Recommendations to the Department of Energy and the National Science Foundation on a Future U.S Program in Neutrino Oscillations

Report to the Nuclear Science Advisory Committee and the High Energy Physics Advisory Panel

Submitted by the Neutrino Scientific Assessment Group

July 13, 2007

Contents

1 Introduction

Neutrinos, nearly massless and electrically neutral elementary particles, provide a unique window on the structure of matter at subatomic scales. They exist in three types: electron, muon and tau-type. In the past decade muon-type neutrinos produced in cosmic ray reactions in the earth's atmosphere and electron-type neutrinos produced in nuclear reactions in the sun's core have been shown to change from one type to another between their source and detection. Further experimentation with both natural neutrino sources and neutrinos from reactors and accelerators has shown that the quantum mechanical mixing of neutrino types, also known as neutrino oscillation, is responsible for this change. A new generation of experiments has been initiated using reactor and accelerator neutrinos to make precise measurements of the parameters that describe the mixing.

The discovery of neutrino oscillation showed that neutrinos have masses, even though those masses are a million times smaller than the mass of the next lightest elementary particle, the electron. The reason the neutrino masses are so small is unknown, but it is expected that physics at energies much higher than those available in our laboratories plays a role. Further, neutrinos are so abundant that the total mass of all the neutrinos in the universe may be comparable to the total mass of all the stars in the universe. Continuing studies of neutrinos will illuminate basic issues in physics at very small distance scales and at very large distance scales.

The three observed neutrino types, called flavor eigenstates, couple to other particles with strengths given by the Standard Model of Elementary Particles. The neutrinos propagate in mass eigenstates that are related to the three flavor eigenstates by a unitary mixing matrix. This matrix is parameterized by three mixing angles, θ_{12}, θ_{23} and θ_{13}, and one phase angle, δ_{CP}. If the phase angle δ_{CP} is neither 0 nor π, CP is violated. Violation of CP invariance leads to different mixing probabilities for neutrinos and antineutrinos.

Access to the mixing is controlled by the differences of the squares of the masses of two mass eigenstates $\Delta m_{ij}^2 = m_i^2 - m_j^2$; two of these mass-squared differences are independent parameters. Using the standard labeling of the mass eigenstates, we know that $m_2 > m_1$ from the solar neutrino experiments, but we do not know if the mass m_3 is greater or less than the relatively degenerate m_1, m_2 pair. This question of the ordering of the mass spectrum is often referred to as the "mass hierarchy" question. Finding the correct result will be important information in our quest to understand the origin of neutrino masses and why those masses are much smaller than the masses of other fermions.

The experimentally measured mixing of neutrinos is very different from the well-measured mixing of the quarks. Contrary to many expectations, two of the mixing angles, θ_{12} and θ_{23}, are large with θ_{23} near its maximum possible value. The third mixing angle, θ_{13}, is unmeasured at this time because it is small. A new set of experiments is being initiated to determine θ_{13}. They are the Daya Bay and Double Chooz reactor experiments in China and France, respectively, and the NOνA and T2K accelerator experiments in the United States and Japan.

If θ_{13} is not too small, it may be possible to mount experiments that will permit us to determine the ordering of the states in the neutrino mass spectrum and to measure CP violation in the neutrino sector of the particle world. Observation of CP violation in neutrino oscillation experiments would be evidence that leptogenesis could account for the dominance of matter over antimatter in our universe. Neutrino experiments to determine the neutrino mass hierarchy and to search for CP violation are the subject of this report.

The Neutrino Science Assessment Group (NuSAG) was established by the Nuclear Science

Advisory Committee and the High Energy Physics Advisory Panel of the Department of Energy and the National Science Foundation "to make recommendations on the specific experiments that should form part of the broad U.S. neutrino science program." To this end, NuSAG has provided advice on the program in neutrino-less double beta decay and on a set of experiments designed to measure $\sin^2 2\theta_{13}$, provided $\sin^2 2\theta_{13} \gtrsim 0.01 - 0.02$.

Concurrently with the development of experiments to measure $\sin^2 2\theta_{13}$, physicists were developing ideas to extend the measurements to test for CP violation in the neutrino sector of particle physics through measurement of δ_{CP}. Given that a 1 MW proton beam is likely to be developed at Fermilab for the NOνA neutrino oscillation experiment, an additional order of magnitude in sensitivity can be obtained using a highly efficient detector such as a 100 kiloton liquid argon time projection chamber or a very massive 300-500 kiloton water Cherenkov detector.

Two strategies, a narrow-band, off-axis neutrino beam using the existing NuMI beam and a wide-band, on-axis, neutrino beam directed to a future Deep Underground Science and Engineering Laboratory (DUSEL) site, have been developed to pursue these goals.

The present charge to NuSAG assumes a megawatt class proton accelerator as a neutrino source and requests answers to the following set of questions in the context of a multi-phase off-axis program and of a very long baseline wide-band beam program:

- **Scientific potential:** What are the important physics questions that can be addressed at the envisioned neutrino beam facility?

- **Associated detector options:** What are the associated detector options which might be needed to fully realize the envisioned physics potentials? What are the rough cost ranges for these detector options?

- **Optimal timeline:** What would be the optimal construction and operation timeline for each accelerator-detector configuration, taking the international context into account?

- **Other scientific considerations:** What other scientific considerations, such as results from other neutrino experiments, will be important to optimally determine the design parameters? What would be additional important physics questions that can be addressed in the same detector(s)?

NuSAG received the charge at the NSAC meeting on March 3, 2006 and at the HEPAP meeting on March 4, 2006. Two vacancies arose on NuSAG and new members were appointed who have particular expertise for the present charges. NuSAG has one European member and one Japanese member who provide expertise on the science and the programs in their regions. As with the first set of charges to NuSAG, all possible conflicts of interest of NuSAG members have been discussed and recorded. A meeting was held in Chicago, IL, on May 20-21, 2006. The agenda for that meeting is presented in Appendix C. The first day of that meeting was devoted to presentations by interested parties. A conference call was held for NuSAG members on November 1, 2006, and a closed meeting was held near Dulles Airport in the Washington, D.C. area on November 12-13, 2006.

