best facility.

5. Conclusions from SNOWMASS

The conclusion from the underground laboratory section was a strong endorsement for a deep national facility. The science potential for new physics and new discoveries were excellent. We are on the frontier of new understanding of neutrinos, neutrino masses and mixing. A deep underground laboratory would address issues of nuclear, particle, astrophyiscs and cosmology as well as sponsor new collaborations with fields as widely separated as geophysics and biophysics. There are several experiments ready within one to five years to address these issues of neutrino physics and astrophysics. It was realized that excellent science and R&D are taking place and should be encouraged to take place at a number of sites, but that ultimately the benefits of a single focussed site would likely provide operations and construction savings.

Finally it was stressed that many experiments, from low energy solar neutrinos, to dark matter, to double beta decay, to ultra-low background counting and material fabrication for industrial and national security issues all share common detector elements, detection techniques, and background suppression requirements. Many fields require extreme depth for the next generation of physics to be uncovered. Almost all experiments would benefit from additional background suppression provided by greater depths. In addition, a national facility would serve as a focus for other experiments that do not require such extreme depth but would benefit from a national facility: topics such as long baseline experiments and proton decay. In some cases, better shielding would permit some of these experiments to be multi-purpose and expand their scientific reach from a single experiment to embrace several.

We are on the leading edge of a new revolution in physics and the formation of much closer ties between of nuclear and particle physics, between astrophysics and cosmology, and other fields as well. At the center of most of this excitement is the common focus of a deep underground laboratory.