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Neutrino Science at LBNL

Present Program and Future Options

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Executive Summary

The study of neutrino properties is undergoing a renaissance. After a long period during which experimental results provided the pieces of a puzzle, such as the solar neutrino problem and the atmospheric neutrino anomaly, key measurements began to provide unambiguous solutions. From these measurements we have discovered that neutrinos can change their flavor and, therefore, have mass — and in the process have taken the first steps beyond the Standard Model of particle physics. We have learned that the explanation of these puzzles is neutrino oscillations. This new understanding of neutrino properties has established a new field of inquiry. We envision an experimental program extending over decades that will establish whether neutrinos are their own antiparticles, determine the absolute mass scale, measure masses and mixing parameters with increasing precision, search for CP violation in neutrino oscillations, and detect neutrinos coming from the cosmological birthplaces of ultra high energy cosmic rays.

While the general direction of neutrino science is clear, the field is awash with ideas for future experiments and theoretical approaches for understanding the possible results. Ideas for the future also abound at LBNL. To capitalize on this creativity and help chart an optimum course for the future, the three divisions in the General Sciences established a Neutrino Working Group (NWG) to survey the theoretical and experimental landscape, place current LBNL work in context, develop options, and lay the groundwork for the development of proposals. This report culminates a process that began in September, 2002.

There are a number of fundamental open questions concerning the properties of neutrinos. The most important question is also the most fundamental, namely, are neutrinos their own antiparticles (Majorana) or not (Dirac)? In order to extend the Standard Model to include neutrino mass, we must answer this question. Beyond this, we must determine the absolute mass scale of neutrinos, or the mass of the lightest mass eigenstate, since we know the mass differences. Tremendous progress has been made on the measurement of neutrino mixing angles. Of the three angles, we have measurements for two of them (θ_{12} and θ_{23}), but for θ_{13} we have only an upper limit. θ_{13} takes on special importance not only because it has not yet been measured, but also because its value will determine whether it will be possible to search for CP violation in the neutrino sector. At the next level we ask whether the ordering or hierarchy of the mass eigenstates is "normal" or "inverted". More precise values of the mass differences and associated mixing angles will be required for tests of models going beyond the Standard Model. Answering these questions will require a variety of experiments — neutrinoless double beta decay experiments (for neutrino type and absolute mass scale), and neutrinos from the Sun, reactors, and accelerators (for masses and mixing angles, mass hierarchy and CP violation). And finally, there is the question whether the LSND result, which would indicate a fourth generation sterile neutrino, or something even stranger, is correct. An experiment, MiniBoone, is underway at Fermilab to answer this.

Neutrinos are messengers bringing us information from otherwise inaccessible places. The core of the Sun and supernova SN1987a are the best examples. It should also be possible to detect neutrinos from deep in the Earth and from the most energetic objects in the cosmos. The detection of high energy cosmic neutrinos could help answer the fundamental open question of the origin of cosmic rays.

There is a vibrant program in neutrino science in progress at LBNL. The SNO and KamLAND experiments, after reporting initial results, are in their most productive phases. We will have values from SNO for the neutral current and charged current reaction rates for ^{8}B solar neutrinos measured by several techniques (salt phase and ^{3}He proportional counters). The analysis of the energy spectrum of anti-neutrinos at KamLAND will result in tighter constraints on the Large Mixing Angle solution and may reveal the anticipated "dip", demonstrating neutrino oscillation. Cuoricino, a prototype for the next generation of double beta decay experiments, has just begun taking data at the Gran Sasso underground laboratory in Italy. LBNL materials scientists developed a key element (NTD thermistors) in the cryogenic measurement technology and LBNL physicists are a part of the CUORE collaboration. AMANDA and IceCube — the present and future high energy neutrino telescopes at the South Pole — are also using LBNL developed measurement technologies and have significant LBNL participation. In the long run, accelerator neutrino beams will be needed for measurements of CP violation and will be used to determine the mass hierarchy. If $\sin^2 2\theta_{13} \lesssim 0.005$, then the search for CP violation will require the very intense and clean neutrino beams made possible only by a neutrino factory. A neutrino factory is a first step toward a muon collider. LBNL is deeply involved in the international R&D effort toward a future neutrino factory through its participation in the Muon Collaboration and in MICE, the Muon Ionization Cooling Experiment. MICE must go forward in order that a muon storage ring neutrino factory can eventually be realized. Finally, there is also an LDRD-supported R&D effort toward a next generation detector for solar pp neutrinos, which would provide a precise measurement of θ_{12} and test the Standard Solar Model. Thus, the present effort in neutrino science at LBNL has breadth and is able to address several of the fundamental open questions.

- The first requirement in addressing the future is to meet the commitments implicit in the present program.

Indeed, success in meeting present commitments provides the basis on which we build the future — a future that will contain elements of the present program and new initiatives.

A study of the open questions and how the field may evolve in answering them leads naturally to a consideration of opportunities that lead beyond our current program. What are the options most appropriate for LBNL? What would it take to pursue or develop them to the point of funded projects? We present four options for consideration. In order of priority they are:

- Neutrinoless double beta decay;
- A reactor measurement of θ_{13};
- Measurements of θ_{12} and tests of the Standard Solar Model;
- Development of the scientific and technical infrastructure for the National Underground Scientific and Engineering Laboratory.

Double beta decay experiments, in the form of CUORE and Majorana are two prime opportunities for LBNL. Both of these experiments will have the ability to observe neutrinoless double beta decay at the level of sensitivity suggested by neutrino oscillation experiments in case of an inverted mass hierarchy, thus addressing the questions of the nature of neutrinos and the absolute mass scale. Both rely on experimental technologies developed at LBNL. We are already participating in Cuoricino and we could decide to join Majorana. These experiments, though having the same goal, differ in their approaches, methodology, cost, and time scale. It seems to us realistic and advisable to pursue both these experiments. R&D for a totally new detector technology, a liquid TPC, is also a possibility.

The value of θ_{13} can be addressed in different but complementary experiments using neutrinos either from accelerators or reactors. A preliminary analysis of these two approaches suggests that the reactor neutrino measurement can have comparable sensitivity. Consideration of the time to construct and to obtain a result, cost, present experience (cf. KamLAND), institutional impact and opportunities for leading a new US collaboration — all these favor pursuing the reactor neutrino option in the near term. In the longer term LBNL participation in an accelerator-based neutrino program is envisioned.

Precise measurements of θ_{12} and further tests of the Standard Solar Model are in the realm of solar neutrinos. KamLAND will be upgraded to detect solar neutrinos, and may be the first to observe ^{7}Be neutrinos from the Sun. A next generation detector to observe solar pp neutrinos is a long term goal of the neutrino science community and a number of technical approaches are being investigated. Pursuing the above options represents a natural continuation of present successes in the LBNL program.

The long-standing goal of the US "non-accelerator" community to have a deep underground laboratory may actually be realized in the near future if the National Science Foundation decides to proceed with the development of the Homestake Mine in South Dakota (or possibly some other site). NUSEL, the National Underground Science and Engineering Laboratory is highly recommended in the Nuclear Science Advisory Committee's recent Long Range Plan. The option for LBNL is to participate in the scientific and technical development of this facility and thereby contribute to its success.

It seems to us both possible and strategically important to pursue several options. Not all are guaranteed to succeed and a diverse portfolio provides a measure of security for the exciting times in which we live. While we have prioritized the options, we stress that all four are well worth pursuing. In summary, the wonderful feature of neutrino science is that there are a number of exciting lines of research to explore with the prospect of fundamental discoveries along the way.

1 Introduction

Neutrino science — the study of neutrino properties and their use as probes of our environment — is blossoming. The recent discovery that neutrinos change from one flavor to another is aptly called the scientific discovery of the decade in the study of fundamental particles. It is the first example of a phenomenon that transcends the Standard Model of particle physics. In the last year we have shown for the first time that the Standard Solar Model, which includes the nuclear reactions in the core of the Sun, is correct. These achievements have reached the public through the awarding of Nobel prizes and the recent ranking by the scientific press of discoveries in neutrino physics near the top in all fields of science.

LBNL is contributing to the flowering of neutrino science in key areas and in significant ways. LBNL is currently involved in three areas — the study of neutrino properties, high energy neutrino telescopes, and accelerator R&D toward a future neutrino factory. This work goes forward in all three divisions of the General Sciences Directorate, which includes the Institute for Nuclear and Particle Astrophysics. LBNL's involvement in neutrino physics is recent and the effort is relatively small. The ratio of scientific reward to investment made is very high.

The present successes and results in neutrino science point to future experiments and facilities with possibilities for even greater advances in our understanding of fundamental particles and in our ability to "see" distant cataclysmic events in "neutrino light." These opportunities have prompted the General Sciences Division Directors "to see if we can formulate a coherent picture of how our current work should evolve in the future. This is important for both scientific and strategic reasons — we are presented with wide ranging scientific opportunities and faced with limited resources." To this end they formed a Neutrino Working Group (NWG) and asked it "to survey the theoretical landscape and recent experimental results to provide a framework for understanding which will be the most compelling next set of neutrino experiments world-wide. All ongoing and planned neutrino-related work at LBNL should be surveyed and placed into the above context by the working group through discussion with the proponents."

This report starts in Section 2 with a survey of the status of theoretical and experimental neutrino science, and the future directions it may take.

The ongoing work at LBNL is presented in Section 3. Experiments on neutrino properties — SNO (solar neutrino oscillations), KamLAND (reactor neutrino oscillations), and CUORE (double beta decay) — are described. LBNL has a major role in IceCube, a high energy neutrino telescope to be built at the South Pole, and the present detector, AMANDA. MICE, the Muon Ionization Cooling Experiment, is part of AFRD's participation in the development of the technology required for a future muon storage ring/neutrino factory. Present effort also includes R&D for possible future experiments.

Section 4 outlines the opportunities for future research. These are opportunities that match LBNL's expertise and experience, and that could be considered if resources were available. There is a broad range of possibilities, which reflects the excitement and interest in neutrino science in the US and internationally.

The limitations faced by the neutrino community at large and at LBNL in particular are discussed in Section 5. These and our own institutional criteria must be factored into the choices for future work.

An analysis of the opportunities in light of the current state of neutrino science, limitations, and institutional criteria is presented in Section 6, along with conclusions and priorities.

2 Status and Future of Neutrino Science

The Standard Model of particle physics is built assuming that neutrinos are massless. Only in the past few years have we finally found strong evidence that they do have nonzero mass, requiring revision of the Standard Model that survived every experimental challenge over a quarter century.

However, many mysteries still remain. What exactly are their masses? We have only measured *differences* in masses-squared because we rely on neutrino oscillation experiments. Are there right-handed neutrinos? We have so far observed only left-handed ones, but the finite mass requires the existence of both right-handed and left-handed states. Are neutrinos and anti-neutrinos distinct or the same? Even such a basic question currently does not have an answer. Only after knowing answers to these questions, will we learn exactly how the Standard Model has to be extended.

The interest in neutrinos goes well beyond their own nature. Having discovered the finite mass of neutrinos, they contribute due to their abundance to the energy budget of the Universe at least as much as all the visible stars combined. Because we do not know precisely what their masses are, they account for anywhere between 0.1–1.5% of the Universe. If on the high side, they must have affected the way galaxies and eventually stars formed.

Arguably the most interesting aspect of neutrinos is their possible role in our very existence. At the time of the Big Bang, an equal amount of matter and anti-matter was created. If it remained so, all matter and anti-matter would have annihilated and we (matter) could not have existed. There must have been some process that changed the balance slightly between matter and anti-matter, allowing approximately one out of ten billion matter particles to survive the Great Annihilation. Theories suggest that neutrino mass may well have been responsible for changing this balance. If this were the case, neutrinos must have distinguished matter and anti-matter in a subtle way, via CP violation. It would be of foremost interest to observe the effect of CP violation in the properties of neutrinos.

In this chapter, we review the status of neutrino science in view of the latest data, list open scientific questions, and discuss plausible progress in the near future. Most of the recent progress is in the study of neutrino properties, i.e., neutrino masses and mixings from the neutrino oscillation experiments, and we discuss these first. Next we move on to the absolute mass scale and its nature, which cannot be studied in oscillation experiments. Finally we discuss the prospects in neutrino astrophysics.

2.1 Neutrino properties

2.1.1 Current status of neutrino oscillations

In the simplest case of two-flavor neutrino oscillation in vacuum, the transition probability from flavor i to flavor j is given by

$$P_{ij} = \delta_{ij} - (2\delta_{ij} - 1)\,\sin^2 2\theta\,\sin^2\left(1.27\,\frac{\Delta m^2}{\mathrm{eV}^2}\,\frac{L}{\mathrm{km}}\,\frac{\mathrm{GeV}}{E}\right), \tag{1}$$

where θ is the mixing angle, $\Delta m^2 = m_1^2 - m_2^2$ is the mass squared difference of the mass eigenstates, E is the energy of the neutrinos (they are assumed to be relativistic, which is a good approximation in all cases we consider), and L is the distance between the production of the ν_i and the detection of the ν_j flavor eigenstates. While matter effects and oscillation involving more flavors complicate the formulae, many qualitative features can be understood from this simple equation.

The first significant evidence for neutrino oscillation was obtained in the atmospheric neutrino data from the Super-Kamiokande experiment. It exploits the availability of a wide range in baselines 20–12000 km and energies 0.1–10000 GeV. The main signature is the disappearance of ν_μ while there is no sign of excess or deficit of ν_e. The fit to the data gives $\Delta m^2 = (1.6 - 3.7) \times 10^{-3}\,\mathrm{eV}^2$ and $\sin^2 2\theta = 0.9 - 1.0$ (90% CL). The data are internally consistent for various event categories over the wide range of baselines and energies. They show a weak (2σ) preference for $\nu_\mu \to \nu_\tau$ oscillation over oscillation to a sterile neutrino, ν_s. There still lacks an explicit demonstration that the deficit is due to oscillation rather than some other mechanism, e.g., neutrino decay, even though the oscillation is a better fit than other hypotheses. The detector is expected to run for at least five more years. However, it is unlikely that the accuracy of the (Δm^2, $\sin^2 2\theta$) measurement will improve substantially.

The K2K experiment shoots a conventional horn-based neutrino beam with an average energy of 1.2 GeV from the 12 GeV Proton Synchrotron at KEK over 250 km. It has observed 56 events in the fiducial volume, whereas $80.1^{+6.2}_{-5.4}$ events are expected in the absence of oscillation. This result provides additional support to the deficit observed in the atmospheric neutrino data, though it does not constitute a proof of oscillation. It is expected to double the data before the KEK PS is shut down in anticipation of J-PARC (formerly JHF). K2K can, in principle, analyze events outside the fiducial volume to further boost the statistical significance. It has a chance of observing the oscillation dip in the event sample enriched in quasi-elastic events. It may also improve the accuracy of Δm^2, but not of $\sin^2 2\theta$.

The second significant piece of evidence for neutrino oscillation was obtained last year by the SNO experiment, in which Nuclear Science Division has played a major role. Rates in solar neutrino experiments had been lower than theoretical expectations (à la Bahcall) for decades, starting from the radiochemical chlorine experiment by Ray Davis in the Homestake mine. Although similar deficits were also seen by the Kamiokande experiment and two radiochemical gallium experiments, SAGE and GALLEX, the community had been skeptical because these experiments are very difficult and the calculation of the neutrino flux is very sensitive to the solar parameters, especially the core temperature. The SNO experiment can study both the charged-current reaction $\nu_e + d \to e^- + p + p$ and the neutral-current reaction $\nu_X + d \to \nu_X + p + n$ followed by the capture of a neutron on chlorine, in addition to the elastic scattering $\nu_X + e^- \to \nu_X + e^-$. The measured neutrino flux from the charged-current process is $\phi_{\mathrm{CC}} = (1.76 \pm 0.05 \pm 0.09) \times 10^6\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ while that from the neutral-current process is $\phi_{\mathrm{NC}} = (5.09^{+0.44}_{-0.43}{}^{+0.46}_{-0.43}) \times 10^6\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. This difference demonstrates a non-electron neutrino flux $\phi_{\mathrm{non}-e} = (3.41 \pm 0.45^{+0.48}_{-0.45}) \times 10^6\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, a 5.3σ deviation from zero. Because the thermonuclear fusion in the Sun cannot produce muon or tau neutrinos, this observation demonstrates the flavor conversion from electron neutrino to muon or tau neutrinos. SNO will install new neutral-current detectors (NCD's) based on ^{3}He proportional counters and

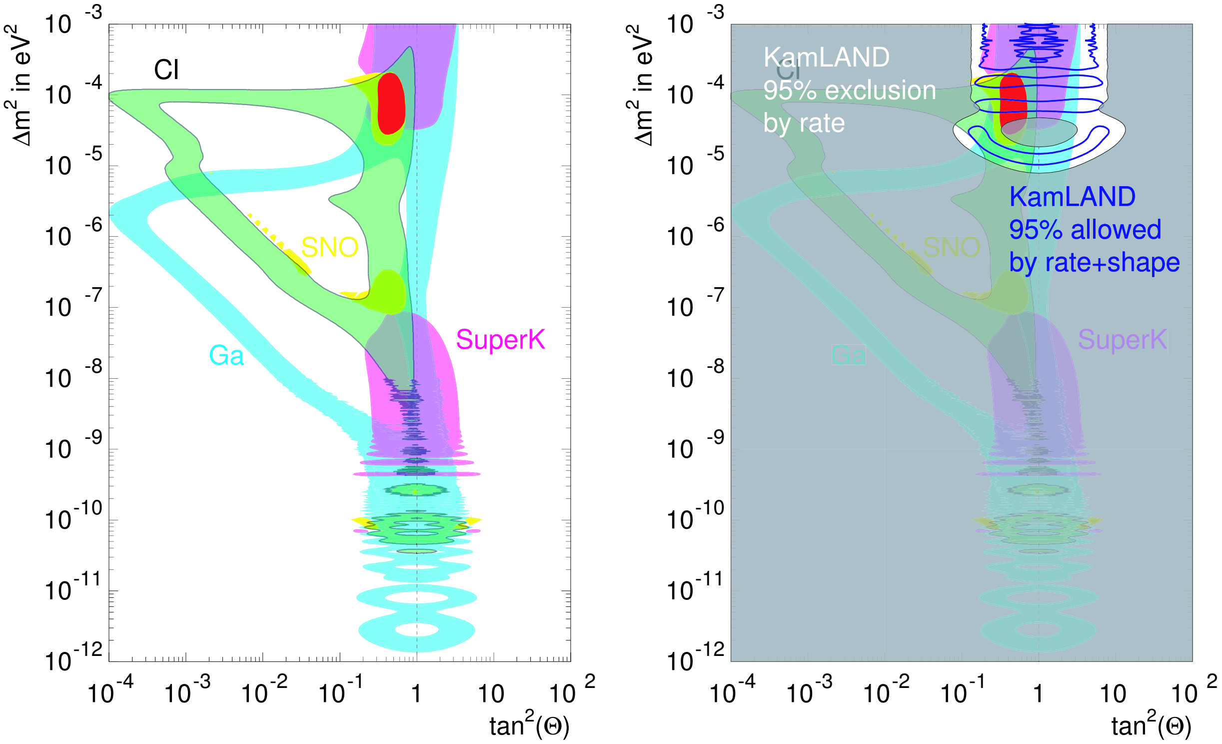


Figure 1: Constraints on neutrino oscillation parameters from all solar experiments (left), and with the KamLAND excluded and preferred regions overlayed (right).

will be able to detect neutral-current and charged-current events separately. This way, it will further improve the accuracy of rate measurements, increase the accuracy of its day/night effect measurement, further develops its NC/CC sensitivity that restricts the θ_{12} range, and even enhances its sensitivity to low energy spectral distortions. Current global analyses incorporating solar neutrino experiments and KamLAND's deficit measurement imply that SNO may be able to observe MSW effects in the solar neutrino spectrum, in its day/night spectra, and possibly in its energy spectrum.