At approximately the same time NuSAG received the present charge, the directorates of Brookhaven National Laboratory and Fermilab established a study group with a charge that parallels the charge to NuSAG. NuSAG has benefited from the calculations and considerations of the study group and expresses its appreciation of their hard work.

Section 2 of this report presents the science of neutrino oscillations and the additional science that might be performed in a new, large detector. Section 3 presents experimental issues including beam requirements, the off-axis and wide-band beam strategies, a comparison of the scientific reach of different approaches to long baseline neutrino oscillation experiments and the international context. Section 4 presents the findings and recommendations of NuSAG.

2 Neutrino oscillations and other science with large detectors

2.1 Neutrino Oscillations

2.1.1 The Open Questions and Their Importance

Three leading questions that we would like to answer through future experiments on neutrino oscillation are:

1. *What is the approximate size of the small mixing angle θ_{13}?*
2. *Is the neutrino mass hierarchy normal or inverted?*
3. *Do neutrino interactions violate CP invariance?*

These questions are both interesting and important:

1. What is the approximate size of θ_{13}?

While we know that the mixing angle θ_{13} is small (the present limit determined by a global fit is $\sin^2 2\theta_{13} < 0.19$ at 90% C.L.[1]), we do not know how small. A recent compilation of the θ_{13} predictions of 63 models of neutrino masses and mixing [2] shows very wide variation, with predictions for $\sin^2 2\theta_{13}$ ranging from values slightly above the present upper bound all the way down to 10^{-5}. Thus, learning the actual size of θ_{13} will discriminate between the models. Quite apart from specific models, from the mathematics of mixing it can easily be shown that it is highly unlikely for θ_{13} to be very different from the other, large mixing angles unless there is some physical mechanism making it so. Hence, should we find that $\sin^2 2\theta_{13} < 0.01$, there will be strong motivation to seek a reason, such as a new symmetry, for this behavior. Clearly, learning the size of θ_{13} will be important to our quest for an understanding of the origin of neutrino mass.

The CP-violating phase factor $\exp(-i\delta_{CP})$ that enters leptonic mixing does so only in the $(\theta_{13}, \delta_{CP})$ combination $\sin\theta_{13}\exp(-i\delta_{CP})$. Thus, the size of any δ_{CP}-induced CP-violating difference between neutrino and antineutrino oscillation will depend on the value of θ_{13}. In addition, our ability to tell whether the neutrino mass spectrum is normal or inverted also depends on θ_{13}. If $\sin^2 2\theta_{13} > 0.01 - 0.02$, then we can establish whether the mass spectrum is normal or inverted, and we may be able to determine whether neutrinos violate CP using intense but conventionally produced accelerator neutrino and antineutrino beams (sometimes called “super beams”). But if $\sin^2 2\theta_{13} < 0.01$, a technically challenging neutrino source such as neutrino factory or beta beam will be required to address these issues. Thus, finding out whether $\sin^2 2\theta_{13}$ is larger or smaller than 0.01 is important, not just to discriminate between theories of the underlying physics, but also as a stepping-stone to the study of CP violation and the mass spectrum.

2. Is the neutrino mass spectrum normal or inverted?

The most plausible explanation for the extreme lightness of neutrinos is the "see-saw mechanism." Given this lightness, the arithmetic of the see-saw mechanism suggests that neutrino masses come from physics near the grand unification energy scale, 10^{16} GeV. Needless to say, such physics is far beyond the scope of the Standard Model. From the standpoint of the Grand Unified Theories (GUTs) that describe physics at the unification scale, we expect the neutrino spectrum (or "hierarchy") to resemble the charged lepton and quark spectra. The reason is simply that, in GUTs, the neutrinos, charged leptons, and quarks are all related; they belong to common multiplets of the theory [3]. On the other hand, some classes of string theories lead one to expect an inverted neutrino spectrum. Thus, in working toward a theoretical understanding of the origin of neutrino mass, we would certainly like to know whether the mass spectrum is normal or inverted.

The nature of the spectrum can also help us determine whether, as is widely expected, neutrinos are their own antiparticles. The only known practical approach to confirming this expectation is to show that neutrino-less double beta decay occurs. The rate for this process is proportional to the square of an effective Majorana neutrino mass, $\langle m_{\beta\beta}\rangle$. As pointed out in NuSAG's first report, if the mass spectrum is inverted, then $\langle m_{\beta\beta}\rangle$ must be larger than 10-15 milli-electron Volts (meV). Thus, if the spectrum should be found to be inverted, and a search for neutrino-less double beta decay can establish that the rate for this process is less than the rate that would correspond to $\langle m_{\beta\beta}\rangle$ =10 meV, then we will have learned that, contrary to prejudice, neutrinos are distinct from their antiparticles. Looking at the matter in another way, if the spectrum should be found to be inverted, and neutrinos are their own antiparticles, then an experimental search for neutrino-less double beta decay is guaranteed to see a signal if its reach extends to $\langle m_{\beta\beta}\rangle$ =10 meV.

The question of the character of the spectrum may involve more than the issue of whether it is normal or inverted. The LSND experiment reported an oscillation with short wavelength that calls for a $(\text{Mass})^2$ splitting much larger than either of those in the three-neutrino spectrum being assumed in this report. The first oscillation results of the MiniBooNE experiment, aimed at testing LSND, do not confirm the LSND oscillation. Thus, NuSAG's assumption of a three-neutrino spectrum seems prudent. However, the reported MiniBooNE results concern the behavior of neutrinos, while the LSND signal is for an oscillation of antineutrinos. Thus, the possibility of high $(\text{Mass})^2$ oscillation cannot be dismissed. Should such oscillation be confirmed, the neutrino spectrum would have to be revised altogether to include one or more additional state, and we would have to re-determine the optimum strategy for future neutrino experiments.