The interpretation of solar neutrino experiments in terms of neutrino oscillation requires a global analysis of the data. No single experiment can determine the parameter range completely. Figure 1 shows the preferred region of two-flavor neutrino oscillation parameter space from the chlorine, gallium (SAGE and GALLEX combined), Super-Kamiokande, and SNO experiments. In addition to the observed deficit, the apparent lack of day/night effect (possible matter effect in the Earth) and the distortion in the energy spectrum are used in the Super-Kamiokande and SNO preferred regions. All of them overlap in the so-called large mixing angle (LMA) region, also shown in Figure 2.

The KamLAND experiment, in which both Physics and Nuclear Science Divisions play major roles, has studied electron anti-neutrinos from nuclear reactors at about 180 km distance on average. In the initial report of the data, it observed 54 events with 86.8 ± 5.6 signal and 1 ± 1 background events expected. The probability of the expected number of events fluctuating down to the observed number is less than 0.05%. However, it has not

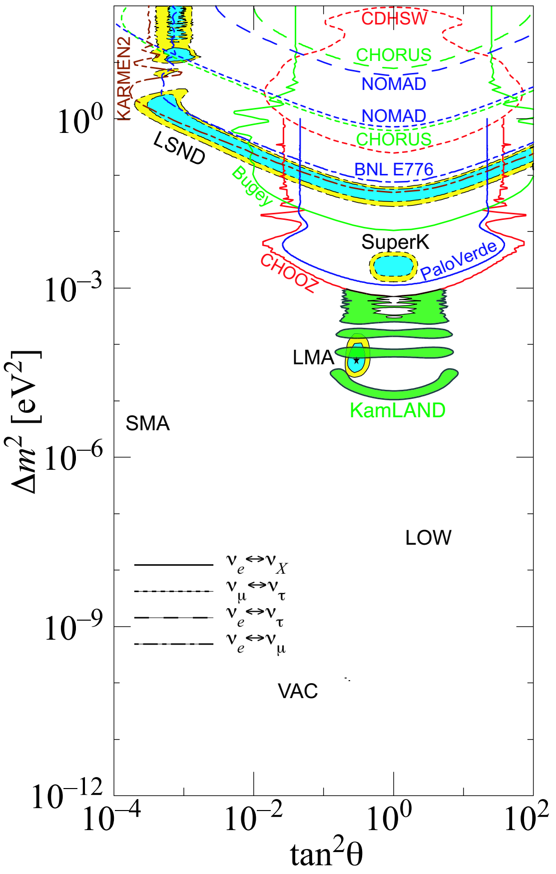


Figure 2: Constraints on neutrino oscillation parameters from all oscillation modes, including the SNO and KamLAND data.

demonstrated the oscillation in the energy spectrum yet. If interpreted as neutrino oscillation, it excludes a large portion of the parameter space for electron neutrinos, while leaving most of the LMA region preferred by the solar neutrino data (assuming CPT invariance). Solar neutrino and KamLAND data are hence consistent, and their combination gives $\Delta m^2 = (0.5 \pm 2.0) \times 10^{-4}$ eV^2 and $\tan^2\theta_{12} = 0.28 - 0.91$ (3σ). Accumulating more data, KamLAND has a good chance of observing the oscillation dip and demonstrating neutrino oscillation.

Finally the LSND experiment looked for the appearance of electron anti-neutrinos from muon anti-neutrinos in stopped muons, and reported evidence for the appearance signal. It reported the appearance probability $P = (0.264 \pm 0.067 \pm 0.045)\%$, 3.3σ signal above zero. This evidence has not been corroborated by other experiments so far. Together with the null oscillation results from Bugey (reactor neutrino experiment) and KARMEN2 (accelerator-based neutrino experiment), this result prefers $\Delta m^2 \approx (0.1 - 1)$ eV^2 and $\sin^2 2\theta \approx 10^{-3} - 10^{-1}$. LSND has also reported a positive result for the electron neutrino appearance from the muon decay in flight, but the signal is not statistically significant.

The combination of atmospheric, solar, and reactor neutrino experiments make a strong case for neutrino oscillation, the first evidence of physics beyond the Standard Model. These

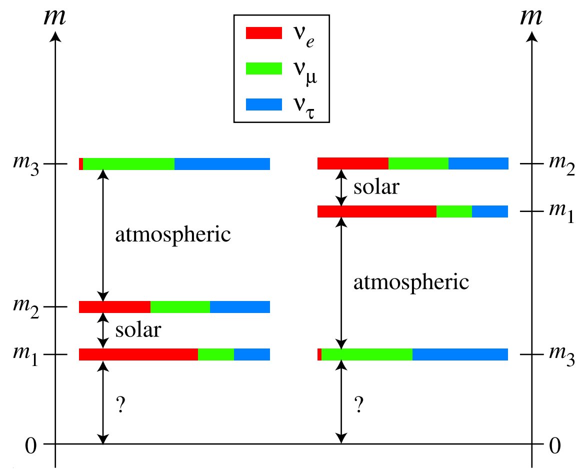


Figure 3: Possible mass hierarchies and flavor decompositions of neutrino mass eigenstates in the three-generation framework. Left is the "normal", right is the "inverted" hierarchy.

results can be accommodated in the framework of three neutrino generations, with the mixing of the neutrino mass eigenstates described by the 3×3 Maki-Nakagawa-Sakata (MNS) matrix,

$$U_{\mathrm{MNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}, \tag{2}$$

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$. Note that if neutrinos are Majorana fermions then there are two additional CP violating phases in the MNS matrix, which, however, do not affect lepton number conserving observables, such as oscillation probabilities. The larger mass splitting $\Delta m^2_{23} = (1.3 - 4.4) \times 10^{-3}\,\mathrm{eV}^2$ and $\sin^2 2\theta_{23} = 0.86 - 1.0$ (99% CL) are responsible for the atmospheric neutrino oscillation, while the smaller one $\Delta m^2_{12} = (0.5 - 2.0) \times 10^{-4}\,\mathrm{eV}^2$ and $0.28 < \tan^2\theta_{12} < 0.91$ (3σ) for the solar/reactor neutrino oscillation. The third mixing angle, θ_{13}, currently has only an upper limit from the CHOOZ reactor neutrino experiment, $\sin^2 2\theta_{13} < 0.33$ ($\Delta m^2_{23} = 1.3 \times 10^{-3}\,\mathrm{eV}^2$) or $\sin^2 2\theta_{13} < 0.068$ ($\Delta m^2_{23} = 4.4 \times 10^{-3}\,\mathrm{eV}^2$) (90% CL). The possible compositions of the neutrino mass eigenstates in terms of flavor eigenstates is shown in Figure 3.

Even within the three-generation framework, there are still many open questions:

1. Are neutrinos Majorana or Dirac?
2. What is the absolute mass scale of neutrinos?
3. What is the value of θ_{13}?
4. Is there CP violation in the neutrino sector?
5. Is the ordering of two mass splittings normal or inverted hierarchy?
6. The oscillation, namely a periodic change in the survival probability, has not been demonstrated in any of the strong evidence mentioned above. Can we verify it?

If we add also the LSND signal, there is another pressing question.

7. How can we accommodate three mass splittings of different orders of magnitudes? Is there a fourth neutrino, is CPT violated, or is there something else going on?

If there is a fourth neutrino, it must be a sterile neutrino that does not have a neutral-current interaction with the Z boson because of the constraint from the invisible width. Then there are three linearly independent mass splittings and it is possible to accommodate the LSND signal in addition to the atmospheric and solar/reactor signals. The global fit, however, yields a poor fit because of constraints from other experiments, including Bugey and CDHSW. The 2+2 spectrum is essentially excluded due to Super-Kamiokande and SNO, and the 3+1 spectrum is also disfavored at 99% CL or more. An alternative possibility is to assign different mass spectra for neutrinos and anti-neutrinos. KamLAND has severely limited this possibility, even though it is still claimed viable.

The question whether the LSND signal is correct will be a major branch point in the future of neutrino physics. MiniBooNE started taking data in Summer 2002, and is expected to definitively verify or exclude the LSND signal in the neutrino mode over a two-year time scale, assuming the expected performance of the Booster. However, if the LSND signal is due to CPT violation then only an anti-neutrino run of MiniBooNE would show an effect.

2.1.2 Future of neutrino oscillations (LSND false)

Here we discuss expected future progress within the three-generation framework assuming the LSND signal is not confirmed by MiniBooNE.

The atmospheric neutrino oscillation will be tested by the MINOS experiment, starting at the end of 2004. It will see the oscillation dip if $\Delta m^2_{23} > 2 \times 10^{-3}\,\mathrm{eV}^2$ or so, and will determine Δm^2_{23} more accurately ($\pm 1 \times 10^{-3}\,\mathrm{eV}^2$) than Super-Kamiokande, using the low energy option of the NuMI beam. The $\sin^2 2\theta_{23}$ measurement is not expected to improve significantly. If $\Delta m^2_{23} > 3 \times 10^{-3}\,\mathrm{eV}^2$ or so, they can switch to a higher energy beam and study the NC/CC ratio, testing ν_τ "appearance" in the final state.

Both ICARUS (Liquid Argon TPC) and OPERA (hybrid emulsion) experiments aim at direct detection of τ appearance in the CNGS beam, starting in 2006. Over a five-year period, they expect to see a few to a few tens of τ events.

The next physics target with Δm^2_{23} is the search for the electron appearance due to θ_{13}. The first one is the proposal to build a 0.75 MW neutrino beamline at the J-PARC 50 GeV proton synchrotron, aiming off-axis at Super-Kamiokande. The neutrino beam energy will be 0.7 GeV. It will be sensitive to electron appearance down to $\sin^2 2\theta_{13} \approx 0.01$. The original proposal was to start the experiment in 2007, but the approval did not materialize last year. If it is approved this year, it could start in 2008. The second one is a similar off-axis experiment using the NuMI beam currently under construction. The detector may be a 40 kt fine grain calorimeter, an RPC, or a 10 kt liquid argon. The currently favored neutrino beam energy is 2 GeV, which requires the medium energy option of NuMI. The performance is expected to be similar to the J-PARC experiment. However, the off-axis NuMI experiment will be more sensitive to the matter effect due to the higher energy and longer baseline compared with the J-PARC experiment. A completely different approach is to build two identical reactor neutrino experiments at different baselines and use the near/far ratio to look for θ_{13}, which may also have a similar sensitivity.

Beyond the discovery and measurement of θ_{13}, the next target will be the CP violation. The CP violation in neutrino oscillation appears as a difference between the oscillation probabilities of neutrinos and anti-neutrinos, which is possible only in the appearance channel if CPT is assumed. Within the three-generation framework, it is given by

$$\begin{aligned} P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = &-16\, s_{12}\, c_{12}\, s_{13}\, c_{13}^2\, s_{23}\, c_{23}\, \sin\delta \\ &\times \sin\left(\frac{\Delta m^2_{12}}{4E}\, L\right) \sin\left(\frac{\Delta m^2_{13}}{4E}\, L\right) \sin\left(\frac{\Delta m^2_{23}}{4E}\, L\right). \end{aligned} \tag{3}$$

Therefore it is sizable only if the baseline is long enough to see the effect of Δm^2_{12}, and if all angles are large enough. After the SNO and KamLAND results, the evidence is strong for large Δm^2_{12}, and θ_{12} and θ_{23} are known to be near maximal. Therefore, all elements except for θ_{13} are in favor of large CP violation. For all conventional neutrino beam designs studied so far, the sensitivity to the possible CP violation will be basically lost if $\sin^2 2\theta_{13}$ is less than 0.01. If it is larger, we have a chance to detect CP violation.

One proposal is to upgrade J-PARC from 0.75 MW to 4 MW, while building a 1 Mt water Cherenkov detector (Hyper-Kamiokande) near the Super-Kamiokande site. The off-axis NuMI program may also evolve to accommodate a higher power beam aiming at CP violation. BNL has a Letter of Intent for a wide-band very long baseline neutrino beam ($\sim$2700 km) with an upgrade of the AGS to 1 MW and a 0.5 Mt water Cherenkov detector. A very different concept is the CERN Super Proton Linac (SPL), based on accelerating protons using the LEP cavities, and sending them to Fréjus. The beam energy is much lower, about 0.25 GeV, and the distance is also shorter, 130 km. Shorter baseline and lower energy in general have the advantage of cleaner kinematics (dominated by quasi-elastic events) and little matter effect contamination to isolate CP violation, while suffering from very low event rate.

If θ_{13} is smaller, the only chance of detecting θ_{13} and discovering CP violation would be to build a neutrino factory based on a muon storage ring. This has the unique capability of producing intense *electron*-neutrino beams with the sign of choice, and one can look for muon appearance, greatly simplifying the demand on the detector design. The cooling of muons is the major obstacle in designing such a facility, and R&D is under way toward the MICE experiment with significant LBNL involvement.

On the solar neutrino front, the most likely outcome is that the LMA solution will be fully established by more data from SNO and KamLAND. If an oscillation dip is seen, then the oscillation hypothesis becomes unambiguous, and Δm^2_{12} will be well measured. The rest of the section assumes this is the case. On the other hand, θ_{12} will not be as well determined. The precise measurement of θ_{12} is a motivation for studying lower energy solar neutrino components whose fluxes are predicted with better accuracy. There is also interest in testing solar astrophysics, and the unitarity test of the MNS matrix. It is important to realize, however, that the solar neutrino experiment will not observe the oscillation, as the matter effect is purely adiabatic in the LMA region and the neutrinos are incoherent. The exception to this statement is that solar experiments, such as SNO, will be able to resolve matter affects for some of the anticipated LMA region through the day/night or zenith angle dependence of the solar neutrinos.

The next solar neutrino experiment likely to collect data is Borexino, which houses 300 t of liquid scintillator in Gran Sasso. It will look for the elastic scattering of the solar neutrinos down to about 250 keV, enabling the measurement of the monochromatic neutrino flux from electron capture on ^{7}Be in the Sun. It has achieved an impressive radiopurity in the scintillator to suppress the radioactivity background, while it was set back by a krypton problem as well as by the spill of the scintillator. The experiment is currently "on hold". Once running, it will detect ^{7}Be at high statistics ($\sim$20 events/day) and will determine its flux much better than the theoretical uncertainty of 7%. KamLAND, once upgraded to remove krypton and clean the liquid scintillator, will have even higher statistics. For the LMA solution, the survival probability of the ^{7}Be neutrino is essentially $\sin^2\theta_{12}$, and hence will provide a 7% measurement of the mixing angle $\sin^2\theta_{12}$.

Several solar experiments to study even lower energy components are under discussion. Especially the so-called pp neutrinos are of great interest as their flux is linked tightly to the solar luminosity and has a very small uncertainty ($< 1\%$) in its prediction. For the LMA solution, the survival probability of the pp neutrino is essentially $1 - \frac{1}{2}\sin^2 2\theta_{12}$, and hence will provide a precise measurement of the mixing angle. It will be useful in extracting the CP violating phase δ if observed with long baseline experiments. These experiments face challenging technological aspects which would greatly benefit from the active participation of a national laboratory, and also provide a wide spectrum of physics topics, as opposed to single purpose measurements or experiments.

2.1.3 Future of neutrino oscillations (LSND true)

If MiniBooNE observes ν_e appearance from the Booster neutrino beam, a period of complete confusion and excitement begins. The first step would be to repeat MiniBooNE in the anti-neutrino beam to test systematic issues. The next step is to build another detector with a different baseline on the same beamline (BooNE) and study the baseline dependence of the appearance rate.

As explained above, the combination of currently available oscillation data disfavors the explanation of the LSND data using a sterile neutrino. One possible remedy is that some of the older experiments were in error. This brings up renewed interest in short baseline neutrino oscillation experiments. Given the relevant range $\Delta m^2_{\rm LSND} = (0.1-1)\,{\rm eV}^2$, baselines of 1–10 km would be interesting, even 100 km if looking for τ appearance. In addition to using a muon neutrino beam, appearance from the electron neutrino beam needs to be studied, eventually calling for a small-scale neutrino factory. The unitarity test with the solar pp neutrinos will also help understand the number of sterile species.

Another possibility is that CPT is violated. In this case, all existing oscillation data needs to be reexamined. For instance, the apparent concordance between the solar neutrino data and KamLAND must be reconsidered. This will give a much stronger case for the low energy solar neutrino experiments. For example, Borexino and KamLAND (solar neutrino) can exclude parameter regions for $\Delta m^2_{12} = (10^{-11} - 10^{-5})\,{\rm eV}^2$ at large angles using day/night effect and seasonal variation without relying on CPT and KamLAND (reactor).

2.1.4 Absolute neutrino mass and its nature

Currently the best limit on the neutrino mass comes from the end point spectrum of tritium beta decay. The Particle Data Group quotes the upper limit of 3 eV on the electron anti-neutrino mass. Once combined with observed small mass-squared differences in the solar, atmospheric, and reactor neutrino oscillation data, all three neutrino species must be below 3 eV. This upper limit still allows for $\Omega_\nu \sim 20\%$, relevant for structure formation. The limit from cosmology is currently about 1.5%. It is not easy to improve this limit from the large-scale structure as the effect of the neutrinos is correlated with other cosmological parameters and the initial spectrum of the density perturbation; a better limit or measurement from the laboratory is called for. Currently KATRIN is the only proposal to improve this limit further using the tritium end point, possibly down to a few times 0.1 eV level.

Another crucial question is if the neutrino is of Majorana or Dirac type. In the case of Dirac neutrinos, we introduce new degrees freedom to the Standard Model, namely right-handed neutrinos, which do not have charges under any of the Standard Model gauge groups. Lepton number is conserved in this case. On the other hand, we do not introduce any new light degrees of freedom in the case of Majorana neutrinos, but rather identify right-handed neutrinos with anti-neutrinos, and hence violate lepton number. For more than twenty years, the theoretical bias has been in favor of Majorana neutrinos. This is because of the so-called see-saw mechanism that explains the small neutrino mass due to the mixing between the light left-handed and the ultra-heavy right-handed Majorana neutrinos as $m_\nu \sim m_D^2/M \ll v$, where m_D is a typical order of magnitude of quark and lepton masses, M is the mass of the right-handed neutrinos, and $v \sim 250\,\text{GeV}$ is the electroweak scale. The atmospheric neutrino mass scale for the third generation, combined with a naive estimate $m_D \sim m_t$ gives $M \sim 10^{15}\,\text{GeV}$, tantalizingly close the energy scale where the gauge coupling constants unify in the Minimal Supersymmetric Standard Model. Most Grand Unified Theories prefer Majorana neutrinos for this reason. However, new theoretical ideas, such as extra dimensions or supersymmetry breaking, explain small neutrino mass even for the Dirac case. Leptogenesis, which explains the cosmic baryon asymmetry, also used to rely on the Majorana neutrinos and the see-saw mechanism, but it is possible with Dirac neutrinos as well. We will not know how to extend the Standard Model to incorporate the finite mass of neutrinos unless we know if the neutrino mass is of Dirac or Majorana type.

Currently the only promising approach to discriminate Dirac and Majorana neutrinos are neutrinoless double beta decay experiments. They look for the lepton number violation in the decay of heavy nuclei, $(A, Z) \to (A, Z+2) + 2e^-$, with no accompanying electron anti-neutrinos. The rate for neutrinoless double β decay ($0\nu\beta\beta$) can be written as

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu}\,|M^{0\nu}|^2\,\langle m_{ee}\rangle^2\,, \tag{4}$$

where $G^{0\nu}$ is a calculable phase space factor, $M^{0\nu}$ is the matrix element for the transition (typically known to an order of magnitude), and the “effective neutrino mass”, $\langle m_{ee}\rangle$, is the ee component of the Majorana neutrino mass matrix. In the three generation framework,

$\langle m_{ee} \rangle = |\Sigma_{i=1}^{3} m_i U_{ei}^2|$. Measuring $0\nu\beta\beta$ requires a superb energy resolution to separate the spike at the endpoint from the two-neutrino double beta decay continuum. Many choices of nuclei and detection methods have been suggested. So far only the Heidelberg-Moscow experiment, using Ge detectors, has reported a positive signal. It caused a heated debate in the community. It translates to $\langle m_{ee} \rangle \sim (0.4 - 1.3)\,\mathrm{eV}$. Cuoricino and Mini-GENIUS, under construction, are expected to settle this issue.

The results of oscillation experiments suggest a minimum neutrino mass that the next generation of $0\nu\beta\beta$ experiments may be able to probe. If the mass spectrum is the inverted hierarchy, which the long baseline experiments can demonstrate if true, the two neutrino states with the solar mass splitting have the mass at least the square root of the atmospheric mass splitting m_1, $m_2 > (\Delta m^2)^{1/2} > 0.04\,\mathrm{eV}$. Even if U_{e1}^2 and U_{e2}^2 have the opposite sign, they cannot completely cancel, because the SNO solar neutrino results have excluded the maximal mixing angle. Therefore, in this case, a sensitivity down to $0.01\,\mathrm{eV}$ would discover or exclude that neutrinos are Majorana. Another interesting case is if the neutrino mass is measured in tritium beta decay. Then the three neutrinos have to be more-or-less degenerate, and again $\langle m_{ee} \rangle$ cannot be too small. On the other hand, if the mass spectrum is the normal hierarchy, $\langle m_{ee} \rangle$ can be extremely small even if the neutrinos are Majorana, and in this case it is possible that none of the proposed experiments would see a signal.

Summary The most outstanding open questions related to neutrino properties are (i) the nature of neutrinos and their absolute mass scale, which can be attacked by neutrinoless double beta decay (a signal is probably observable in case of inverted hierarchy or degenerate neutrinos, while not in the case of normal hierarchy); and (ii) the value of θ_{13}, since it is the only mixing angle not yet observed, and its value is critical to deciding whether CP violation in the lepton sector may be observable.

2.2 Neutrino astrophysics: neutrinos as messengers

Because neutrinos interact only weakly, they emerge rapidly from optically opaque regions, providing information directly related to primary astrophysical events and processes. We can therefore "see deep" with neutrinos, both into the dense core of astrophysical objects, and into far away regions in space from which high energy particles or photons cannot reach us due to absorption along the way. A spectacular example is the observation of a neutrino burst from the supernova SN1987A, in the Large Magellanic Cloud. The neutrino burst lasted for only a few seconds, whereas the optical signal peaked several hours later, when the explosive expansion arrived at an optically thin state. The estimates of galactic type-II supernovae vary from one every 10 years to perhaps 50 years. A High-statistics measurement of the neutrino energy spectrum and time profile would provide useful tests of our understanding of the explosion mechanism.

In addition, the study of solar neutrinos has demonstrated that neutrinos are useful quantitative astrophysical probes, which was described in the context of neutrino oscillations above. Real-time solar neutrino experiments are also capable of detecting neutrinos from a supernova.

A qualitative picture of the various sources of neutrinos emerges. At the lowest energies (MeV scale) the Sun is the principal source, followed by a smaller contribution from radioactivity in the Earth. At GeV–TeV scales, neutrinos are predominantly produced by cosmic-ray induced showers in the Earth's atmosphere. These are most easily detected using the Earth as a shield by requiring that the muon daughter of neutrino-nucleon interactions be up-going. These neutrinos should be isotropic. At higher energies still (>100 TeV), large detectors could begin to be sensitive to the diffuse neutrinos produced by galactic cosmic rays, which are most abundant in this energy range. Finally, at extremely high energies (PeV–EeV) kilometer-scale detectors would become sensitive to point sources of the highest energy cosmic rays.

2.2.1 High energy neutrinos of cosmic origin

The main interest in studying very high energy neutrinos is to understand the origin of the high energy cosmic rays. The most compelling motivation is the fact that cosmic rays with energies beyond 10^{17} eV have been observed. These cosmic rays are presumed to be extragalactic because their momentum is much too high to be contained by galactic magnetic fields. Collisions of protons with any interstellar particles will lead ultimately to neutrino production through pion decay. Yet, even after decades of study, fundamental uncertainties remain about the sources and acceleration mechanisms of ultra-high energy cosmic rays.

Above TeV energies, muon detectors with good angular resolution can image the neutrino source, perhaps providing information about the production process through companion optical measurements. A characterization of the almost completely uncharted high energy neutrino sky may provide genuine surprises. There are many cosmological candidates for accelerating cosmic rays to extremely high energies: compact objects with extremely high fields (e.g., Active Galactic Nuclei, BL Lacertae, pulsars), extended objects with lower fields (supernova remnants), and powerful explosive shock waves (gamma ray bursts).

Supernova remnants can plausibly accelerate protons up to 1000 TeV. Beyond this energy, there are no candidate sites in our galaxy. The cosmic rays do not point back to their sources (except at ultra-high energies) because of the galactic and extra-galactic magnetic field, and we do not know where they come from. Above 10 TeV, photons from extra-galactic sources do not reach us because of the absorption on background photons. Neutrinos are a unique probe of sources of high energy cosmic rays, as they point back to their sources and are not absorbed even at the highest energies far beyond the most energetic cosmic rays observed to date. However, because of the low event rates, a km-scale detector appears to be the minimum requirement for this goal. IceCube, at the South pole, and several experiments in the Mediterranean are planned to reach this size.

Some models of active galactic nuclei (AGN) produce high energy neutrinos in the 100 TeV range. The jets from the blazers are often assumed to be of leptonic origin, but the underlying engine supporting jet creation may contain hadrons. Detection of neutrinos in the 1–1000 TeV range would address this question. If about half of the power in AGN jets goes into acceleration of hadrons and if the energy spectrum is fairly flat, a km-scale detector can observe neutrinos from this potential source.

Gamma-ray bursts (GRB) are another possible source of high energy cosmic rays. The fireball models for GRBs assume and exploding relativistic gas of electrons, which should not contain too many hadrons. However, a small amount of baryons may account for high energy cosmic rays and, if so, about ten neutrino events at 100 TeV energies may be detected at km-scale detectors. The collapse of massive stellar progenitors may add more to the ultra-high energy neutrino events.

There are also diffuse components of high energy neutrinos. For example, ultra-high energy cosmic rays interact with the cosmic microwave background and produce pions. Their decays produce very high energy neutrinos (GZK neutrinos), producing about one event per year at km-scale detectors.

The general arguments can be turned into a bound on high energy neutrino production. By considering typical photon densities in optically thin sources, Waxman and Bahcall estimated the bound on very high energy neutrino production from photo-pion production. The high energy neutrino fluxes implied by Waxman-Bahcall bound are quite small, $E^2\,\mathrm{d}N/\mathrm{d}E = 5\times10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$, such that km-scale neutrino detectors are required.

2.2.2 Dark matter: WIMPs

Recent cosmological measurements of the cosmic microwave background, large scale structure of galaxies, and Type Ia supernovae have led to a remarkably concordant picture of the structure of the Universe. In this picture, approximately 30% of the critical density of the Universe consists of dark matter of unknown origin. Weakly interacting massive particles (WIMPs) comprise one candidate for the dark matter. The WIMPs and their antiparticles are stable relics from the very early epoch of the Big Bang.

TeV-scale dark matter particles in the halo may be gravitationally trapped by the Sun, sink to the core, get accumulated, and annihilate. The annihilation process most of the time produces high energy neutrinos in the 10–1000 GeV range. Neutrino detectors can look for this signature from the Sun. They can also look for a signal from the center of the Earth, although the Edelweiss direct detection limit suggests that such a signal will not be observed. Observing neutrinos from WIMP annihilation is an indirect method. Contrary to the direct detection methods, where the event rate goes down linearly as the mass of the dark matter increases, the rising neutrino cross section compensates the decrease in the flux and the event rates for indirect detection remain roughly constant for heavy dark matter particles. In the case of neutralino dark matter in supersymmetric models, km-scale detectors cover a wide range of the parameter space.

2.2.3 Very high energy neutrino detectors

As noted, the product of anticipated flux and cross-section indicates that a km-scale detector is required. Cost requirements then dictate that the active detector medium be free, and thus the only practical choices are either very clear water (in either solid or liquid state) or the atmosphere. Of the atmospheric detectors nearing completion, the Pierre Auger Project is the most advanced. However, its energy and angular range for neutrino detection limits its sensitivity. For the long term, space-based air fluorescence detectors, OWL and EUSO, hold out the prospect of enormous fiducial volumes and a high sensitivity for ultra high energy neutrino detection. (UC Berkeley is participating in EUSO.) For the near term, however, the most promising technique for neutrino detection involves instrumenting very large volumes of clear water or ice with strings of photomultiplier tubes to detect the Cherenkov light from the charged products of neutrino interactions.

The pioneering project to explore this technique was the Deep Underwater Muon and Neutrino Detector (DUMAND), which was to be deployed in the deep water off the Hawaiian coast. Due to deployment difficulties and reliability issues, the DUMAND project was canceled before it was able to establish neutrino detection.

At present, there are two operating water Cherenkov neutrino detectors: the Lake Baikal detector deployed in a deep Russian lake, and the AMANDA detector deployed in the ice at the South Pole. AMANDA is the more sensitive of the two. Its current version consists of over 600 photomultiplier modules arranged on 19 stings. These are deployed at depths of 1300 to 2300 meters. Even at these depths, the muons from cosmic rays showering in the atmosphere overwhelm the neutrino signal for zenith angles down to the horizon. However, by selecting upgoing muons, AMANDA has demonstrated the detection of atmospheric neutrinos, thus establishing the feasibility of neutrino telescopes for astrophysics.

AMANDA is also considered a proof-of-principle for proceeding to a true kilometer-scale detector, IceCube. IceCube uses similar technology to AMANDA, the principal difference being that PMT signals are digitized locally in the optical module before being transmitted over cables to the surface. This reduces signal degradation and improves the noise performance. IceCube will consist of 80 strings of 60 optical modules each. Deployment is scheduled to begin in the 2004–5 austral summer season, and should be complete approximately six years later. IceCube will have sufficient sensitivity and resolution to discover astrophysical point sources of neutrinos such as active galactic nuclei and gamma-ray burst sources if some of the current models of these objects are approximately correct. Because the ice contains no radioactivity and is therefore a low-noise environment, AMANDA and IceCube are sensitive to a supernova explosion in the galaxy.

In addition to the South Pole station activity, a European collaboration is now actively constructing ANTARES, an array of optical modules deployed in the deep Mediterranean sea off Marseille. ANTARES will consist of 10 strings and a total of 1000 optical modules. The active area is approximately $0.1\,\mathrm{km}^2$. ANTARES is scheduled for completion in 2005.

Just as AMANDA was a first step to constructing IceCube, ANTARES is expected to lead to a true kilometer-scale follow-up detector to be deployed in the Mediterranean. One such study, called NEMO, is considering a site off Sicily, although the exact nature of the collaboration, design, and site for a kilometer-scale detector will evolve with more ANTARES experience. NESTOR has one stage of its tower design ready for deployment at an excellent site near Pylos, Greece. The European community is seeking to establish a coherent approach among all the various efforts to move toward the km-scale.

It is worth pointing out the complementarity of AMANDA/IceCube and ANTARES/NEMO. From an astrophysics perspective, both detectors are needed to achieve full-sky coverage. The Mediterranean detectors, for example, are sensitive to the AGN in our own galaxy. From a detector perspective, the two sites face different challenges. At the South

Pole, the ice is extremely transparent but suffers from a relatively short scattering length. The strings, once deployed, are extremely stable but cannot be accessed after deployment for repairs or modifications. By contrast, the sea water has more optical absorption but almost no scattering. The optical modules suffer from high background rates due to Potassium 40 in the seawater and to some extent, obscuration from bio-fouling. The strings are less stable since they respond to ocean currents but can be accessed for repair or modification.

Summary The present and planned neutrino detectors are opening a new window on the sky. Historically, the advent of new instruments has always led to new discoveries and neutrino telescopes hold the promise of new insights into some of the most energetic, violent, objects in the Universe, including perhaps the origin of the ultra high energy cosmic rays.

3 Neutrino Science at LBNL

LBNL has a strong program in neutrino science that addresses a number of scientific topics discussed above. The current efforts are described here, ordered according to their status — experiments in progress or recently funded or submitted proposals. A summary table connects each of these projects to the scientific topics. R&D projects conclude this section.

3.1 Experiments in progress

3.1.1 SNO

The field of solar neutrino research has provided significant new information on the properties of neutrinos. In particular, the Sudbury Neutrino Observatory (SNO) has recently produced a model-independent demonstration that solar neutrinos undergo flavor transformation.

SNO is a 1000-ton heavy water Cherenkov detector. It was designed to address the long-standing solar neutrino problem, the observed deficit of ν_e. Its use of D_2O as target enables the simultaneous measurements of the ν_e flux from ^{8}B decay in the Sun and the total flux of all active neutrino species through the charged-current and the neutral-current interactions on the deuterons. Assuming the standard ^{8}B shape, the ν_e component of the ^{8}B solar neutrino flux and the total flux differ by 5.3σ, thus providing strong evidence for flavor transformation in the solar neutrino sector. The total active neutrino flux is measured with the neutral-current reaction at a neutrino energy threshold of 2.2 MeV. This flux is consistent with solar model predictions. A precise measurement of the NC/CC ratio may provide a 5–10% measurement of $\sin^2\theta_{12}$. SNO is also detecting atmospheric neutrinos, searching for hep and solar anti-neutrinos, and has unique modes for detecting proton decay.

SNO can also detect supernovae. Neutrinos are believed to be the primary driver for the explosion and provide the most sensitive probe of core collapse physics, including the explosion mechanism, proto neutron star cooling, quark matter, and black hole formation. Since the couplings of ν_e, $\overline{\nu}_e$, and ν_μ/ν_τ are different, the various flavors decouple at different temperatures and thus have characteristic energy distributions. This, coupled with the high densities in supernovae, leads to the possibility of flavor oscillations playing an important role in the supernova evolution. Studies of the neutrino arrival time, energy spectra, and flavor composition allow us to carry out mass measurements with a potential sensitivity of a few eV and to understand the mass hierarchy and flavor transformations.

As for the operation and future plans of SNO, the D_2O lease and current run plans for SNO Phase-III extend into 2006. Longer term options for running SNO or hybrid detector designs aimed at detecting additional oscillation handles are being discussed by the collaboration.

Solar neutrino experiments (coupled with an understanding of neutrino properties) provide a stringent test of the SSM. To provide much more sensitive tests of the SSM, precision measurements of the total flux of the low energy pp and ^{7}Be neutrinos are required.

At present the SNO group at LBNL consists of Lesko, Chan, Heeger, Marino, Norman, Poon, Stokstad, and a UCB student. The group maintains strong involvement and high visibility within the SNO collaboration. Lesko is chairman of the SNO executive board. LBNL plays a major role in the data analysis and analysis coordination.