3. Do neutrino interactions violate CP?

We would like to know why the universe contains matter but almost no antimatter. An explanation for this crucial feature of the universe is suggested by the see-saw mechanism. This mechanism gives the light neutrinos extremely heavy neutrino "see-saw partners." Both the light neutrinos, ν, and their heavy see-saw partners, N, are their own antiparticles. The heavier the N are, the lighter the ν are. The heavy neutrinos N are too massive to be produced in our laboratories, but they would have been created in the hot Big Bang. They would then have decayed via the modes $N \to \ell + H$ and $N \to \overline{\ell} + \overline{H}$, where ℓ is a lepton and H is the Standard-Model Higgs boson. If today's light neutrinos violate CP, then quite likely so do their heavy see-saw partners. As a result, the CP-mirror-image decays $N \to \ell + H$ and $N \to \overline{\ell} + \overline{H}$ have different rates, so that N decays in the early universe would have produced a world with different numbers of leptons and antileptons. Processes predicted by the Standard Model would then have converted some of this lepton-antilepton asymmetry into a baryon-antibaryon asymmetry, producing the matter-antimatter asymmetric world that we see today. Clearly, to explore the possibility that leptogenesis is indeed the origin of the matter-antimatter asymmetry of the universe, we must find out whether the light neutrinos violate CP.

2.1.2 How the questions can be answered

So long as $\sin^2 2\theta_{13} > 0.01 - 0.02$, the three open questions we are discussing can all be answered by a program of experiments using conventionally generated accelerator neutrino and antineutrino beams and reactor antineutrinos. In a previous NuSAG report, we discussed the determination of θ_{13}. In the present report, we focus on determining the neutrino mass hierarchy and searching for CP violation.

The mass hierarchy and CP violation can both be probed via accelerator neutrino experiments that study the oscillations $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ [4]. The appearance probability for ν_e in a beam that is initially ν_μ can be written for $\sin^2 2\theta_{13} \lesssim 0.20$

$$P(\nu_\mu \to \nu_e) \cong T_1 \sin^2 2\theta_{13} - T_2 \alpha \sin 2\theta_{13} + T_3 \alpha \sin 2\theta_{13} + T_4 \alpha^2 \tag{1}$$

Here, $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ is the small ($\sim 1/35$) ratio between the solar and atmospheric (Mass)^2 splittings, and

$$\begin{aligned}
T_1 &= \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta)]}{(1-x)^2} \\
T_2 &= \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\
T_3 &= \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\
T_4 &= \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}
\end{aligned}$$

In these expressions $\Delta = \Delta m^2_{31} L/4E$, with L the distance between the neutrino source and the detector and E the neutrino energy, is the kinematical phase of the oscillation, and $x = 2\sqrt{2} G_F N_e E/\Delta m^2_{31}$, with G_F the Fermi coupling constant and N_e the electron number density, is a measure of the importance of the matter effect.

In the appearance probability, $P(\nu_\mu \to \nu_e)$, the T_1 term represents the oscillation due to the atmospheric mass scale, the T_4 term represents the oscillation due to the solar mass scale, and the T_2 and T_3 terms are the CP violating and CP conserving interference terms, respectively. The solar term leads to ν_e appearance even if $\sin^2 2\theta_{13} = 0$.

The probability for the corresponding antineutrino oscillation, $P(\overline{\nu}_\mu \to \overline{\nu}_e)$, is the same as the probability $P(\nu_\mu \to \nu_e)$ of Eq. (1), but with the signs in front of both x and $\sin\delta_{CP}$ reversed; both the matter effect and CP violation lead to a difference between the $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillation probabilities. In view of the dependence of x on Δm^2_{31}, and in particular on the sign of Δm^2_{31}, the matter effect can reveal whether the neutrino mass hierarchy is normal or inverted. However, to determine the nature of the hierarchy via the matter effect, and to establish the presence of CP violation in neutrino oscillation, it obviously will be necessary to disentangle the matter effect from CP violation in the neutrino-antineutrino probability difference that is actually observed. To this end, complementary measurements will be extremely important. These can take advantage of the differing dependences on the matter effect and on CP violation in $P(\nu_\mu \to \nu_e)$ Eq. (1).

Given that $|\Delta m^2_{31}| \cong 2.7 \times 10^{-3}$, the matter-effect parameter $|x| \cong E/12$ GeV. With this in mind, we imagine, as an illustration, measurements made at accelerator neutrino energies of ~ 1 GeV, and at the L/E corresponding to the first maximum of the "atmospheric" oscillation term, $\sin^2 2\theta_{13} T_1$ of $P(\nu_\mu \to \nu_e)$, that is, at L/E such that $[(1-x)\Delta] = \pi/2$. Then, from Eq. (1) we see that—at this given L/E—the effect of matter on this term, $1/(1-x)^2 \cong 1 \pm (E/6\text{GeV})$, grows with energy, enhancing (suppressing) the term if the mass hierarchy is normal (inverted). In contrast, at this same fixed L/E, the CP-violating T_2 term in $P(\nu_\mu \to \nu_e)$ is approximately proportional to Δ, hence to L/E, so that it grows with L and decreases with E. At fixed L/E, it does not vary with energy or distance. However, if we go from the first atmospheric oscillation maximum to the second one by reducing the energy a factor of three, the effect of matter on the $\sin^2 2\theta_{13} T_1$ term is reduced by a factor of three while the CP-violating term proportional to $\sin \delta_{CP}$ is tripled.