3.1.2 KamLAND

For three decades experiments measuring the flux of neutrinos from the Sun have observed deficits indicating that neutrinos are not stable in time and can oscillate into other types of neutrinos. Previous experiments trying to verify this result with reactor neutrinos failed to find an effect. The solar neutrino experiments indicated that these experiments at about 1 km were too close to the reactors. KamLAND (Kamioka Liquid Scintillator Anti-Neutrino Detector) is located in the Kamioka mine in Japan. With 1000 tons of light-emitting liquid target viewed by 1879 50-cm diameter photomultiplier tubes, KamLAND is the largest scintillation detector ever constructed. In December 2002, KamLAND reported first evidence for the disappearance of reactor electron anti-neutrinos. In the 50-year long history of reactor neutrino physics KamLAND is the first experiment to measure a deficit of neutrinos from distant reactors at 180 km away on average. This result combined with previous solar neutrino experiments is evidence for neutrino oscillation. KamLAND's first experimental goal, the measurement of the anti-neutrino flux from reactors in Japan and Korea has been achieved. The next goal of KamLAND is the search for direct evidence for neutrino oscillations in the spectral signature of reactor neutrinos.

The nominal duration of the first phase of operation of the KamLAND experiment is 3 years, starting at the beginning of 2002. With reduced backgrounds, KamLAND may be able to measure ^{7}Be solar neutrinos in a future phase of the experiment. This future phase is not yet funded in the US, but a study investigating the physics potential of a ^{7}Be solar neutrino measurement at KamLAND is in preparation. As mentioned above, this experiment could establish a $\sim$10% measurement of $\sin^2\theta_{12}$ if the value of Δm^2 ultimately measured by SNO and KamLAND is below 1×10^{-4} eV^2.

The effort on KamLAND is supported by both the Nuclear Science and Physics Divisions and has participants from UC Berkeley as well. The funding for the US KamLAND collaboration is managed by LBNL/UCB. Because of joint support from DOE HEP and DOE NP, KamLAND serves as a "model" for future experiments that have participants from both

NSD and PD and for which shared support makes it easier for each agency to make that critical initial financial commitment. At present the KamLAND group includes Freedman, Berger, Chan, Decowski, Fu, Fujikawa, Goldman Heeger, Lesko, Luk, Murayama, Nygren, Poon, Steiner, and several students. Freedman is the US KamLAND co-spokesperson and DOE principal investigator.

3.1.3 CUORICINO

CUORE (Cryogenic Underground Observatory for Rare Events) is a proposed array of 1000 cryogenic thermal detectors of TeO_2, of a mass of 760 g each, to investigate rare events, in particular, double beta decay and non-baryonic dark matter. A first step toward CUORE is CUORICINO, which consists of one of the 25 towers of forty 750 gm TeO_2 bolometers that will be used in the full-scale CUORE project. CUORICINO has been mounted in the Gran Sasso Laboratory (LNGS) and is at present the largest operating cryogenic detector. It contains approximately 8 kg of ^{130}Te. The most conservative nuclear structure calculations imply that ^{130}Te is 2 times more sensitive to neutrino mass than ^{76}Ge, so that CUORICINO is equivalent to at least 16 kg 86% enriched ^{76}Ge. CUORICINO has sufficient sensitivity to check within a year's operation the recently claimed (and widely disputed) observation of a peak arising from the double beta decay of ^{76}Ge. Successful operation of CUORICINO will result in the submission of the full CUORE proposal.

The LBNL staff that are currently involved with CUORICINO are: Norman, McDonald, and Smith (NSD); Beeman and Haller (MSD).

3.1.4 AMANDA

AMANDA (Antarctic Muon and Neutrino Detector Array) uses the 2.8 km thick ice sheet at the South Pole (and the rock beneath it) as a neutrino target, Cherenkov medium and cosmic ray flux attenuator. The detector consists of vertical strings of optical modules — photomultiplier tubes sealed in glass pressure vessels — frozen into the ice at depths of 1300–2300 m below the surface. The scientific goals for high energy neutrino telescopes and for AMANDA in particular were described in Section 2.2. Results from AMANDA addressing these goals have recently been published.

AMANDA began collecting data with ten strings in 1997 and by 2000 included 19 strings. AMANDA includes a fully digital string ("String 18") which is the prototype of the new technology to be included in IceCube. String 18 was developed at LBNL. The AMANDA/IceCube group consists of personnel from the Physics, Nuclear Science, NERSC and ICSD divisions. Current members include Carithers, Goldschmidt, Lamoureux, Matis, McParland, Nygren, Patton, Przybylski, Stokstad, and several guests. The majority of the group's effort is now directed toward IceCube. Buford Price's group at UCB is also involved in both AMANDA and IceCube.

3.2 Recently funded or submitted proposals

3.2.1 IceCube

The successful deployment and operation of the AMANDA detector have shown that the Antarctic ice sheet is an ideal medium and location for a large neutrino telescope. The detection of atmospheric neutrinos in agreement with expectations established AMANDA as a neutrino telescope. Searches for neutrinos from supernovae, dark matter, point sources of muon neutrinos and sources of high energy electron, and muon neutrinos have demonstrated the physics potential of a deep ice neutrino detector. However, a much larger detector is needed to reach a sensitivity required for the detection of many predicted neutrino fluxes. IceCube is a future under-ice neutrino detector consisting of 4800 PMTs on 80 strings distributed over an area of $1\,\mathrm{km}^2$ and instrumented at a depth between 1400 m and 2400 m. A surface air-shower detector consisting of 160 stations over $1\,\mathrm{km}^2$ augments the deep-ice component by providing a tool for calibration, background rejection and air shower physics.

One of the principal objectives of IceCube is the detection of sources of high energy neutrinos of astrophysical origin. IceCube is sensitive to all neutrino flavors over a wide range of energies. Muons can be observed from about 10^{11} eV to 10^{18} eV and beyond. Cascades, generated by ν_e, $\overline{\nu}_e$, ν_τ, and $\overline{\nu}_\tau$ can be observed and reconstructed at energies above 10^{13} eV. Tau events can be identified above energies of about a PeV. Interactions with the Earth will modulate the neutrino fluxes emerging at an underground detector.

Funding for IceCube in FY02 ($15M) and FY03 ($25M) has been obtained. IceCube attained MRE (Major Research Equipment) status in the FY 04 President's budget submission. The first deployment at the South Pole is scheduled for FY05 and construction should be completed in another 6 years. The current IceCube effort at LBNL comprises about 12 FTE. LBNL responsibilities for IceCube include the Data Acquisition System and software architecture. Members of the LBNL group are listed in Section 3.1.4.

3.2.2 MICE

LBNL staff from AFRD and Engineering are participating in preparations for the International Muon Ionization Cooling Experiment (MICE). The experiment involves fabricating and installing several cells of a realistic cooling channel (comprising high-field superconducting solenoids, liquid-hydrogen energy absorbers, and high-gradient, normal conducting RF cavities) in a beam of roughly 200 MeV/c muons and measuring the channel's properties using standard particle-physics single-particle measurement techniques. An upstream and a downstream solenoidal spectrometer, with tracking devices and particle identification capability, will be used to characterize the "beam" emittance before and after the cooling channel. The experiment is intended to produce roughly a 10% emittance reduction that will be measured to a precision of 0.1%.

A Letter of Intent was prepared last year for both Paul Scherrer Institute and Rutherford Appleton Laboratory (RAL), two labs with the ability to provide a muon beam suitable for the experiment. After discussions, RAL gave a favorable response and asked that a formal proposal be submitted. This has now been done, and an international review of the proposal took place at RAL in February, 2003. LBNL is one of a number of US institutions that has joined the proposal. LBNL is also part of the US funding proposal for MICE submitted to NSF in September, 2002, participating as a subcontractor to the Illinois Institute of Technology. LBNL staff members have carried out the initial design of the cavities and the solenoids, and provided the cost estimates and time lines for their fabrication.

The scale of this experiment provides an opportunity for PD and or NSD staff to become involved at a significant level. The measurements are based on single-particle counting techniques involving tracking detectors, particle identification, time-of-flight determination, and the like — just the techniques that PD and NSD scientists utilize routinely. Having one or two graduate students or post-docs able to work on the experiment would give LBNL a significant presence, and some "credentials" to become involved in a future neutrino factory scientific program, and at an affordable cost. A small experiment such as MICE is an ideal training ground for students. Indeed we should look for ways of supporting postdocs and students to work in an area that will become a critical ingredient in the community's long-term accelerator research and neutrino science programs.

The current effort level, suitable for carrying out the initial design work, is roughly 1.5 FTE, shared equally between AFRD and Engineering. Our commitment for MICE is to provide the 8 RF cavities required for the experiment, along with the two high-field, large bore "coupling" solenoids. This would involve some $6M worth of work at LBNL along with overseeing about $2M in work being carried out at the University of Mississippi in support of the RF cavity fabrication. LBNL has been very visible in the MICE Collaboration, providing one member of the International Steering Committee (Zisman) and two of the MICE Technical Conveners (Green for magnets and Li for RF systems). Zisman was selected to present the accelerator physics aspects of MICE for the LOI review at RAL in March, 2002, and also presented it at the recent proposal review.

Summary Table 1 shows the existing neutrino projects at LBNL and the key physics topics that are addressed in each of these experiments. Also shown is the involvement of the three divisions (AFRD, NSD, and PD) in the current neutrino effort at LBNL.

3.3 Research & development

3.3.1 Neutrino factory

The scientists and engineers in AFRD have unique expertise to contribute to Neutrino Factory R&D. There is considerable experience in designing superconducting magnets of all types, including dipoles, quadrupoles, and solenoids, in the design of high-power RF cavities, the design of ring lattices, particle tracking and dynamic aperture calculations, and the analysis of coherent instabilities. The experience and understanding of the underlying physics needed to design the Front End of a neutrino factory as well as in the overall design of complex facilities is demonstrated in the low energy ring of the PEP-II B Factory, presently one of the world's highest current positron storage rings. This research complements the AFRD work on linear colliders and it clearly builds upon the core competency of LBNL in

		Existing Projects				
Physics	Topics	**SNO**	**KamLAND**	**Amanda/ IceCube**	**Cuoricino**	**MICE**
I. Neutrinos from the Universe	High Energy Neutrinos			▨		
	Solar Astrophysics	▨				
	Solar Neutrinos	▨				
	Supernovae	▨	▨	▨		
	Relic Neutrinos					
II. Mechanism of Flavor Transformation	Neutrino Flavor Change	▨	▨			
	MSW Effect	▨	▨			
	Neutrino Oscillations	▨	▨			
	Sterile Neutrinos	▨	▨			
III. Mixing & Mass Matrix	theta(12)	▨	▨			
	deltam2(solar)	▨	▨			
	theta(13)					
	CP Violation in Neutrino Sector					
	theta(23)					
	deltam2(atm)					
	Absolute Mass Scale				▨	
IV. Nature of Neutrinos	Majorana or Dirac				▨	
V. Geophysics	geo neutrinos		▨			
VI. Future Accelerators	Muon Cooling Techniques					▨
LBNL Divisions	*Accelerator&Fusion Research*					▨
	Physics		▨	▨		
	Nuclear Science	▨	▨	▨	▨	

Table 1: Overview of present neutrino projects at LBNL grouped according to physics goals. Also shown is the involvement of the three divisions, AFRD, NSD, and PD.

accelerator physics and engineering. In addition, the theoretical work nicely complements AFRD work on more conventional accelerators and on SciDAC.

Work on a Neutrino Factory can be separated into the following areas: target and capture section, decay and phase rotation channel, bunching and cooling section, acceleration section, and storage ring. The first three areas are collectively referred to as the "front end." This is the broad area that is presently the main focus of LBNL activity. All front end systems require high-gradient radio frequency (RF) systems operating at relatively low frequency (a few hundred MHz) and superconducting solenoids operating at fields of about 5 T. Design of the Front End system requires considerable expertise in complex physics simulations, and LBNL plays a role here as well, working in close collaboration with UC Berkeley scientists.

LBNL, along with BNL and FNAL, is one of the sponsoring laboratories of the Neutrino Factory and Muon Collider Collaboration (MC), and serves as lead laboratory for this effort. LBNL provides the project manager, three scientists to serve on the MC Executive Board and one scientist to serve on the MC Technical Board. (Previously the collaboration spokesperson and the leader of the simulation and theory group were from LBNL.) The present level of effort is small, roughly 1.5 FTE. The experimental R&D program is described above in the section on MICE. The R&D effort for a Neutrino Factory, both at LBNL and community-wide is severely hampered by funding limitations.

Personnel involved are Sessler, Wurtele, and Zisman.

3.3.2 Next generation solar neutrino experiment

The ^{8}B neutrinos seen by SNO and Super-Kamikande represent $\sim 3 \times 10^{-5}$ of the total flux of solar neutrinos. However, the confirmation of this small branch of neutrinos has permitted a careful calibration of solar models and it is commonly held that the sun is now a calibrated source of neutrinos to the 1% level. The measurement of the pp neutrinos, the lowest energy solar neutrinos will permit at least three important fields to be pursued: (i) the measurement of low energy neutrinos will permit us to obtain crucial information on neutrino oscillations and the determination of mixing angles, possible magnetic moments; (ii) these same neutrinos will enable a careful test of solar models to new levels of precision; and (iii) the use of this well calibrated neutrino source will enable tests of unitarity of the MNS neutrino oscillation matrix and enabling searches for sterile neutrino species.

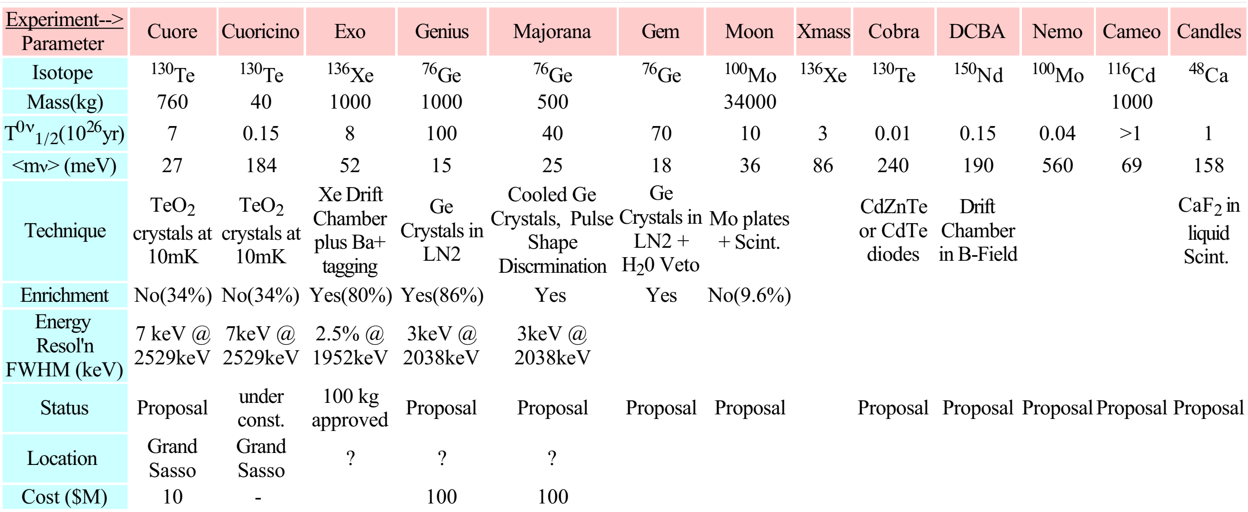
In order to measure low energy neutrinos new technologies, advance detectors, and special laboratory environments are required. An LDRD proposal for R&D on next generation solar neutrino experiments was initially funded at the end of FY02. The proposal is being used to investigate a new detection technology using superfluid helium as a detector medium for low energy solar neutrinos (the HERON concept). The first focus will include detailed Monte Carlo simulations of detector materials and research into state-of-the-art levels of radioactive contamination in these materials to produce an optimized detector design for the detection of neutrinos. These studies include the localized environmental factors likely to be encountered at the National Underground Scientific and Engineering Laboratory (NUSEL), specifically the muon intensities and secondaries resulting from cosmic ray muons in the native rock and within the detector materials. Following these studies an active R&D program in superfluid helium detectors will be conducted and will concentrate on detector readout techniques for the scintillation light. A major focus of this detector R&D will be on resolving intrinsic radioactive backgrounds and neutrino signals and obtaining optimal event reconstruction. In later years of the program we envision the fabrication of a proof-of-principle detector for early deployment at NUSEL to confirm operational aspects of the detector, signal to background ratios and environmental backgrounds signals, and initial investigations into operational aspects of large cryogenic detectors in the NUSEL environs.

This LDRD effort is pursued by Lesko, Chan, and Poon (NSD).

4 Opportunities

The opportunities in neutrino science discussed here are all suitable for LBNL in that they are matched to our strengths, and the Laboratory could make a significant contribution to the experiment, program, or facility. They represent candidates for consideration in planning our future, items for which decisions or choices are needed. Ongoing effort representing present commitments is not listed here, even though it is equally important for the future. Thus, IceCube, MICE and the AFRD R&D program are not discussed in this section.

Constraints such as the availability of funding, manpower, existing local interest, etc., have not been imposed at this point. The opportunities here are grouped according to the the type of measurement or physics topic.



Experiment--> Parameter	Cuore	Cuoricino	Exo	Genius	Majorana	Gem	Moon	Xmass	Cobra	DCBA	Nemo	Cameo	Candles
Isotope	$^{130}\mathrm{Te}$	$^{130}\mathrm{Te}$	$^{136}\mathrm{Xe}$	$^{76}\mathrm{Ge}$	$^{76}\mathrm{Ge}$	$^{76}\mathrm{Ge}$	$^{100}\mathrm{Mo}$	$^{136}\mathrm{Xe}$	$^{130}\mathrm{Te}$	$^{150}\mathrm{Nd}$	$^{100}\mathrm{Mo}$	$^{116}\mathrm{Cd}$	$^{48}\mathrm{Ca}$
Mass(kg)	760	40	1000	1000	500		34000					1000	
$T^{0\nu}{}_{1/2}(10^{26}\mathrm{yr})$	7	0.15	8	100	40	70	10	3	0.01	0.15	0.04	>1	1
$<m_\nu>$ (meV)	27	184	52	15	25	18	36	86	240	190	560	69	158
Technique	TeO_2 crystals at 10mK	TeO_2 crystals at 10mK	Xe Drift Chamber plus Ba+ tagging	Ge Crystals in LN2	Cooled Ge Crystals, Pulse Shape Discrmination	Ge Crystals in LN2 + H_20 Veto	Mo plates + Scint.		CdZnTe or CdTe diodes	Drift Chamber in B-Field			CaF_2 in liquid Scint.
Enrichment	No(34%)	No(34%)	Yes(80%)	Yes(86%)	Yes	Yes	No(9.6%)						
Energy Resol'n FWHM (keV)	7 keV @ 2529keV	7keV @ 2529keV	2.5% @ 1952keV	3keV @ 2038keV	3keV @ 2038keV								
Status	Proposal	under const.	100 kg approved	Proposal	Proposal	Proposal	Proposal		Proposal	Proposal	Proposal	Proposal	Proposal
Location	Grand Sasso	Grand Sasso	?	?	?								
Cost ($M)	10	-		100	100								

Table 2: Overview of proposed neutrinoless double beta decay experiments.

4.1 Double beta decay

While next generation tritium endpoint experiments may be able to probe masses of about 0.3 eV, neutrinoless double beta decay is the only tool for reaching the 10–50 meV level suggested by recent neutrino oscillation results, which provide compelling arguments for new experiments with 100-fold increases in sensitivity. Several promising experiments using distinct technologies have reached an advanced stage of development. Because the ultimate sensitivity of new techniques is difficult to anticipate, more than one next-generation experiment may be necessary. Because the nuclear matrix elements necessary to interpret the results have large uncertainties, it is important to observe the decays in different nuclei.

The irreducible physics background is from allowed two neutrino double β decay, for which the rate is of order 10^4 times larger, and can only be removed via a cut on the $\beta\beta$ total energy. The sensitivity to the effective neutrino mass, $\langle m_{ee}\rangle = |\sum_{i=1}^{3} m_i\, U_{ei}^2|$, is

$$\langle m_{ee}\rangle_{\min} = \left(\frac{A}{x\eta\epsilon N_A G^{0\nu}|M^{0\nu}|^2}\right)^{1/2} \times \begin{cases} [B\Delta E/(MT)]^{1/4} & \text{with background,} \\ [1/(MT)]^{1/2} & \text{without background.} \end{cases} \tag{5}$$

Here A is the compound molecular mass, x is the number of $\beta\beta$ atoms per molecule, η is the isotopic abundance, ϵ is the detection efficiency, N_A is Avogadro's number, B is the background rate, ΔE is the energy resolution, M is the mass and T is the running time of the experiment. This shows that there is a premium to (i) zero background, (ii) excellent energy resolution, and (iii) long exposures of large masses with high isotope concentration. A comparison of recent experiments and proposals is shown in Table 2.

The 0.01 eV goal requires sensitivity to half-lives in excess of 10^{28} years. This, in turn, requires source masses of order 1000 kg and unprecedented suppression of cosmic ray and radioactivity backgrounds. Several of the most promising experiments need enriched isotopes, so their scale and cost are significant. The definitive experiment will have to be able to present results such as the energy spectrum of both the $2\nu\beta\beta$ and $0\nu\beta\beta$ decays.

4.1.1 CUORE

CUORE (Cryogenic Underground Observatory for Rare Events) is a proposed tightly packed array of 1000 TeO_2 bolometers, each being a cube 5 cm on a side with a mass of 760 g. The array consists of 25 vertical towers, arranged in a square of 5 towers by 5 towers, each containing 10 layers of 4 crystals. The design of the detector is optimized for ultralow-background searches: for neutrinoless double beta decay of ^{130}Te, cold dark matter, solar axions, and rare nuclear decays. A preliminary experiment involving 20 crystals $3\times3\times6$ cm of 340 g has been completed, and a single CUORE tower has been constructed in CUORICINO.

CUORE is a bolometric detector. The temperature change in Tellurium Oxide can be recorded with thermal sensors and in particular using Neutron Transmutation Doped (NTD) germanium thermistors. These devices were developed and produced at LBNL and at the UC Berkeley Department of Materials Science. For a given half-life sensitivity, a ^{130}Te detector can be between a factor of 2 and 4.6 more efficient in probing the Majorana mass parameter as a ^{76}Ge detector. However, because of the ratio of the molecular weights and the ratio of the isotopic abundances in the detector materials, there are 5.41 times as many ^{76}Ge atoms in a kg of Ge metal isotopically enriched to 86% in ^{76}Ge, as there are ^{130}Te atoms in a kg of natural abundance TeO_2.

There are now six proposals in various stages of development for new large-scale double beta decay experiments (see table). All but CUORE and MooN would require significant time for research and development as well as large-scale funding for isotopic enrichment. CUORE requires no isotopic enrichment because the natural abundance of ^{130}Te is sufficiently high (33.8%) to achieve the sensitivity required for double beta decay measurements, and because the principle of using TeO_2 bolometers for double beta decay experiments has already been demonstrated in the Mibeta project.

The CUORE array will have 9.5×10^{25} nuclei of ^{130}Te. If the background is reduced to 0.01 counts/keV/kg/yr, then in one year of running, the sensitivity of CUORE would be $t_{1/2}(0\nu) > 1.1 \times 10^{26}$ y. This corresponds a limit $m_\nu < 0.05$ eV. If eventually, the background could be reduced to 0.001 counts/keV/kg/y, the sensitivity with one year of counting would be $t_{1/2}(0\nu) > 3.6 \times 10^{26}$ y, corresponding to $m_\nu < 0.03$ eV. If in the two cases mentioned above, the detector were operated for a decade, the bounds on m_ν would be < 0.028 eV, and < 0.017 eV, respectively.

The capital equipment cost for CUORE is estimated to be approximately $10M. Roughly half of this amount will be requested from US funding agencies in a proposal to be submitted once CUORICINO has obtained sufficient data to demonstrate performance. LDRD is a logical source of support for preparing such a proposal.

The LBNL staff that are currently involved with CUORE are listed in Section 3.1.3. In order for LBNL to play a major role in CUORE, the level of LBNL effort on this experiment will need to increase. The US proposal for CUORE will need to provide a stable and adequate level of funding to support the efforts of the existing LBNL participants and, at a minimum, add a postdoc who will spend most of his/her time on data analysis, and a graduate student.

4.1.2 Majorana

The difficulties of calculating the necessary nuclear matrix elements suggest that several double beta decay experiments will ultimately be required to interpret the results. One natural candidate is isotopically separated ^{76}Ge. This species can be made into sensitive solid state detectors with excellent energy resolution. The Ge beta decay technique is very mature. However, as limits have effectively doubled every few years, higher purity and lower background Ge detectors will be required. In addition, new techniques for rejecting backgrounds need to be developed. One of the most promising techniques involves the use of segmented detectors. By providing a degree of three-dimensional imaging of charge within the Ge, single vertex sites (i.e., potential double beta decay events) can be cleanly separated from Compton scattering events, a particularly troubling background. In developing segmented Ge for Gammasphere and GRETA, LBNL has developed critical expertise in modeling and understanding detector response and in developing sensitive electronics to achieve the best resolution of signals from backgrounds. There exist significant construction challenges for the fabrication of this type of experiment for which a close union of LBNL's engineering and physics interests and expertise would benefit the Majorana project.

Majorana will require great overburden to reach its ultimate sensitivities and is another natural candidate for NUSEL. The fabrication of the Majorana detectors will also require significant underground infrastructure.

The avenues for obtaining support for developing an LBNL role in Majorana as well as for long-term funding are the same as for CUORE.

4.1.3 Study of a $\beta\beta$ time projection chamber using an insulating liquid detector medium

The successful identification of very rare events requires clean signatures for both signal and background processes. The trajectories of a pair of electrons emitted in the double beta decay of a nucleus point back to a single vertex whereas electrons from background processes will typically originate from multiple sites. The topology of a pair of electrons from a double beta decay, moving in a medium in a magnetic field would be an S-shaped spiral with curled-up tips at the ends of the bends. A time projection chamber based on drifting ions in an insulating liquid medium could be a way to observe the unique topology of double beta decay and provide at the same time adequate resolution for measuring the energy in the decay. By identifying double beta decay candidates through topology, both 0-neutrino and two-neutrino modes will be simultaneously observed. This is the subject of an R&D effort to develop non-cryogenic detectors capable of providing simultaneously high efficiency, high-resolution spatial imaging, and energy measurement with potential application to observe neutrinoless double beta decay.

There is a class of experiments searching for rare processes including $0\nu\beta\beta$ decay that do not require the high drift speed of electrons. Here, room-temperature insulating liquids, rather than cryogenic liquids, may be suitable. The R&D plan is to study potential liquids, build a simple test device, and estimate performance through simulations. If the results are sufficiently encouraging, a second stage will focus on the design, construction and test of detectors with relevance to the broad domains of basic nuclear/particle physics.

This effort has been started by Nygren and others from the Physics and Nuclear Science Divisions. Interest has also been expressed by members of the Radiation Detection Group at LLNL to collaborate on this subject.

4.2 Measurement of θ_{13}

SNO, KamLAND, and Super-Kamiokande have determined all matrix elements of the neutrino mixing matrix, U_{MNS}, except for $|U_{e3}|$. $|U_{e3}|$ gives the contribution of the mass-3 state to the electron neutrino flavor eigenstate. The discovery and measurement of $|U_{e3}|$, is one of the main goals in neutrino physics. The corresponding mixing angle θ_{13} is the only mixing angle not yet measured and its value is critical for the question whether CP violation in the lepton sector might be observable in the future.

A positive measurement of, or a new limit on, θ_{13} would be invaluable for our understanding of the structure of U_{MNS} and the planning of future neutrino experiments. At present, we only know that $U_{e3}^2 < 0.03$, due to the bound imposed by the CHOOZ reactor experiment. Since KamLAND confirmed the large mixing angle MSW solution of the solar neutrino problem, a measurement of CP violation in the lepton sector might be within reach if $|U_{e3}|$ is not too small. The crucial next step toward the goal of understanding the neutrino mixing matrix and determining the feasibility of a CP measurement in the lepton sector is the determination of θ_{13}.

4.2.1 Accelerator-based neutrino projects and long baseline experiments

The primary goal of the first generation of accelerator-based long baseline neutrino experiments is to confirm the observation of atmospheric neutrino oscillation. As a result, these experiments, K2K, MINOS, OPERA, and ICARUS, are not optimized to measure the mixing angle θ_{13} in the vicinity of $\Delta m_{23}^2 = 2.5 \times 10^{-3}$ eV^2. To significantly improve our knowledge of θ_{13} beyond the CHOOZ limit, a new generation of experiments is needed. With high energy ν_μ beams readily available at accelerator centers, we can measure θ_{13} by observing $\nu_\mu \to \nu_e$ oscillation. The probability of ν_e appearance at a distance L from the source is given by

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \, \sin^2 \theta_{23} \, \sin^2 \left(\frac{\Delta m_{13}^2 L}{4E} \right), \tag{6}$$

where E is the energy of ν_μ. At this moment, there are two major neutrino experiments on the drawing board that are designed to probe θ_{13} down to $\sim$0.035, or $\sin^2 2\theta_{13} \sim 0.005$. Both experiments, one in Japan and the other one in the US, adopt the so-called off-axis ν_μ neutrino beam configuration. The off-axis beam takes advantage of the fact that the transverse momentum of the π decay is finite and is independent of the energy of the π. As a result, the spread in the ν_μ momentum decreases as a function of the emission angle with respect to the π beam produced at 0 mrad, thus forming a narrow-band ν_μ beam with decent intensity and about 0.5% ν_e contamination coming from K_{e3} decays. The challenge of these experiments is to have high efficiency in identifying electrons and excellent background discrimination. In addition, this new round of experiments should be able to carry out high-precision determination of θ_{23} and Δm^2_{23}, and explore the feasibility of studying CP symmetry in the lepton sector by comparing $\nu_\mu \to \nu_e$ with $\overline{\nu}_\mu \to \overline{\nu}_e$.

4.2.2 Neutrino program at J-PARC

The Japanese Proton Research Accelerator Complex (J-PARC, formerly JHF) is a new 50 GeV and 1 MW proton accelerator complex under construction at Tokai, Japan. This accelerator is scheduled to be operational by the end of 2006. In addition to offering a diverse program in nuclear science using a rapid-cycling 3 GeV proton synchrotron, which shares the linac with the 50 GeV machine, J-PARC is planning to provide a very intense neutrino beam for long baseline experiments. In the first phase of the J-PARC neutrino program, Super-Kamiokande at a distance of 290 km from the target will be used as the far detector. This 25 kt water Cherenkov detector is ideal for detecting sub-GeV neutrino interactions, predominately quasi-elastic $\nu_\ell \, n \to \ell^- p$ scattering. In addition to the far detector, there will be two near detectors at 280 m and at about 2 km from the target. The purpose of the 280 m detector is to monitor the direction and profile of the neutrino beam as well as to study low energy neutrino reactions that are essential for understanding the systematics at the far detector. Monte Carlo studies indicate that the energy spectrum of the ν_μ beam observed at the location of the 2 km detector is almost identical to that at the far detector with no oscillation. Having this "near" or intermediate detector will greatly reduce the systematic error of the measurement, and is better than just having the 280 m detector.

The outstanding issues of the J-PARC neutrino experiment are the construction of the neutrino beam line, the 280 m, and the 2 km detectors. There was also an expression of interest in replacing the readout electronics for the Super-Kamiokande detector. The technical challenges of the neutrino beamline are the design of the fast-abort system and the extraction of the high-intensity proton beam, and the superconducting transport arc to guide the proton beam from the fast extraction to the target area. The designs of the target and the horns are also non-trivial. For the two near detectors, the immediate issues are defining the specifications, and the detector technologies that are optimal for studying the final states of the low energy neutrino reactions.

4.2.3 Long baseline experiments in the US

The NuMI facility at Fermilab is scheduled to provide an intense ν_μ beam in the US by 2005. In response to the J-PARC neutrino experiment, an idea for determining θ_{13} with a sensitivity comparable or better than the J-PARC experiment has emerged, using off-axis ν_μ's from the neutrino beam aimed at MINOS. A 20–50 kt surface detector with some overburden and about 10 km away from MINOS will be constructed. Since the design of NuMI is already frozen, without incurring additional cost, the energy of the off-axis ν_μ beam is chosen to be about 2 GeV. In this energy range, neutrino-induced resonance production is the dominant process — a nuisance to the measurement due to the presence of π^0's that are more difficult to detect, and it is a serious background to the experiment.

Since the baseline of the NuMI off-axis experiment is about 800 km, the matter effects have a profound impact on the study of CP symmetry. At the first maximum of the oscillation pattern, the matter effect could be used to solve the mass-hierarchy problem with the ν_μ and $\overline{\nu}_\mu$ beams, hence addressing one of the remaining questions in neutrino oscillations.

In contrast to the J-PARC neutrino program, NuMI is already under construction. The outstanding question of the off-axis experiment is the optimization of the near and far detectors (even though many interested parties argue the near detector is unnecessary), followed by the construction of the detectors.

BNL has developed a proposal in which the AGS will be upgraded to provide 28 GeV protons with a beam power of about 1 MW. A wide-band neutrino beam with energy up to 10 GeV is combined with a 0.5 MT water Cherenkov detector in a underground site about 2500 km from the target. By measuring the oscillation pattern for different neutrino energies, this experiment can determine all the parameters in the neutrino mixing matrix. If the value of $\sin^2 2\theta_{13}$ is greater than 0.01, even the CP violating parameter δ can be determined in this experiment using only a neutrino beam. Furthermore, the mass ordering of neutrinos can be resolved through the observation of matter effect in the $\nu_\mu \rightarrow \nu_e$ mode.

To keep a minimum involvement in accelerator-based projects at LBNL, Luk and Heeger (PD) signed Letters of Intent for the NuMI off-axis and J-PARC experiments.

4.2.4 Reactor neutrino experiment to search for θ_{13}

Reactor neutrino experiments are also sensitive to θ_{13}. Indeed, the present upper limit for θ_{13} is from the CHOOZ experiment. In a reactor neutrino experiment with two or more detectors, the comparison of the observed spectra enables the observation of the subdominant contribution to $\overline{\nu}_e \rightarrow \overline{\nu}_{\mu,\tau}$ oscillation, and determines the θ_{13} contribution to the $\overline{\nu}_e$ survival probability. The possibility of a reactor neutrino experiment to measure θ_{13} has generated significant interest world-wide. A specific proposal has been made for an experiment in Russia (KR2DET) and a collaboration is being formed. There is also significant interest in the US to pursue a reactor neutrino experiment to search for θ_{13}. Table 3 summarizes the proposed θ_{13} measurements at accelerators and reactors.

The possibility of a θ_{13} search with reactor neutrinos is intriguing as it offers the opportunity for a smaller scale experiment with a time scale for completion that is shorter than any accelerator experiment. A θ_{13} search with reactor neutrinos could be conducted in ~5 years. Preliminary results of this study by Freedman (NSD), Heeger, Kadel and Luk (PD) are available, and a report is in preparation. This report includes calculations for the optimization of detector locations and considers possible domestic nuclear reactor sites.

The technology required for such an experiment, mainly large-volume (perhaps modular) scintillator detectors, is also of scientific interest outside the neutrino physics community. There are large-scale development efforts for scintillator detectors at LLNL and other national laboratories that might offer opportunities for collaboration and additional funding. A θ_{13} reactor neutrino experiment also provides an opportunity for an interdivisional effort in neutrino physics, involving both the Physics and Nuclear Science Divisions, much as has been done with KamLAND.

Project	J-PARC–SK	NuMI off-axis	BNL	KR2DET	Japan θ_{13}	LBNL θ_{13}
Source & signature	accelerator ν_μ; study $\nu_\mu \to \nu_e$			reactor $\overline{\nu}_e$; study $\overline{\nu}_e$ spectrum and rate		
$\sin^2 2\theta_{13}$ sensitivity	~ 0.005	~ 0.005	~ 0.005	~ 0.01	~ 0.01	~ 0.01
Construction end	2008	2007	?	?	?	2007 (1)
First results	2012	2012	?	?	?	2009
Detector I (km)	0.28	1	> 2500	0.15 (2)	0.15 (3)	1 (6) (4)
Detector II (km)	2	750 (phase I)		1.1	1.1	3 (7.8)
Detector III (km)	295	985 (phase II)		N/A	N/A	N/A
Status	LOI	LOI	LOI	preprint	preprint	in preparation
Location	Japan	US	US	Russia	Japan	US
Lead group	KEK	FNAL	BNL	Kurchatov Institute	Tokyo & Tohoku	LBNL & UCB
Est. cost (\$M)	~ 200	$\sim 100 - 200$	~ 500	?	?	< 50

(1) If funded; (2) Given by underground infrastructure; (3) By assumption; (4) For two detectors possible locations in the "near-far" configuration are 1 and 3 km, while in a "far-far" configuration it is 6 and 7.8 km.