As the probability $P(\nu_\mu \to \nu_e)$ of Eq. (1) and the subsequent definitions also make clear, measured oscillation probabilities will depend on several intertwined parameters, so, again, complementary measurements will be very important. (One of the parameters involved is the atmospheric mixing angle, θ_{23}, which is known to produce large mixing. In this report, we do not consider degeneracies associated with non-maximal θ_{23}. We take θ_{23} to have the value that fits the data best: $45°$. Calculations done by the study group propagate the 5% uncertainty on this value.)

The violation of CP can either enhance $\nu_\mu \to \nu_e$ and suppress $\overline{\nu}_\mu \to \overline{\nu}_e$, or *vice versa*, depending on the value of the phase δ_{CP}. Similarly, the matter effect can either enhance $\nu_\mu \to \nu_e$ and suppress $\overline{\nu}_\mu \to \overline{\nu}_e$, or *vice versa*, depending on the sign of Δm^2_{31}. For a given θ_{13}, the neutrino-antineutrino asymmetry obviously is easiest to observe when CP violation and the matter effect happen to add together in the same direction. When they do, it may be possible to determine the mass hierarchy with NOνA Phase-I for a limited range of the oscillation parameters. It is more likely that one of the more sensitive approaches considered in this report will be needed.

2.2 Other science

Neutrino detectors sensitive enough to measure $\sin^2 2\theta_{13}$ at the 1% level must have very large fiducial masses and efficient fine grained instrumentation, and may be shielded against radiological and cosmic ray backgrounds. These are also the characteristics of next generation proton-decay and neutrino astrophysics detectors. In evaluating proposed neutrino experiments it is important to consider the value added by sensitivity to other important physical phenomena.

2.2.1 Nucleon decay

The observed non-vanishing baryon number B of the universe developed from an initial state that is thought to have had B = 0. This development obviously required non-conservation of B. Thus, one expects that the proton is not stable. Indeed, proton decay is a signature feature of grand unified theories, which place leptons and quarks in a common multiplet and have transitions between members of this multiplet. There are numerous varieties of unified theories that predict proton decay, including non-supersymmetric versions, supersymmetric ones, versions involving extra spatial dimensions, and string theories. A recent review of proton decay theory is given in Reference [5].

Data on the Standard-Model coupling constants suggest that the unification mass scale, M_U, where these coupling constants become equal, is of order 10^{16} GeV. If the proton decays via exchange of a particle with this mass, then one expects that, very roughly, the proton lifetime τ_p will be given by

$$\frac{1}{\tau_p} = a_U^2 \frac{M_p^5}{M_U^4}.$$

Here, a_U is a coupling parameter of order 1/30, and M_p is the proton mass, so that this expression leads one to expect that $\tau_p \sim 10^{36}$ yr. However, the actual predictions of the various unified models cover a very broad range. For example, in models with extra spatial dimensions, the proton lifetime depends on where matter is located in the extra dimensions and can vary from being far longer than 10^{36} yr down to values that would be detectable in the next generation of experiments. The precise prediction of a given unified model depends on details that include the quark flavor physics and neutrino physics within the model. Thus, neutrino physics and proton decay, two windows on physics at the unification scale, may be related.

The ability of a given detector to observe proton decay depends not only on the mass of the detector, but also on the ability of the given type of detector to see at least one of the dominant decay modes. The identity of the dominant modes varies from model to model. In non-supersymmetric unified theories, and also in certain models with extra dimensions and certain string theories, $p \rightarrow e^+ + \pi^0$ is expected to be a dominant mode. In supersymmetric $SU(5)$, as in some string models, $p \rightarrow \overline{\nu} + K^+$ is the dominant mode. In general, the uncertainties in the predictions of relative branching fractions are smaller than those in the prediction of the lifetime, so observations of relative branching fractions could serve to discriminate among the candidate models.

The most stringent current limit on proton decay, from the Super-Kamiokande Collaboration, is the 90% C.L. bound $\tau_p/B(p \rightarrow e^+ + \pi^0) > 8 \times 10^{33}$ years on the decay $p \rightarrow e^+ + \pi^0$ [6]. For the SUSY favored mode, the best limit is $\tau/B(p \rightarrow \overline{\nu} + K^+) > 2.3 \times 10^{33}$ years [7]. A substantial increase in the sensitivity to these and other decay modes would permit very important probes of the natural ideas of unification.

2.2.2 Astrophysics applications

The primary motivation for the program of experiments discussed here is the study of neutrino oscillations. The very large detectors (100 kton or more) that are being considered for that purpose offer unique possibilities to detect neutrinos of astrophysical origin. These applications can often be pursued with a minimum of added costs. A few basic requirements must be fulfilled in order to observe much lower energy events of astrophysics origin: notably the detection threshold should be of the order of 10 MeV or less, and the background rates at these low energies must be sufficiently low.

Large detectors can be used to detect, with high statistics and therefore great detail, neutrino pulses of a galactic supernova (SN), can observe and characterize the diffuse supernova neutrino background, can gather sufficient statistics of solar neutrinos in order to observe the so far elusive day-night effects, and can determine the so far unobserved flux of the *hep* solar neutrinos from the solar fusion reaction $^3\mathrm{He} + \mathrm{p} \rightarrow ^4\mathrm{He} + \mathrm{e}^+ + \nu_\mathrm{e}$.

Galactic supernova

Consider a reference SN located at 10 kpc, roughly the distance to the center of our galaxy, with a total neutrino luminosity of 3×10^{53} ergs equally shared by the three neutrino and three antineutrino flavors, and with a hierarchical temperature (or average energy) scale of $T = 3.5$ MeV ($\langle E_\nu \rangle = 11$ MeV) for ν_e, $T = 5$ MeV ($\langle E_\nu \rangle = 16$ MeV) for $\bar{\nu}_e$, and $T = 8$ MeV ($\langle E_\nu \rangle = 25$ MeV) for all the other neutrino flavors. Flavor oscillations of the neutrinos are neglected. Under these assumptions the neutrino fluence for each flavor will be $2.6 \times 10^{12}/\langle E_\nu \rangle$ cm^{-2} when the average energy is measured in MeV.

A detector on Earth would ideally distinguish four classes of events: Charged current events initiated by $\bar{\nu}_e$, charged current events initiated by ν_e that require nuclear targets, neutral current events that do not distinguish neutrino flavors, and the neutrino-electron scattering that combines the charged and neutral current events.

For reference, a 100 kton (fiducial) water Cherenkov detector will observe $\sim$ 25,000 $\bar{\nu}_e + p \rightarrow e^+ + n$ events, $\sim$ 1000 forward peaked ν, e and $\bar{\nu}, e$ scattering events, $\sim$ 2000 5-10 MeV γ-rays from the neutral current excitation of ^{16}O, and its subsequent de-excitation, and also $\sim$ 500 events for the charged current reactions of (primarily) $\bar{\nu}_e$ on ^{16}O. With such statistics, a detailed determination of the spectra, and their temporal development, would be possible.

While the cross sections on free protons and electrons are straightforward, and for ^{16}O numerous calculations exist, for ^{40}Ar only rather crude estimates of the cross sections in the supernova energy range are available. A 30 kton liquid argon detector will observe several hundred events from the ν_e charged current excitation. While this is a relatively modest yield, it might be the only signal available that is sensitive primarily to the ν_e flux; it is also very sensitive to the oscillation effects.

Diffuse supernova neutrino background

By adding neutrino fluxes of SN from galaxies up to the redshift of $z \sim 1$, we arrive at a continuous flux of diffuse supernova background neutrinos (DSNB). That flux depends on the redshift evolution of the supernova rate and on the neutrino emission rate and spectrum per supernova. Observation and characterization of the DSNB would be an important achievement.

Detection of $\bar{\nu}_e$ seems to be easiest, particularly in the water Cherenkov detectors with Gd admixtures to detect neutrons, thereby enhancing background rejection capabilities. A 100 kton detector might contain of the order of 20 $\bar{\nu}_e$ interactions per year above the 10 MeV threshold. That rate might be substantially enhanced when oscillations are taken into account. Without the Gd, the rate would be lower, but still a positive identification of the DSNB should be possible.

Solar neutrinos: the day-night effect

To set the scale, recall that Super-Kamiokande-I recorded $22,404 \pm 226^{+784}_{-717}$ solar neutrino events in 1496 days of data taking and in the 5-20 MeV interval of the energy of the recoiling electrons. Large water Cherenkov detectors considered here can, in principle, have better statistics, and perhaps reduce the systematic uncertainties as well. Solar neutrinos coming to terrestrial detectors at night travel through the Earth interior and so their oscillations are affected by the Earth matter, leading to the expected "regeneration" or day-night effect in the solar neutrino signal. The expected day-night asymmetry depends on the values of the oscillation parameters, including to some extent also θ_{13}, and ranges between -1.7% and -1.0%.The day-night asymmetry was determined by Super-Kamiokande-I to be $A = -0.021 \pm 0.020^{+0.013}_{-0.012}$, consistent with zero. To actually observe the asymmetry would be an important confirmation of the consistency of the neutrino oscillation phenomena, including the matter effects.

Solar hep neutrino flux

The so called *hep* solar neutrinos originate from the $^{3}\mathrm{He} + \mathrm{p} \rightarrow\ ^{4}\mathrm{He} + \mathrm{e}^{+} + \nu_{\mathrm{e}}$ reaction in the Sun. The corresponding flux is predicted to be about three orders of magnitude weaker than the solar ^{8}B neutrino flux, but—due to its higher endpoint—it might be observable in a large detector. The present upper limit from SNO is about 3-4 times the solar model prediction. Observation of the *hep* solar neutrino flux would be an important confirmation of our understanding of the Sun, and in particular of the role of the pp cycle as the primary solar energy generating mechanism.

Summary

Neutrino detectors of $\sim$100 kton size could have important and unique applications as "neutrino telescopes". While the primary motivation for building a large detector underground is further study of neutrino oscillations and nucleon decay, the astrophysics applications are an additional significant bonus.

3 Planning for a future neutrino oscillation program

3.1 Introduction

Accelerator long baseline neutrino oscillation experiments that are sensitive to CP violation effects and to the neutrino mass spectrum ordering are quite difficult. At distances of many hundreds of kilometers from the neutrino source, the neutrino flux is spread over an area much larger than any detector. With a beam power of ~ 1 MW, the detectors must be very large to have a useful event rate. For a high efficiency detector, having a useful event rate implies a detector mass of 100 ktons or more within the fiducial volume, almost five times the fiducial volume of the Super-Kamiokande detector.

For either the off-axis beam approach or the wide-band beam approach to long baseline neutrino oscillations, optimization is a many dimensional problem. The NuSAG panel does not have the resources to perform independent calculations for all the options, but has used the following resources in its deliberations:

- Presentations made to NuSAG by proponents.
- The results of the BNL-Fermilab long baseline neutrino oscillation study group.
- Phenomenological calculations in the published literature.

- Calculations performed by members of NuSAG.

With these inputs it is possible to come to conclusions regarding the two approaches.

In the following subsections we begin with a discussion of the signal and background issues for neutrino oscillation experiments. This is followed by a discussion of the issues related to obtaining the neutrino beam for the two experimental approaches considered in this report. The off-axis and the wide-band beam strategies are then presented, followed by the options for neutrino detectors. This section concludes with a discussion of possible time-lines for implementing the beam-detector options, a discussion of estimated costs, and a discussion of the international context of a program in long baseline neutrino oscillation physics.