Table 3: Summary and comparison of proposed θ_{13} measurements. The $\sin^2 2\theta_{13}$ sensitivity depends on Δm^2_{13} and yet unknown experimental details.

The next step will be an LDRD proposal for a more detailed study of the physics potential of a reactor-based θ_{13} experiment and to develop a full detector concept. LDRD activities will include (i) site evaluation and engineering studies; (ii) detailed development and simulation of a detector concept; (iii) prototyping of detectors, possibly in collaboration with other laboratories; (iv) background measurements at the proposed site; and (v) development of a full-scale proposal.

4.3 θ_{12} and the SSM

There are two major milestones ahead in the study of solar neutrinos, the observation of the ^{7}Be and of the pp neutrinos. Each of these will bring increased precision in our knowledge of neutrino properties and provide detailed tests of the Standard Solar Model. The ^{7}Be neutrinos belong to the present generation of neutrino detectors — Borexino and KamLAND. Once upgraded to remove backgrounds from ^{85}Kr and to further purify the liquid scintillator, KamLAND will be able to detect solar ^{7}Be neutrinos and determine its flux with high statistics. KamLAND's measurement of the solar ^{7}Be neutrino flux is limited by the 7% theoretical uncertainty in the Standard Solar Model prediction of the ^{7}Be flux. This will result in a $\sim 8 - 10\%$ measurement of the mixing angle θ_{12}. A measurement of the astrophysical S-factor for $^3\mathrm{He} + {}^4\mathrm{He} \to {}^7\mathrm{Be}$, which determines the flux of solar neutrinos from decay of ^{7}Be and ^{8}B in the Sun, could reduce the uncertainty in the solar model predictions of the ^{7}Be flux, and hence increase KamLAND's sensitivity to θ_{12} by up to a factor of two. This poses an opportunity for NSD to combine its effort in nuclear astrophysics and neutrino physics to improve the θ_{12} sensitivity of KamLAND. The combination of SNO's ^{8}B and KamLAND's future ^{7}Be measurement may provide evidence for the energy dependence of the neutrino survival probability, which would be an important verification of the MSW effect.

Still lower in energy, the pp neutrinos ($E < 0.4\,\mathrm{MeV}$) will be even more difficult to

Experiment	Technique	$\tan^2\theta_{12}$ (95% CL)	Year
SNO + KamLAND reactor	global fit	$[0.37, 0.6]$	2002
KamLAND ^{7}Be	rate + background discrimination	$[0.47, 0.56]$	2007 (?)
new solar pp experiment	rate + spectrum	$[0.5, 0.54]$	2010 (?)

Table 4: Expected sensitivity of future solar neutrino experiments to the mixing angle θ_{12}.

detect, but will provide correspondingly more information, both for the value of θ_{12} and for our understanding of the Sun. These neutrinos comprise 99.9% of all neutrinos emitted by the Sun and represent a superbly calibrated neutrino source. The energy spectrum of these neutrinos is equally well known (as opposed to, say, the ^{8}B neutrino spectrum). Such a well-calibrated source lends itself to the determination of neutrino mixing parameters that make use of the absolute neutrino source intensity. The main objectives of a low energy solar neutrino experiment will be to (i) produce the highest resolution θ_{12} measurement and define fundamental MNS matrix elements; (ii) demonstration of the MSW effect; (iii) search for the presence of sterile neutrinos; and (iv) search for neutrino magnetic moments. A precise measurement of θ_{12} is also helpful for future CP violation experiments as it determines (together with the other mixing angles) the size of CP violation; see Eq. (3). Such an experiment would also provide valuable astrophysical results, namely to verify the Solar Model and to search for evidence for CNO neutrinos in the solar neutrino spectrum. Table 4 summarizes future prospects for measuring θ_{12}, assuming the present central value.

Low energy solar neutrino experiments will be extremely sensitive to intrinsic and external radioactive backgrounds. This sensitivity to backgrounds requires extraordinary planning for these experiments. To reduce cosmic ray backgrounds and cosmic ray induced activities, these experiments will require extremely well shielded experimental locations, at least as deep as SNO (>6000 mwe). Construction materials and fabrication techniques will also require extraordinary selection and control to insure adequately low levels of activity. Many of the techniques being discussed for this generation of experiment use cryogenic targets to detect low energy neutrinos with reasonable efficiency. While these techniques have made significant progress in overcoming the experimental difficulties, many significant challenges remain before these bench-top prototypes can be scaled up to the required sizes. The LDRD supported R&D in progress for the HERON (superfluid helium) detector addresses several of these questions and will be a significant step toward demonstrating the feasibility of the next generation of solar neutrino detectors.

4.4 NUSEL — National Underground Science and Engineering Laboratory

Underground science includes studies at the frontiers of particle physics, nuclear physics, astronomy, geology, and biology, as well as applied areas such as materials science and nuclear proliferation. In the past decade, fundamental progress has been made in underground experiments in such diverse and exciting fields as nucleon decay, atmospheric neutrino oscillations, the solar neutrino measurements, searches for dark matter, the measurement of nuclear fusion cross sections at stellar temperatures, and the discovery of novel microorganisms that live deep in the Earth. In order to participate in these discoveries, US scientists have had to either take their equipment to other countries or, in a few cases, to make use of non-optimal facilities in the US.

The next generation of underground experiments is more challenging technically than previous studies and will therefore require both significant resources and good planning and management to succeed. Over the past three years there has been an initiative in the US with significant involvement from Lesko to create a National Underground Science and Engineering Laboratory (NUSEL). The goal of this initiative is to establish the conditions that will enable the science, which must be done with large, sophisticated equipment, to succeed in a cost effective way. Recognizing the need for a facility to house these future experiments, the most recent Long Range Plan by the Nuclear Science Advisory Committee identified the construction of NUSEL as one if its highest priorities.

NUSEL would open new opportunities in nuclear physics, astrophysics, high energy physics and geosciences. For LBNL this could include the development of detectors and approaches for the next generation experiments in these domains.

Future roles for LBNL in NUSEL include: (i) the development of both traditional and ultra-sensitive low background counting facilities to be sited at NUSEL such as will be required by many of the future experiments; and (ii) development of engineering and scientific plans for NUSEL experimental space to insure that the proper criteria and planning models are used in the development of this scientific space. Scientific challenges of providing appropriate environmental factors match well with our scientific experience: radon reduction, background control, shielding, and veto detectors. These roles naturally suggest LBNL should become a participating institution in the NUSEL proposal.

In addition to these supporting roles, LBNL's major role would be in the development of scientific initiatives and experiments to be deployed in NUSEL. The Earth Sciences Division has championed the development of major geophysics and Earth sciences initiatives for NUSEL. There exist several potential cooperative efforts between ESD and NSD.

Lesko from the NSD is a member of the executive committee for the NUSEL. Collaboration members include Poon from NSD and Heeger from PD. The project has been reviewed by the National Science Foundation and is waiting for a hearing by the NSF Science Board.

Summary Table 5 shows possible future neutrino projects at LBNL and the key physic topics that are addressed in each of these experiments.

5 Limitations

The current work at LBNL in neutrino science is embedded in Divisions, in a Laboratory, and in external communities — all of which must function within certain limitations. These limitations must be examined as they affect not only what we can do now, but what we plan for the future. As options for the future are considered, we need not only scientific but also institutional criteria for guiding our choices.

Physics	Topics	Future Projects						
		KamLAND II	IceCube	pp Solar	Cuore/ Majorana/TPC	Reactor theta(13)	J-PARC/NuMI BNL	Neutrino Factory
I. Neutrinos from the Universe	High Energy Neutrinos		▨					
	Solar Astrophysics	▨		▨				
	Solar Neutrinos	▨		▨				
	Supernovae	▨	▨	▨				
	Relic Neutrinos							
II. Mechanism of Flavor Transformation	Neutrino Flavor Change	▨		▨		▨	▨	▨
	MSW Effect	▨		▨				
	Neutrino Oscillations	▨		▨		▨	▨	▨
	Sterile Neutrinos	▨		▨		▨	▨	▨
III. Mixing & Mass Matrix	theta(12)	▨		▨				
	deltam2(solar)	▨		▨				
	theta(13)					▨	▨	▨
	CP Violation in Neutrino Sector						▨	▨
	theta(23)						▨	
	deltam2(atm)						▨	
	Absolute Mass Scale				▨			
	Mass Hierarchy					▨	▨	▨
IV. Nature of Neutrinos	Majorana or Dirac				▨			
V. Geophysics	Geo Neutrinos	▨						
VI. Future Accelerators	Muon Storage Techniques							▨
Facilities	*NUSEL*			▨	▨	▨		

Table 5: Overview of possible future neutrino projects at LBNL and their physics topics. Also shown is the overlap of NUSEL with possible future neutrino projects at LBNL.

5.1 Limitations faced by the neutrino science community at large

Historically, neutrino experiments at accelerators have not been the primary reason for the funding and construction of the accelerator complex. Given that neutrino experiments are, in this sense, secondary activities, they must expect, and indeed have, received lower priority in facility operation and planning and in the distribution of (accelerator) laboratory funding. While there are some significant and expensive neutrino beams coming on line, the fate of new proposals and the amount of effort expended by a laboratory on neutrino physics often hangs on the performance of the flagship experiment and the accelerator itself. If the latter gets in difficulty, resources will be diverted to solve that problem, at the expense of secondary activities.

Non-accelerator neutrino experiments face a different set of problems. Lacking access to the base funding of a large operations budget that (even secondary) accelerator-based experiments have, non-accelerator experiments can experience difficulty in getting started, i.e., in obtaining funds for R&D and, once a proposal is prepared, in competing for funding in a scientific area where the majority of all work is based at accelerators. Major underground experiments are usually scattered throughout the world, located at isolated "sites of opportunity," a situation that does not foster creation of a scientific community as does the clustering of experiments at a major accelerator complex.

There are encouraging exceptions to the above generalizations — the Gran Sasso Laboratory being the most notable. The Kamioka mine in Japan hosts two major and several smaller experiments. It is reasonable to expect that construction of a NUSEL would establish a similar center of activity in the US. Finally, the strength and coherence of national neutrino science communities will vary with country and the extent to which national funding agencies choose to emphasize this field.

5.2 Limitations faced by the neutrino science community at LBNL

Neutrino science is a relatively small part of each of the General Sciences Divisions, as discussed below.

The Nuclear Science Division has relativistic heavy ion collisions and low energy nuclear science (structure, reactions, and chemistry) as the traditional foci for research and funding. This, of course, mirrors the situation in DOE Nuclear Physics, where neutrino science is a small part of the pie. Neutrino science is a relatively recent addition to LBNL compared to the traditional efforts. DOE Nuclear Physics does not operate any accelerator facilities that produce neutrino beams, which accounts for the preponderance of non-accelerator neutrino experiments in the NSD and in US nuclear physics in general. The main limitation for neutrino science in the NSD has been the availability of funding and manpower, in a division whose main roles have been in heavy ion physics and nuclear structure. The low energy program, however, is undergoing a transition associated with the scheduled cessation of operations at the 88-inch cyclotron in FY04. How this may affect the number of NSD people working in neutrino science remains to be seen as the NSD evaluates its options.

The Physics Division plan has ATLAS and SNAP as its two primary foci. Unless there is substantial financial relief, these two projects will consume most resources in the division. In particular, both CDF and BaBar will need to be ramped down, starting very soon, to make room for increased efforts on cosmology and LHC. In these circumstances it would be very hard to mount any new large effort, in neutrinos or elsewhere. The number of senior people available currently to work on neutrino physics is few. Despite the great promise of KamLAND (now being fulfilled), Physics Division participation is quite small. The phasing out of CDF and BaBar might be expected to provide some new senior personnel, but probably not many. CDF will mostly merge into LHC. Moreover, the number of non-retired senior people on BaBar is not great. Some have left completely or partially to join SNAP. Some will likely stay with BaBar as long as there is some credible number of LBNL postdocs working on it. Even more of a limitation is the paucity of postdocs. The total number in the division may decline (even if base program funds arrive to support SNAP science) and these will increasingly be devoted to ATLAS and SNAP. Finally, success can also present a kind of limitation for future options. Since IceCube has funding now from NSF and the prospects for long-term funding are very good, continued Physics Division and Nuclear Science participation appears certain. Meeting this new commitment in neutrino science also affects the availability of manpower to pursue new options.

With regard to the neutrino-related activity in AFRD, similar issues arise. The activity of most interest to the neutrino community is to design and build a Neutrino Factory based on a muon storage ring. This is likely to be an expensive undertaking, and hence requires a long lead time. It is likewise a technically challenging project that requires a substantial R&D effort in preparation for proposing an actual machine. The limitation here is that the community-wide funding for long-term R&D has been squeezed to the point that maintaining continuity and momentum in the program is severely jeopardized. In order to make the Neutrino Factory a viable future option for the scientific community, it is essential that the scientific community make a strong case to the agencies for long-term R&D funding.

The absence of a "neutrino science program" in the funding agencies (not just in DOE) represents a major limitation. The result is that neutrino science tends to fall in the cracks, and that the agencies' criteria for deciding which experiments are in their purview tend to be historical rather than rational. For example, DOE NP traditionally emphasized the importance of nuclear reactions in the Sun as a justification for building a solar neutrino detector, while DOE HEP regarded searching for proton decay as its mission. Fortunately, discovering the fundamental properties of neutrinos has emerged as the strongest justification, one behind which all agencies can hopefully unite. In the meantime, in nuclear physics, neutrino experiments are regarded as individual, one-off experiments as opposed to integral parts of an ongoing scientific program. Once the experiment is completed, the funds can be released for other purposes. This has led to the painful situation in which the SNO group at LBNL faced reductions in funding once the construction of SNO had been completed, and again, when scientific results were first obtained.

Although funding from DOE High Energy and Nuclear Physics is the standard mode, the Physics and Nuclear Science Divisions do have funding from other sources. The example of NSF funding for IceCube is an interesting and complex example. The money actually comes through the University of Wisconsin. This means, however, that LBNL has less control and experiences greater uncertainty. In addition, IceCube gets money mainly through Polar Programs at NSF, with less from Elementary Particle Physics or Nuclear Physics. This complicated situation nevertheless demonstrates that NSF money can come to LBNL to support projects that LBNL scientists want to do. It also provides another of the relatively rare examples in which scientists and engineers at national laboratories can make significant contributions to NSF-based projects. Significant amounts of money from sources other than NSF or DOE seem unlikely, however. Only unusual arrangements, like DOD support of neutrino detectors for national security purposes, come to mind.

The limitations described above, however, should be viewed not as insurmountable obstacles, but rather as challenges to be met over time by constantly working to reduce them. One need only look at the gradient for neutrino science over the last twenty years to see the value of this approach.

5.3 Requirements for credible participation

It is generally accepted that LBNL should not participate in a minor way in a large experiment. The reason is that this makes LBNL appear no different from a university group and thus undermines the basis for being funded at a level beyond that. KamLAND provides an example of how an LBNL team can make important contributions to an experiment whose size is moderate to large by nuclear physics standards though small for high energy physics. In this instance, a very small Physics Division team together with a larger Nuclear Science Division team joined to make a very effective unit, one that represents a large and strong group within KamLAND. A small NSD team joined with a larger PD group to make a very effective unit in the IceCube project, one that represents a major group in the IceCube Collaboration. These are good models. There is not yet a model of PD/NSD team forming a large group to work on a large accelerator experiment, though this is possible in principle.

The uniqueness of the LBNL contribution to a project is also a defining factor, one that may be more relevant than the size of the effort. LBNL played a major role in the early double beta decay experiments based on its expertise in germanium detector fabrication and low-noise electronics. Today, a similar example can be found in LBNL's development of the NTD germanium thermistors to be used in CUORE (also a small experiment). When a technical contribution is joined with a scientific role, the justification for participation is compelling.

Accelerator R&D is in a different category when considering the criteria for involvement in a project. In this area there is no danger of appearing to be "just another university group," since few universities participate in such work. LBNL has an outstanding reputation in accelerator physics, and the only criterion for having a distinguished role in Neutrino Factory R&D becomes that of obtaining funding. We regard the Neutrino Factory R&D effort in AFRD and the MICE project in particular as an on-going commitment rather than an option.

5.4 What our limitations permit

Limited funding and limited personnel mean that our new neutrino efforts must necessarily start out small. If we adhere to the general principle that LBNL should avoid a small effort in a large project, the conclusion is that we should pursue options for experiments in which the nature of the experiment and the size of the collaboration enable us to have significant impact. Note that experiments satisfying this criterion can still cost a lot of money!

For the foreseeable future, then, it appears that the growth of neutrino science will remain subject to these limitations, and that even a small growth will represent a significant achievement. Nevertheless, the initiation of a new neutrino effort might be well received by LBNL Management. (The existence of our Neutrino Working Group is the result of a suggestion by Management that we come up with a coherent neutrino program as a basis for requests for LDRD, and is thus a positive sign.) Such an initiative would likely be evaluated on the basis of recent achievements in neutrino physics internationally and here at LBNL, as well as on the prospects for future success. On this basis, we should be optimistic about seeking Laboratory support.

6 Analysis and Conclusions

We present here an analysis of the opportunities in light of scientific and institutional factors and the limitations and criteria in the preceding sections. The discussion is organized in the following order — present commitments, double beta decay, θ_{13}, θ_{12} and the SSM, and NUSEL. Conclusions are interspersed in the section. Resources, strategy, priorities and the role of LDRD are discussed.

6.1 Present commitments

Present commitments must be met. In other words, we must obtain the best possible results from the experiments, the R&D activities and the detector construction for which we have been successful in obtaining funding. While this can be viewed as limiting our ability to begin new experiments, our present commitments are in fact the basis on which we build the future. That this basis must be kept strong and be successful is axiomatic.

SNO is entering the third phase of its experimental program (neutral-current detectors), with results still to come from the second phase (salt). This is an intense period of construction and data analysis. LBNL will be heavily involved in both for the next four to five years.

After reporting its initial confirmation of the LMA solution in December, 2002, KamLAND now enters a stage in which high statistics results for the energy spectrum will be obtained to improve the precision and observe the minimum of the oscillation pattern. The LBNL-UCB group is the largest member of the US KamLAND collaboration and is expected to play a significant role through the lifetime of the experiment (another five to seven years).

The construction of IceCube seems assured, given its present funding and inclusion as Major Research Equipment in the FY04 budget request. LBNL has developed the digital system that is the backbone of the IceCube detector and will design and build the data acquisition system. It also has a leadership role in developing the architecture for data handling. The group expanded significantly in 2002 to meet its commitments.