3.2 Neutrino oscillation experiments

3.2.1 Scientific goals

The first of the key physics issues for neutrino oscillation experiments is to determine if $\sin^2 2\theta_{13}$ is non-zero. The experiments that are in the construction and planning phase—Double Chooz, Daya Bay, NOνA and T2K—are designed to address this question. These experiments typically quote sensitivity to non-zero $\sin^2 2\theta_{13}$ if $\sin^2 2\theta_{13} \gtrsim 0.02$ at 2σ or 3σ confidence level depending on the experiment, with some dependence on the value of the CP violating phase δ_{CP} for the accelerator experiments. The new experimental approaches using a conventional beam that are discussed in this report have more sensitivity to $\sin^2 2\theta_{13}$, but are limited by systematic uncertainties to $\sin^2 2\theta_{13}$ of several times 10^{-3}. NuSAG has concluded that knowledge that $\sin^2 2\theta_{13} > 0.01$ is required to proceed with an experiment of the type to study the mass hierarchy and CP violation, so the reach in $\sin^2 2\theta_{13}$ will not be considered further.

The second physics issue is whether $\Delta m^2_{31} > 0$ or $\Delta m^2_{31} < 0$. Measuring the sign of Δm^2_{31} is, for some regions in parameter space, critical for determining whether CP is violated, due to degeneracy between a CP conserving solution with one mass hierarchy and a CP violating solution with the other mass hierarchy. Sensitivity to the mass hierarchy is attained through matter effects as the neutrinos propagate. Larger source-to-detector distance gives larger matter effects, and, for the experiments considered here, increasing the neutrino energy also increases the matter effects. The smallest value of $\sin^2 2\theta_{13}$ for which the mass hierarchy is resolved for all values of δ_{CP} is an important discriminant among experiments.

The ultimate goal for future neutrino oscillation experiments is to measure violation of CP symmetry in the neutrino sector for the reasons discussed in Section 2. If degeneracies due to the uncertainty in the mass hierarchy are resolved, sensitivity to δ_{CP} depends on the value of δ_{CP} and the value of $\sin^2 2\theta_{13}$. If δ_{CP} is near zero or π, it will be very difficult to establish CP violation.

3.2.2 Sensitivity to oscillation parameters

To describe the sensitivity of an experiment it has become conventional to define a confidence level at which a physics parameter such as $\sin^2 2\theta_{13}$ can be shown to be non-zero. Monte Carlo data sets of appearance signals and backgrounds are generated for non-zero $\sin^2 2\theta_{13}$, and a fit to the null hypothesis $\sin^2 2\theta_{13} = 0$ is performed. The difference in χ^2 between the fit for the null hypothesis and the fit for the generated $\sin^2 2\theta_{13}$ is used to establish the confidence level. The sensitivity to CP violation is similarly determined by inputting a CP violating value of δ_{CP} and fitting the data with $\delta_{CP} = 0, \pi$. All other parameters are free and both mass hierarchies are tested. Requiring the hypotheses $\delta_{CP} = 0$ and $\delta_{CP} = \pi$ be excluded at some confidence level establishes the violation of CP invariance. Similarly, to exclude one mass hierarchy, a point in parameter space with the other mass hierarchy is chosen. A fit varying all parameters with the incorrect hierarchy is performed, and the minimum χ^2 value is compared to the χ^2 for the correct hierarchy. The χ^2 distribution for one degree of freedom is used to convert the $\Delta\chi^2$ values into standard deviations.

A difference in the appearance probabilities $P(\nu_\mu \to \nu_e)$ and $P(\overline{\nu}_\mu \to \overline{\nu}_e)$ can arise from either violation of CP invariance or from the matter effect. For a given experiment, establishing the violation of CP symmetry ($\delta_{CP} \neq 0$ and $\delta_{CP} \neq \pi$) may require resolution of parameter degeneracies for some regions of parameter space. In some cases, the violation of CP symmetry may be established independently of ambiguities in other parameters. Resolution of ambiguities may simply require more statistics, but it may require a change in experimental design. Note that matter effects increase with energy, while the CP asymmetry is inversely proportional to energy.

The literature on future long baseline experiments typically uses a confidence level of three standard deviations as the standard for rejecting a null hypothesis such as $\sin^2 2\theta_{13} = 0$ or $\delta_{CP} = 0$ or π. NuSAG has adopted a stronger five standard deviation standard for the rejection of null hypotheses. The large investment required to execute a future long baseline experiment demands this higher degree of confidence in a future result.

3.2.3 Neutrino oscillation signal and background

All the measurements discussed here involve the observation of $\nu_\mu \to \nu_e$ oscillations through the detection of the electron from ν_e charged current interactions in an accelerator-produced ν_μ beam. At the energies under consideration, 20-30% of the appearance events are quasi-elastic scattering events with the balance dominated by pion production, mostly through the production of nucleon resonances but with a component of deep inelastic scattering. The neutrino energy, which is needed to determine oscillation parameters, can be measured for a subset of the events appropriate to a given detector technology.

The principal detector-associated background to detection of oscillated ν_e arises from events in which a single π^0 is produced, but the two gammas cannot be distinguished from a single electron. For some detectors, the π^0's are easily rejected while they are a serious concern for other detectors. For low energy π^0's in the latter detectors, there is typically a large angular separation between the π^0's decay γ's leading to good π^0 identification and rejection. For energies above 1-2 GeV, the angular separation is smaller and rejection by angular separation or tracking places greater demands on the detector technology.

Conventional beams that produce neutrinos through the decay of π and K mesons include an intrinsic component of ν_e that arises from the decay of these mesons. These ν_e in the beam produce background interactions that are irreducible and are a barrier to discovery of CP violation for $\sin^2 2\theta_{13} \lesssim 0.01$. New beam technology will be required if $\sin^2 2\theta_{13}$ is this small. One advantage of beta beams and neutrino factories is that the irreducible background from beam-associated neutrinos of the appearance flavor is not present.

3.2.4 Accelerator issues

The existing NuMI neutrino beam at Fermilab is produced by 120-GeV protons from the Main Injector (MI). It has reached 315 kW and has a designed power of 400 kW. Planning is in progress to increase the total power from the MI to 1.2 MW after the Tevatron program ends and to upgrade the NuMI beam. Further upgrades in beam power to 2 MW are under consideration. These further upgrades will add some sensitivity to the experiments under consideration here, but, for the purpose of this report, beam power of 1 MW is assumed.

3.3 The off-axis and wide-band beam strategies

Two strategies, using either a narrow-band neutrino beam produced by selecting neutrinos in a limited range of off-axis angles or a wide-band neutrino beam, have been put forward for experiments to measure CP violation in the neutrino sector if $\sin^2 2\theta_{13} \gtrsim 0.01$. This subsection presents these two strategies.

In the development of the two strategies, the proponents adopted different detector technologies. For the off-axis approach, a liquid argon time projection chamber with a total fiducial mass of 100 kilotons was used. The efficiency of the liquid argon detector is taken to be eighty percent for all charged current ν_e events based on hand scans of simulated events. The wide-band beam proponents initially considered a water Cherenkov detector for detailed study. This technology utilizes the single ring events that are dominated by the quasi-elastic channel, a subset of the charged current ν_e events that is smaller than that available using the liquid argon detector, but one for which an accurate determination of the incoming neutrino energy is possible. To compensate for lower detection efficiency, the wide-band studies have utilized a 300 kiloton water Cherenkov detector. The wide-band beam group also considered deployment of a 100 kton liquid argon detector. More discussion of the detector characteristics is found in Subsection 3.4.

3.3.1 The off-axis neutrino beam approach

An off-axis neutrino beam is based on the observation [8] that, for a given off-axis angle relative to the proton beam direction, the neutrinos entering the detector all have approximately the same energy irrespective of the energy of the pions that produced them, effectively creating a narrow-band beam at this energy. The energy of an off-axis beam is directly related to the off-axis angle chosen.

The off-axis beam approach to neutrino oscillations discussed in this report uses the well-understood NuMI beam from Fermilab that points to northern Minnesota. The distance from Fermilab to the future NOνA detector site is 810 km, and the site is off-axis by a distance of 12 km from the center of the neutrino beam. The NOνA baseline is close to the maximum for a detector that is south of the U.S.-Canada border. The off-axis nature of this site results in a “narrow-band” neutrino beam, which has advantages for background rejection and for the knowledge of the neutrino energy in neutrino-oscillation experiments but which results in a lower overall neutrino flux. An advantage of the upgraded NuMI beamline is that a first version of this beam line already exists.

For a ν_e appearance experiment, the principal background associated with the neutrino detection is neutral current π^0 production in the detector. For a fixed neutrino energy, the π^0s from neutral current interactions will have a lower average energy than the electrons from the quasi-elastic process. The off-axis strategy thereby reduces this background by suppressing the neutrino flux above the desired neutrino energy. The neutrinos in the beam that are produced from K-meson decay typically have larger energies than those produced from pion decay and will therefore be a source of neutral current π^0 background.

The off-axis beam neutrino oscillation strategy picks a beam energy and a source-to-detector distance that is matched to a neutrino oscillation appearance maximum. The off-axis angle is chosen to maximize the neutrino flux at the chosen E_ν/L within geographical constraints on L. For example, to access the first appearance maximum, the NOνA detector is 810 kilometers from Fermilab and 12 kilometers or 0.9° from the NuMI beam axis, while the T2K experiment uses the Super-Kamiokande detector at 295 kilometers from the JPARC neutrino source and is 2.5° from the neutrino beam axis. The second oscillation maximum for the NuMI beam considered for this report utilizes neutrinos that are 3.3 degrees off-axis and 700 kilometers from the source at Fermilab.

3.3.2 The wide-band neutrino beam approach

A wide-band neutrino beam has a large flux of neutrinos, typically at or near 0°, and a broad spectrum of neutrino energies. For long baseline neutrino oscillation experiments, a wide-band beam may access more than one appearance maximum with the range of neutrino energies available [9].

In a wide-band beam, neutral current backgrounds, predominantly from π^0 production, are shifted downward from the value of the incident neutrino energy to a lower value of reconstructed energy, as the outgoing neutrino takes away much of the incoming energy. This has the advantage that π^0s are produced at lower momentum, where the opening angle of the two decay photons may be large enough to allow the events to be rejected. This has the disadvantage that any high energy tail can feed a significant rate of background events into the regions of the first and second maxima; minimizing this rate was one of the chief design features of the off-axis approach discussed above. In the BNL-FNAL study, an off-axis angle of 0.5 degrees was used for the wide-band beam to achieve reasonable background levels at both the first and second maxima. The first maximum, at around 2.5 GeV, is near the maximum neutrino energy such that the signal and background can be distinguished in a water Cherenkov detector. The second maximum, at around 1 GeV, is a region of better performance for a water Cherenkov detector, but the neutral current background rate is large there.

Proponents of the wide-band beam approach envision building a detector in the National Science Foundation's proposed Deep Underground Science and Engineering Laboratory. This laboratory would be located up to 2600 km from Fermilab. Because the matter effect increases with distance and the CP violation asymmetry depends on the kinematical oscillation phase Δ in Eq (1), this approach does not lose significant sensitivity to the neutrino oscillation parameters as the distance from source to detector increases within this range.

The wide-band beam approach was originally developed in conjunction with a proposal for a high intensity upgrade of the 28 GeV AGS proton synchrotron at Brookhaven National Laboratory, and many of the calculations have been done for 28 GeV beams. In using a beam produced by protons from the Main Injector at Fermilab, full optimization of the neutrino beam spectral shape and intensity remains to be performed.