Research and development for future accelerators is one of AFRD's primary missions. The work it now does toward a muon collider and neutrino factory will see its realization in a working facility only in the quite distant future. A logical progression toward that physics goal has been developed by an enthusiastic community of physicists and engineers. The rate of progress is largely a matter of funding. A continuing and significant LBNL role in the first muon cooling experiment will be assured when proposal for MICE that has been submitted to NSF is funded, which should be known in about six months. The participation of graduate students, postdocs, and NSD or PD staff in MICE would be both appropriate and welcome.

These represent the major present commitments. Additional commitments are the LBNL role in Cuoricino and the LDRD-supported R&D for HERON.

Given the rapid developments we have seen and are expecting, it is difficult to predict precisely the contours of the neutrino science landscape a decade or longer from now. However, it is clear that the measurement of neutrino properties will continue well into that period, and equally clear that we want to do the experiments that will determine that landscape. We now consider the opportunities for the near term in this context and in light of the limitations.

6.2 Double beta decay

The search for neutrinoless double beta decay has taken on new importance given the evidence for neutrino mass from neutrino oscillation experiments. Consistent with this importance is the existence of a variety of proposed approaches. (See Table 2).

6.2.1 CUORE

LBNL is involved in a significant way in a leading candidate for the next generation of double beta decay detectors. The advantages of CUORE — its progress in building a prototype, using a natural isotope, low cost, etc., have been discussed. Since CUORE is a relatively small international collaboration with two US participating institutions, a modest research effort would still be in keeping with criteria for a national laboratory's participation. Ultimately, scientific participation will depend on the US institutions submitting a proposal to the US funding agencies and obtaining the support they and their European collaborators require. In the meantime, establishing a firmer financial basis for the existing small effort on CUORE is the first step to take in establishing a program at LBNL in double beta decay. In addition to requesting support from DOE NP through NSD base funding for additional physics manpower, requesting LDRD support for preparing the US proposal should be considered.

6.2.2 Majorana

Majorana, in contrast to CUORE, is based on use of a separated isotope, ^{76}Ge, and the use of a segmented Ge detector array to reduce background. It is in this latter area that LBNL, through its pioneering application of highly segmented Ge detectors for gamma-ray spectroscopy, could make a significant contribution to this experiment. (Indeed, LBNL's help was sought.) Given the commitments of the gamma-ray spectroscopy group, it may be unrealistic to expect or assume that this could be accomplished solely through their participation. A role in Majorana can certainly be envisioned if new effort is forthcoming, either through redirection or a new hire. A scientist working full time on double beta decay and collaborating with the gamma-ray spectroscopy group to exploit the technology they are developing for GRETA in the Majorana double beta decay experiment would represent a significant start in this field. This is something that the NSD should consider.

6.2.3 A new approach to observing double beta decay

The search for rare processes, such as double beta decay, depends on the innovative application of existing methods and the development of new technologies. The idea to build a liquid TPC having high spatial resolution and energy resolution is very appealing. Studying the feasibility of this idea through building a small test device can be justified not only on the importance of $0\nu\beta\beta$, but also on the generic value of R&D for innovative detectors. LBNL has a strong reputation in this area and maintaining this reputation is important. While LDRD is certainly an appropriate source of funds, the concept may be attractive enough to enlist support from sources outside LBNL.

6.2.4 An initiative in double beta decay

A combination of the above activities would represent a new initiative in double beta decay for LBNL. This would be in keeping with the Laboratory's historical contributions to the study of double beta decay, its present involvement in CUORE, its tradition in innovative detector development, and increased national and international focus on this fundamental study of neutrino properties. As these activities progress, there will be the opportunity to add or shift resources among the elements of the initiative to optimize results in the light of performance and new developments.

Conclusion: Double beta decay Double beta decay measurements are at the forefront in the study of neutrino properties. LBNL is contributing to CUORE, a leading candidate for the next generation of double beta decay experiments. Moreover, an initiative for a broader program in double beta decay combining CUORE, Majorana, and detector R&D is possible through a modest increase of effort. The elements of this initiative should be pursued in ways most appropriate to each.

6.3 Search for θ_{13}

The direction neutrino physics will take a decade from now will be influenced greatly by the value of θ_{13}, a mixing angle for which we currently have only an upper limit. For this reason, θ_{13} takes on special significance and one finds intense activity in the planning of experiments to measure it. Most of the current activity is focused on long baseline experiments, which are being planned or considered using accelerators at J-PARC, FNAL, or BNL. A measurement of θ_{13} using reactor neutrinos may also be possible. (See Table 3).

LBNL is presently not actively involved in any experiment to measure θ_{13} but has been considering this possibility and examining alternatives. A recent preliminary study by several NWG members of the feasibility of a θ_{13} experiment with reactor neutrinos indicates that a reactor neutrino experiment offers some significant advantages over a long baseline experiment. The advantages are in the areas of cost, sensitivity, and measuring time. In general, the challenge for a reactor neutrino experiment is to find a suitable site at the right distance from the source and that could provide adequate shielding from cosmic rays.

A timely measurement of θ_{13}, could impact the entire field of neutrino physics and help with the planning of future efforts and facilities. After a positive measurement of θ_{13} and with a value large enough for further studies, including CP violation, one would proceed using accelerator neutrino beams. The physics potential of next-generation neutrino facilities is immense, ranging from precision studies of the oscillation phenomena and the mixing matrix elements to searches for CP violation in the lepton sector.

In addition to the technical advantages of a reactor-based search for θ_{13}, there is the opportunity for LBNL to lead the US effort in this experiment. Furthermore, the scope of a θ_{13} reactor neutrino experiment would be well matched to LBNL's resources. (In contrast, it is questionable whether LBNL would be able to play a leading role in the detector developments for accelerator neutrino experiments at J-PARC or FNAL without significant additional resources.) A collaboration for a θ_{13} reactor experiment has not been formed yet and LBNL's experience with a reactor neutrino experiment and large-scale detector development would provide an ideal environment for innovative efforts in a search for θ_{13}.

The current effort toward a θ_{13} reactor experiment involves personnel from both the Nuclear Science and Physics Divisions. Collaboration with other national laboratories in the detector development might be possible.

In the long run, if a positive measurement of θ_{13} demonstrates that the search for CP violation in the lepton sector is feasible, LBNL will need to participate in an accelerator based long baseline experiment. Eventually, the ongoing efforts in neutrino science found in AFRD, NSD and PD may coalesce at a future neutrino factory.

Conclusion: Search for $\boldsymbol{\theta_{13}}$ The most important experiment for determining the future direction of neutrino physics is the measurement of θ_{13}. Measurement of θ_{13} using reactor neutrinos appears competitive with the accelerator approaches and superior in certain aspects. LBNL should pursue this option vigorously with the goal of leading a US experiment. A request for LDRD to support the necessary R&D and proposal preparation is warranted. There is some urgency in this, since in the race to measure θ_{13} timeliness is a key factor.

6.4 $\boldsymbol{\theta_{12}}$ and the SSM

Precise measurements of θ_{12}, as well as further tests of the Standard Solar Model and the MSW effect are in the realm of solar neutrinos. Because the flux of solar neutrinos increases dramatically as one moves to lower energies, the sensitivity of the experiments (and their difficulty) also increases with a lower energy threshold. The next milestone in this direction will be made by Borexino and KamLAND with the detection of ^{7}Be neutrinos. Due to environmental, health and safety problems Borexino is temporarily on hold and completion of construction is not expected before 2004. Lowering the backgrounds in KamLAND to make the first direct measurement of solar ^{7}Be neutrinos (referred to as KamLAND-II) has strong motivations. It will be the first real-time observation of solar neutrinos other than ^{8}B, providing a stringent test of our understanding of the Sun and of neutrino oscillations. This measurement will also improve the constraint on θ_{12}. Participation by LBNL in this future phase is important to the entire collaboration because of LBNL's leadership role in the US KamLAND collaboration. It also capitalizes on the significant investment already made in KamLAND.

The most precise measurements of θ_{12}, and definitive tests of the SSM are to be made by measurements of the pp neutrino flux ($E < 0.4\,\text{MeV}$). All proposed methods to measure pp neutrinos in real time are in the R&D stage at this point. One does not know yet if such a detector is feasible, much less which will be the best technology. Liquid helium has been under development for some time and has made steady progress. LBNL is working with the developers of HERON to determine the feasibility of scaling up this technology from a small demonstration of principle to a full size solar neutrino detector to be located at a deep site. Assuming this R&D is successful, future steps will be the preparation of a proposal, the selection process (if there is a competitive technology), funding, and the expansion of the LBNL effort to lead the design and construction. DOE NP is the agency most likely to fund the next generation solar neutrino detector, and LBNL is well positioned here through its role in SNO to assume leadership.

Conclusion: $\boldsymbol{\theta_{12}}$ and the SSM The importance of precise values for the constants that represent the fundamental properties of neutrinos and the intimate connection between θ_{12} and the solar neutrino problem justifies pursuing these measurements to yield new information beyond that obtained from SNO and KamLAND. Precision tests of the Standard Solar Model are obtained at the same time. The options described above continue LBNL's established role in this field.

6.5 NUSEL

The longstanding goal of a national underground laboratory to house experiments requiring low-background conditions may be achieved in the near future in a facility that would be funded by the NSF.

6.5.1 Experiments

LBNL will likely participate in NUSEL through the experiments that it houses. The opportunities around a next generation solar neutrino experiment and double beta decay indicate this. In general, LBNL's strong involvement in non-accelerator physics and present use of underground facilities outside the US argue for LBNL supporting NUSEL. Indeed, LBNL has helped significantly in this most recent campaign.

6.5.2 Scientific and technical infrastructure

It is clear that, if a national underground laboratory is realized, LBNL could contribute significantly to the design, construction, and management of the scientific and technical infrastructure (as distinct from civil construction). This would be very much in LBNL's interest as its physicists are doing the types of experiments that would be sited there. The sequence of events would be (i) the NUSEL collaboration indicates a desire for LBNL to expand its role in NUSEL; (ii) includes LBNL as a participating institution in the proposal to the NSF; and (iii) NSF develops a mechanism for providing funding to LBNL. The NSAC recommendation in favor of such a facility, along with LBNL's initial role in furthering the case for a national underground laboratory are a solid basis on which to build. LBNL's potential role should be explored with the leadership of the NUSEL collaboration as soon as possible.

Conclusion: NUSEL It is important to a large community of researchers extending beyond neutrino science that there be a national underground facility in the US. It is also in LBNL's interest because some of the experiments it wants to pursue could be sited there. LBNL should further the cause of NUSEL in any way it can, including participation in the development of the scientific and technical infrastructure of the underground laboratory.

6.6 Resources, strategy, and priorities

The NWG believes that the first requirement in addressing the future is to meet the commitments implicit in the present program. Indeed, success in meeting present commitments provides the basis on which we build the future — a future that will contain elements of the present program and new initiatives based on the options developed here.

An option can be pursued with far less resources than will be required if and when it leads to a successful, i.e., funded, proposal. The resources required to develop each of the above options and bring them to proposal status are within the realm of LDRD. Some can even be pursued for the time being without LDRD. Resources will also become available as existing neutrino experiments mature and some of the participants move toward new opportunities. Finally, it is possible that some scientists currently working in other areas may wish to become involved in a neutrino experiment. Once an activity moves from option to funded proposal, though, the level of effort will have to increase commensurate with level of funding obtained through that proposal. It is often the case that the funding accompanying a successful proposal is a combination of new money and a redistribution of "base" funding. It is through such changes that level of base funding can be preserved or even increased.

The nature of neutrino science makes it difficult to predict far in advance which particular experiments will be successful and be the first to achieve the most significant results. Furthermore, we must anticipate that not all options will be successful. The best strategy, therefore, is a well-balanced portfolio of agency-funded experiments in progress, and an equally well-balanced portfolio of options being pursued.

The NWG has considered the above options on the basis of the following criteria:

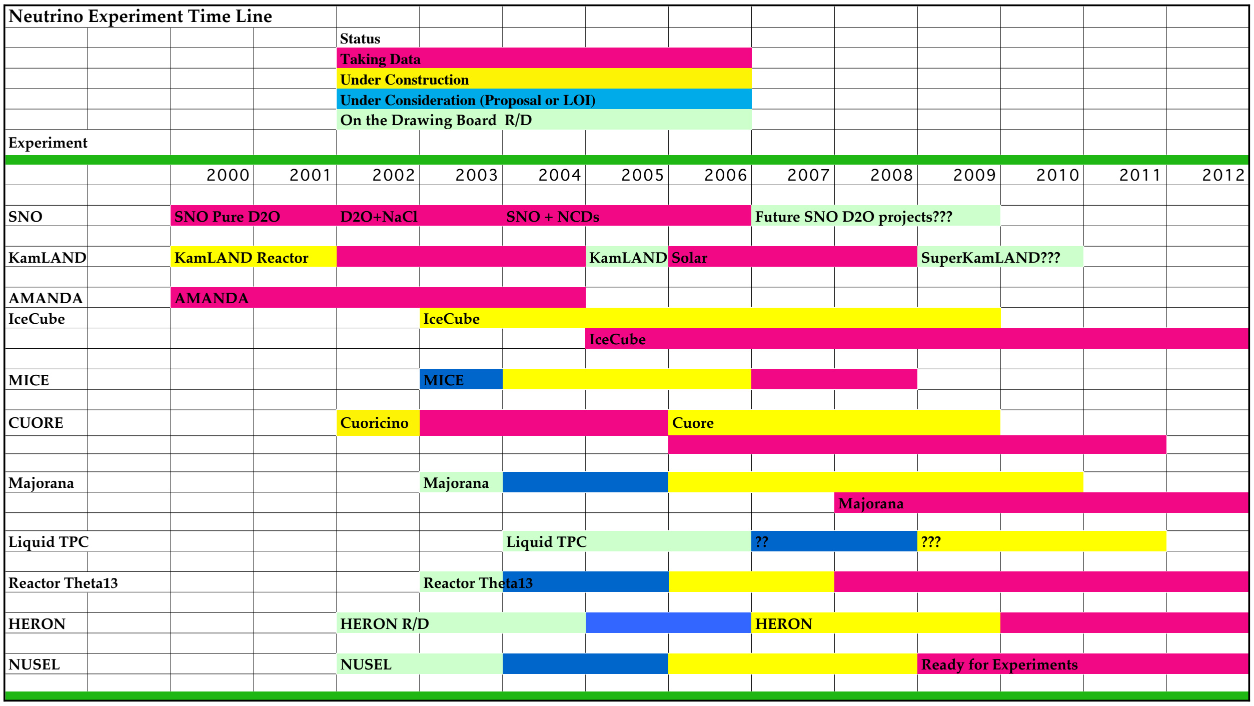
- *Is the science outstanding?*
  Yes — the measurement of neutrino properties, masses and mixing is fundamental to nuclear and particle physics.
- *Are they appropriate for LBNL?*
  Yes — in various ways they constitute a unique contribution, whether in scale, technology, experience or resources and are consistent with the NSAC or HEPAP Long Range Plans.
- *Is there local interest and expertise?*
  Yes — only those options satisfying this requirement are considered in this section.
- *Is it within the realm of possibility?*
  Yes — the prospects for funding, local resources, interdivisional/UCB collaboration, are sufficiently good to warrant pursuing the option.

Considering the options on the basis of these criteria also makes it possible to establish priorities. Assigning priorities is a complex process and a measure of subjectivity is unavoidable. Nevertheless, a clear ordering has emerged from our work.

1. The first requirement is to meet our present commitments.

Beyond that, we order the options as follows:

2. Neutrinoless double beta decay;



Neutrino Experiment Time Line

Status
🟥 Taking Data
🟨 Under Construction
🟦 Under Consideration (Proposal or LOI)
🟩 On the Drawing Board R/D

Experiment	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
SNO	🟥 SNO Pure D2O	🟥	🟥 D2O+NaCl	🟥	🟥 SNO + NCDs	🟥	🟥	🟩 Future SNO D2O projects???	🟩	🟩			
KamLAND	🟨 KamLAND Reactor	🟨	🟥	🟥	🟥	🟩 KamLAND	🟥 Solar	🟥	🟥	🟩 SuperKamLAND???	🟩		
AMANDA	🟥 AMANDA	🟥	🟥	🟥	🟥								
IceCube				🟨 IceCube	🟨	🟨	🟨	🟨	🟨	🟨			
						🟥 IceCube	🟥	🟥	🟥	🟥	🟥	🟥	🟥
MICE				🟦 MICE	🟨	🟨	🟨	🟥	🟥				
CUORE			🟨 Cuoricino	🟥	🟥	🟥	🟨 Cuore	🟨	🟨	🟨			
							🟥	🟥	🟥	🟥	🟥	🟥	
Majorana				🟩 Majorana	🟦	🟦	🟨	🟨	🟨	🟨	🟨		
									🟥 Majorana	🟥	🟥	🟥	🟥
Liquid TPC					🟩 Liquid TPC	🟩	🟩	🟦 ??	🟦	🟨 ???	🟨	🟨	
Reactor Theta13				🟩 Reactor Theta13	🟦	🟦	🟨	🟨	🟥	🟥	🟥	🟥	🟥
HERON			🟩 HERON R/D	🟩	🟩	🟦	🟦	🟨 HERON	🟨	🟨	🟥	🟥	🟥
NUSEL			🟩 NUSEL	🟩	🟦	🟦	🟨	🟨	🟨	🟥 Ready for Experiments	🟥	🟥	🟥

Table 6: Time lines for possible neutrino projects at LBNL.

3. A reactor neutrino measurement of θ_{13};
4. Measurements of θ_{12} and tests of the Standard Solar Model;
5. Development of the scientific and technical infrastructure for NUSEL.

We realize that these recommendations are only input to a more complex set of decisions that Management must undertake. We hope that this evaluation nevertheless will be useful. However future decisions may turn out, we can state with confidence that each of these options is well worth pursuing.

6.7 Time lines

The approximate time lines for the neutrino projects included in this report are shown in Table 6. The four states of a project shown here are: (i) the R&D phase (or "on the drawing board"); (ii) a proposal or LOI that is under consideration; (iii) under construction; and (iv) taking data. It is a given that the earliest possibility for new construction is FY06. Projects with modular construction (double beta decay, IceCube) can be under construction and taking data at the same time. A date for the beginning of construction is usually the soonest that construction could begin. For example, Majorana plans to submit a proposal this Spring. If CD0 status is attained this fall, then construction could begin in FY06, as indicated in the time line. Thus this schedule, as well as others, tends to be optimistic.

A comparison of time lines for a large number of neutrino projects was prepared by K. Lesko in April 2002 for the Snowmass meeting. It is updated in Appendix B.

6.8 The LDRD process

The Laboratory has facilitated, indeed enabled, LBNL's current prominence in neutrino science through its judicious use of LDRD. This has occurred through the normal processes once the LDRD proposals are transmitted upward by the respective Divisions.

We have thought about the process that precedes this, namely, that by which LDRD proposals are generated and considered in the Divisions and the importance of this for proposals involving neutrino science. We subscribe to the view that proposals in neutrino science are best prepared by individuals or small groups rather than by a committee. However, given several proposals, we considered whether it would be best to

A. Do nothing beyond submitting them as separate individual proposals, as is presently the case. The individual Divisions evaluate them according to their respective procedures.

B. Attempt to coordinate them before submission? This would mean that the proponents get together and look for synergies, common themes, etc., and write a common cover letter, if it looks like that would be valuable.

C. Have them reviewed by an ad-hoc group convened by the Division Heads? Priorities assigned? And then submitted. Clearly, B could precede C.

Our view is that it would be better to go beyond the present approach, A, and initiate a process, preferably informal, along the lines of B or C above. The discussion of ideas and proposals within our working group has been valuable and this type of interaction among proponents would also be worthwhile in the early stages of the LDRD process.

Conclusion: The LDRD process A coordination and review of neutrino science related LDRD proposals at the General Sciences level, before submission to Laboratory review is desirable.

6.9 Summary

The above considerations all point toward a continuing role for LBNL in neutrino science. This role is already strong. The number of people involved in experimental neutrino science at LBNL has increased significantly in recent years. (Fifteen years ago there only a few.) If this role continues it will likely grow as it has in the past — around individual experiments and projects with participation cutting across divisional boundaries and a healthy overlap among participants.

The above considerations all point toward neutrino science, but do not point in a single direction within this field. They indicate several paths to take, concurrently. It is to be expected that not all paths will be equally successful, indeed, some may not succeed at all. But it is through the exploration of a variety of paths — paths opened as the result of individual and group creativity and sweat — that we end up on the most rewarding ones.

The question is invariably asked: wouldn't it be better, more efficient, more effective to pick the best experiment and focus all your resources on it, and to have the largest possible impact because of the size and focus of the effort? The apparent concentration of the Relativistic Nuclear Collisions group's entire effort on the STAR detector at RHIC is often cited as an example.

We suggest that the nature of neutrino science and non-accelerator physics argues for our having a portfolio of experiments and following several paths rather than the monolithic approach that may work well in other fields. One still has to make choices (one sees examples of this in the above discussion) and hopefully the Neutrino Working Group will have facilitated making the best choices in the near future. The wonderful thing about neutrino science right now is that there are a number of inviting paths to explore with the prospect of fundamental discoveries along the way.

Appendices

A Neutrino Working Group

Charge to the committee

"The working group should survey the theoretical landscape and recent experimental results to provide a framework for understanding which will be the most compelling next set of neutrino experiments world-wide. All ongoing and planned neutrino-related work at LBNL should be surveyed and placed into the above context by the working group through discussion with the proponents. The resulting theoretical context, the ongoing program, and future options should be presented at a joint one-day retreat and workshop in early December open to members of all three divisions. The future plan should lay the groundwork for development of proposals (both LDRD and external) for support of our work."

Email from Siegrist, Schroeder, and Barletta to the NWG members, July 26, 2002

Working group members

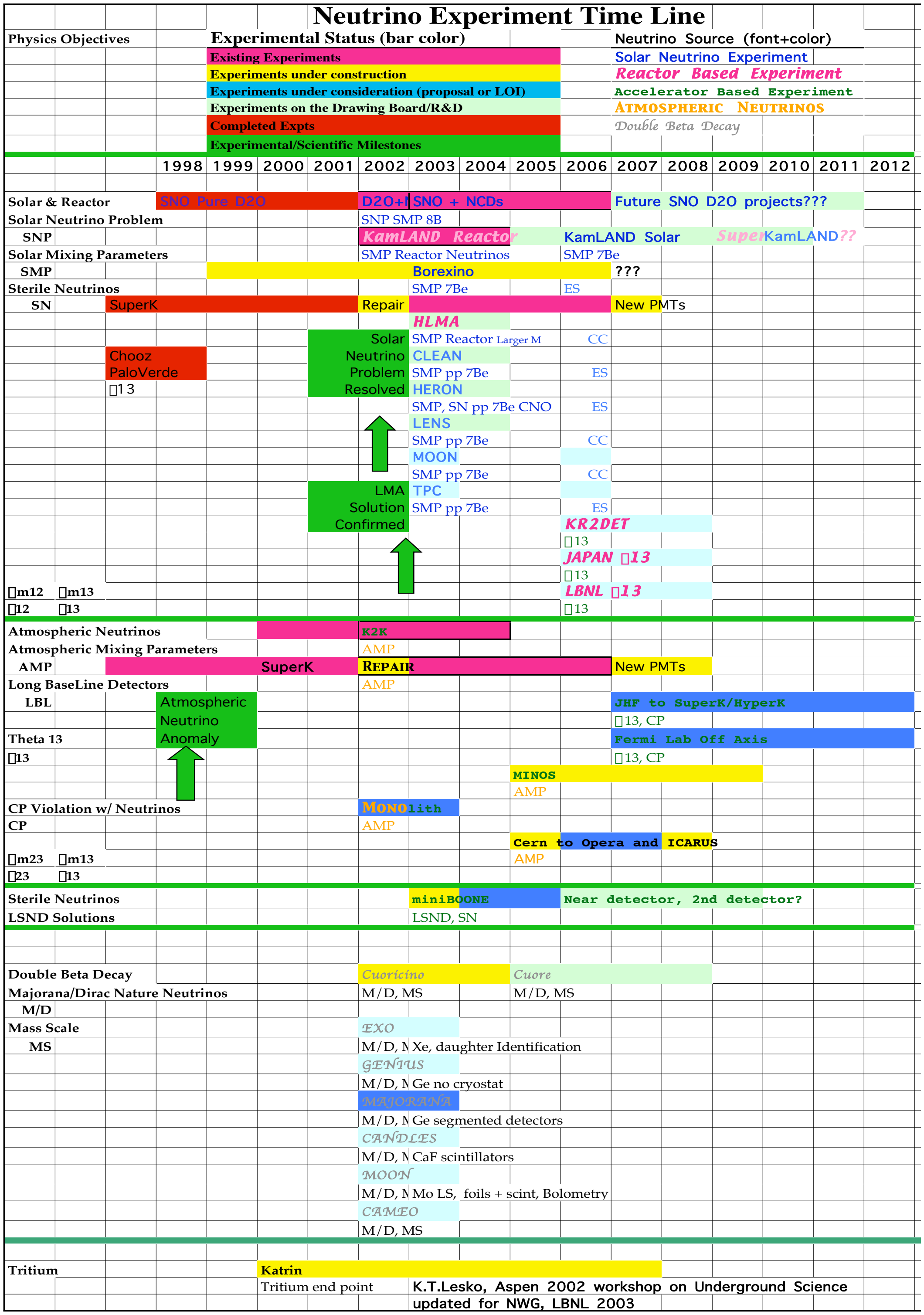
Robert Cahn (PD)
William Carithers (PD)
Stuart Freedman (NSD, UCB)
Karsten Heeger (PD)
Richard Kadel (PD)
Volker Koch (NSD)
Kevin Lesko (NSD)
Zoltan Ligeti (PD), *deputy*

Kam-Biu Luk (PD, UCB)
Hitoshi Murayama (PD, UCB)
Eric Norman (NSD)
David Nygren (PD)
Andrew Sessler (AFRD)
Robert Stokstad (NSD), *chair*
Jonathan Wurtele (AFRD, UCB)
Michael Zisman (AFRD)

Working group meetings

Topic	Presenter	Date
NWG organization	R. Stokstad, Z. Ligeti	Aug 28, 2002
Theoretical overview; individual viewpoints	H. Murayama; all	Sep 4, 2002
Low energy experiments and solar neutrinos	K. Heeger, K. Lesko	Sep 25, 2002
Accelerator neutrinos	K-B. Luk	Oct 9, 2002
Neutrino astronomy	D. Nygren	Oct 16, 2002
Underground laboratories	K. Lesko	Oct 23, 2002
Neutrino factories	S. Geer (Fermilab)	Oct 24, 2002
Neutrinoless double beta decay	E. Norman	Oct 30, 2002
Analysis and development of plan	all	Nov 7, 2002
Analysis and development of plan	all	Nov 13, 2002
Double beta decay; writing the report	I-Y. Lee; all	Nov 20, 2002
Report outline and assignments	all	Dec 18, 2002
Reactor-based measurement of θ_{13}	K. Heeger, K-B. Luk	Jan 31, 2003
Discussion of final report	all	Mar 20, 2003

B Time Lines of Neutrino Experiments



Neutrino Experiment Time Line

Physics Objectives — **Experimental Status (bar color)** — Neutrino Source (font+color)

Existing Experiments — Solar Neutrino Experiment
Experiments under construction — *Reactor Based Experiment*
Experiments under consideration (proposal or LOI) — Accelerator Based Experiment
Experiments on the Drawing Board/R&D — ATMOSPHERIC NEUTRINOS
Completed Expts — *Double Beta Decay*
Experimental/Scientific Milestones

1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012

Solar & Reactor — SNO Pure D2O — D2O+I — SNO + NCDs — Future SNO D2O projects???
Solar Neutrino Problem — SNP SMP 8B
SNP — *KamLAND Reactor* — KamLAND Solar — SuperKamLAND??
Solar Mixing Parameters — SMP Reactor Neutrinos — SMP 7Be
SMP — Borexino — ???
Sterile Neutrinos — SMP 7Be — ES
SN — SuperK — Repair — New PMTs
HLMA
Solar — SMP Reactor Larger M — CC
Chooz — Neutrino — CLEAN
PaloVerde — Problem — SMP pp 7Be — ES
□13 — Resolved — HERON
SMP, SN pp 7Be CNO — ES
LENS
SMP pp 7Be — CC
MOON
SMP pp 7Be — CC
LMA — TPC
Solution — SMP pp 7Be — ES
Confirmed — *KR2DET*
□13
JAPAN □13
□13
□m12 □m13 — *LBNL □13*
□12 □13 — □13

Atmospheric Neutrinos — K2K
Atmospheric Mixing Parameters — AMP
AMP — SuperK — REPAIR — New PMTs
Long BaseLine Detectors — AMP
LBL — Atmospheric — JHF to SuperK/HyperK
Neutrino — □13, CP
Theta 13 — Anomaly — Fermi Lab Off Axis
□13 — □13, CP
MINOS
AMP
CP Violation w/ Neutrinos — MONOlith
CP — AMP
Cern to Opera and ICARUS
□m23 □m13 — AMP
□23 □13

Sterile Neutrinos — miniBOONE — Near detector, 2nd detector?
LSND Solutions — LSND, SN

Double Beta Decay — *Cuoricino* — *Cuore*
Majorana/Dirac Nature Neutrinos — M/D, MS — M/D, MS
M/D
Mass Scale — *EXO*
MS — M/D, M — Xe, daughter Identification
GENIUS
M/D, M — Ge no cryostat
MAJORANA
M/D, M — Ge segmented detectors
CANDLES
M/D, M — CaF scintillators
MOON
M/D, M — Mo LS, foils + scint, Bolometry
CAMEO
M/D, MS

Tritium — Katrin
Tritium end point — K.T.Lesko, Aspen 2002 workshop on Underground Science
updated for NWG, LBNL 2003

Table 7: Time lines for possible neutrino projects world-wide.

C Excerpts from Recent Reports, Plans, and ad hoc Studies

Neutrino science recently has received considerable attention in long range planning processes as well as from several dedicated workshops and ad hoc committees.

The National Academy of Sciences' Board on Physics and Astronomy produced a report Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century in 2003. Two of these eleven questions are addressed by the program in neutrino science at LBNL. These questions and the report's comments on each are:

"What Are the Masses of the Neutrinos, and How Have They Shaped the Evolution of the Universe? The discovery that neutrinos have mass and can oscillate among their different types has implications for both the Universe and the laws that govern it. Further progress in understanding the masses and oscillations of neutrinos will require an ongoing program of large-scale detectors to study neutrinos from atmospheric and solar sources, striving eventually for sensitivity to the low-energy neutrinos from the proton-proton sequence of nuclear reactions......Finally, the absolute scale of neutrino masses can be probed by end-point studies of beta decay and high-sensitivity searches for neutrinoless double beta decay. ... Elements of this program will require a deep underground laboratory. ..."

"How Do Cosmic Accelerators Work and What Are They Accelerating? .... Identifying the sources of ultrahigh-energy cosmic rays requires several kinds of large-scale experiments to collect sufficiently large data samples .... Dedicated neutrino telescopes of cubic kilometer size in deep water or ice can be used to search for cosmic sources of high-energy neutrinos...."

The Nuclear Science Long Range Plan of 2002 lists the construction of an underground laboratory as its third recommendation:

"3. 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."

In addition to the recommendation for a underground laboratory neutrino science is discussed broadly in the nuclear science long range plan.

The HEPAP Subpanel Report, `http://doe-hep.hep.net/HEPAP/lrp_report0102.pdf`, issued in January 2002, comments on many aspects of neutrino physics. For example, in the scenario with the linear collider built on-shore it suggests

"Significant U.S. participation in the worldwide neutrino program, possibly including use of a new proton decay detector."

while in the event the linear collider is off-shore:

"A major new neutrino facility in the U.S., with significant international participation, as part of the worldwide neutrino program. The facility might be coupled with a new proton decay detector."

On the topic of accelerator R&D, the HEPAP report states

"We support the decision to concentrate on the development of intense neutrino sources, an recommend continued R&D near the present level of $8M per year. This level of effort is well below what is required to make an aggressive attack on all of the technological problems on the path to a neutrino factory. Therefore, we strongly support further development of concepts and detailed simulations, activities that require great intellectual effort but minimal

additional costs."

Again,

"We urge that an international collaboration be formed toward developing an intense neutrino source, to pursue and compare opportunities in the U.S., Japan, and Europe."

And

"A further generation of accelerator-based neutrino oscillation experiments is a key element of the worldwide neutrino program. An intense neutrino source will require a new (or upgraded) proton driver capable of delivering one or more megawatts of beam power."

And further,

"We believe that experiments requiring very deep underground sites will make important contributions to particle physics for at least the next twenty years, and should be supported by the high energy physics community. Particle physic would benefit from the creation of a national underground facility."

The underground laboratory was also recommend by a recent report of the National Research Council (NRC) entitled Neutrinos and Beyond: New Windows on nature.

This panel provided the following assessment:

"A deep underground laboratory can house a new generation of experiments that will advance our understanding of the fundamental properties of neutrinos and the forces that govern the elementary particles, as well as shedding light on the nature of the dark matter that holds the Universe together. Recent discoveries about neutrinos, new ideas and technologies, and the scientific leadership that exists in the U.S. make the time ripe to build such a unique facility."

The NRC also looked at the IceCube experiment and gave it the following recommendation:

"The planned IceCube experiment can open a new window on the Universe by detecting very high energy neutrinos from objects across the Universe. The science is well motivated and exciting, the detection technique is proven, and the experiment appears ready for construction."

Recently, the International Workshop on Neutrinos and Subterranean Science (NESS) was convened in order to produce a road map that will guide neutrino science and related topics worldwide over the next few years. The working groups have presented summaries of their deliberations, which include the entire range of neutrino physics, such large scale neutrino detectors, double beta decay experiments, underground laboratory etc., and give a strong recommendation for the the various facets of neutrino science. It also stresses that both an underground laboratory as well as a large scale neutrino detector such as IceCube would be important for the future of neutrino science.

D Glossary and Acronyms

AMANDA — Antarctic Muon And Neutrino Detector Array
ATLAS — A Toroidal LHC ApparatuS
BABAR — Experiment at SLAC to study B-mesons
CDSHW — CERN–Dortmund–Saclay–Heidelberg–Warsaw experiment, studied charged current neutrino interactions on iron
CHOOZ — Reactor neutrino experiment located near Chooz, France
CNGS — CERN Neutrinos to Gran Sasso
CUORE — Cryogenic Underground Observatory for Rare Events
CUORICINO — small-scale prototype of CUORE
FFAG — Fixed-Field Alternating Gradient
GENIUS — GErmanium NItrogen Underground Setup
GRETA — Gamma Ray Energy Tracking Array
HIPA — High Intensity Proton Accelerator
ICARUS — Imaging Cosmic And Rare Underground Signals
IceCube — Muon and neutrino detector at the South Pole
JHF — Japanese Hadron Facility
J-PARC — Japan Proton Accelerator Complex (formerly JHF)
KATRIN — Karlsruhe Tritium Neutrino Experiment
KamLAND — Kamioka Liquid Scintillator Neutrino Detector
KEK — Research organization for science with high energy accelerators in Japan
LHC — Large Hadron Collider
LMA solution — large mixing angle solution to the solar neutrino problem
LNGS — Gran Sasso Laboratory
LSND — Liquid Scintillating Neutrino Detector (at LANL)
Majorana — Double beta decay experiment named after Ettore Majorana
MICE — Muon Ionization Cooling Experiment
MINOS — Main Injector Neutrino Oscillation Search
MiniBooNE — Mini Booster Neutrino Experiment
MSW effect — Mikheev-Smirnov-Wolfenstein effect of matter-enhanced neutrino oscillations
NuMI — Neutrinos at the Main Injector
NTD — neutron-transmutation-doped
NUSEL — National Underground Science and Engineering Laboratory
OPERA — Oscillation Project with Emulsion-tRacking Apparatus
RAL — Rutherford Appleton Laboratory
RPC — Resistive Plate Chambers
SciDAC — Scientific Discovery through Advanced Computing (program in DOE)
Super-Kamiokande — Neutrino water Cherenkov detector located near Kamioka, Japan
SNAP — Supernova Acceleration Probe
SNO — Sudbury Neutrino Observatory
SSM — Standard Solar Model
θ_{12}, θ_{13}, θ_{23} — neutrino mixing angles related to elements of the MNS matrix [see: Eq. (2)]