3.4 Detectors for long baseline experiments

Detectors for long baseline neutrino oscillation experiments that are sensitive to CP violation must be massive in order to have an acceptable event rate. To set the scale, the MINOS detector in the NuMI beam at Fermilab has a 3.3 kton fiducial mass, and the Super-Kamiokande detector used with the K2K and T2K experiments in Japan has a fiducial mass of 22.5 kton. The NOνA detector planned for the NuMI beam will have a fiducial mass of approximately 20 ktons. To measure CP violation for $\sin^2 2\theta_{13} \sim 0.01$, a high efficiency detector must be designed with a fiducial mass of 100 ktons or more. Detectors of 100 kton mass can also be used to extend the search for nucleon decay and for other science as discussed in Sections 2.2.1 and 2.2.2.

Two detector technologies have been proposed for this measurement: water Cherenkov detectors and liquid argon time projection chambers. The liquid scintillator technology used by NOνA was rejected on the basis of cost. A brief description of the water Cherenkov and liquid argon detectors follows.

3.4.1 Water Cherenkov detectors

The Super-Kamiokande collaboration has demonstrated that a water Cherenkov detector can be used to observe neutrino oscillations using both atmospheric neutrinos and neutrinos produced by the KEK proton synchrotron. It has also established the present limits on most of the possible decay modes of nucleons. Water Cherenkov detectors are instrumented with many photo-multiplier tubes viewing the same large volume of water. Since every through-going cosmic ray muon illuminates almost all of the photo-multiplier tubes, water Cherenkov detectors must be located underground where the muon flux is attenuated. As there are no suitable deep sites near the NuMI beamline, the proponents of the off-axis approach do not consider water Cherenkov detectors.

Electron neutrino appearance in a water Cherenkov detector is identified by comparing the number of single ring electron-like events, which constitute roughly one-third of the total number of electron neutrino events, with the number of single ring electron-like events expected for the hypothesis of no oscillation. The single ring samples for the beams under consideration are predominantly ν_μ quasi-elastic events with charged current pion production modes comprising the balance of the events. The electrons from ν_e-induced electron events in the water Cherenkov detector are discriminated from muons and other particles using the pattern of hit photo-multiplier tubes in the event.

At energies near 1 GeV the water Cherenkov technique has been demonstrated to work well by the Super-Kamiokande and K2K collaborations. There has been concern that at higher energies the background from π^0 events will reduce the sensitivity of water Cherenkov detectors. Two recent studies, both using the Super-Kamiokande analysis package, have shown that tighter cuts lead to an acceptable background rejection factor at the somewhat higher energies studied here [10].

In these studies, the overall signal efficiency for the water Cherenkov detectors is found to be 0.15-0.20 while the overall signal efficiency for the liquid argon detectors discussed in the following subsection is 0.80. This factor of four to five advantage in charged current electron detection efficiency per unit mass for liquid argon was initially estimated to be a factor of three. For the work performed by the BNL-FNAL study group, calculations for 300 kilotons of water Cherenkov detector are compared to 100 kilotons of liquid argon.

The Super-Kamiokande simulations that show that the neutral current π^0 background can be rejected have a photo-cathode coverage of the detector surface of 40%. The minimum photo-multiplier coverage and pixel density needed for this rejection has not been established. Data from Super-Kamiokande I (40% coverage) and II (20% coverage) suggest that the neutrino oscillation program could proceed with 20% coverage, but that greater coverage is needed to identify the nuclear gamma-ray tag critical to certain nucleon decay modes. Because photo-multiplier tubes are the cost driver for water Cherenkov detectors, and photo-multiplier tube delivery is the schedule driver, further R&D is required to optimize the cost and schedule for this detector type.

Water Cherenkov detectors have been used by the IMB, Kamiokande, SNO and Super-Kamiokande collaborations to search for nucleon decay and to study solar neutrino interactions and a variety of other low energy phenomena. Using a 300 kton fiducial volume detector, the limits on proton lifetime could be extended by one order of magnitude over the limits obtained by Super-Kamiokande if a signal is not seen. If a signal is seen, it will be one of the great achievements of science. One order of magnitude gain in nucleon lifetime sensitivity is insufficient to motivate the construction of a 300 kton detector; if such a detector is built for neutrino oscillation studies, that detector should be constructed with sufficient photo-multiplier coverage and overburden to search for nucleon decay and astrophysical neutrinos.

Two approaches for extending the water Cherenkov technique to the megaton detector range have been put forward. The UNO collaboration design uses a single, very large detector of fiducial mass 440 kton, optically segmented into three cubical volumes. The UNO design calls for 56,000 20 inch photo-multipliers and 15,000 8 inch photo-multipliers. The single large cavity approach gives good energy containment for high energy events.

The approach that has been studied in most detail by the BNL-FNAL study group is to build modular detectors of 100 kilotons fiducial mass to reach the megaton scale. The initial goal is to construct three 100 kiloton detectors. The baseline design uses 50,000 photo-multiplier tubes of 10 to 13 inch diameter in each detector for a total of 150,000 photo-multiplier tubes. Technical issues such as excavation of the large cavities appear to be feasible, but are beyond the scope of this report and the expertise of NuSAG.

3.4.2 Liquid argon time projection chambers

Experience to date with large liquid argon detectors is based on the ICARUS 600 ton time projection chamber that is being deployed in the Gran Sasso laboratory in the spring of 2007 to detect neutrinos produced at CERN. The excellent track resolution of a liquid argon detector results in almost complete rejection of neutral current π^0 background. The signal events are electron events produced in charged current quasi-elastic and other low multiplicity charged current interactions. Based on a scan of a modest number of simulated events, this results in an estimated detection efficiency for the electrons produced by oscillation of ν_μ to ν_e in the appearance experiment of 80%. This is roughly a factor of four better than the water Cherenkov detector and much closer to the ideal detector.

The R&D program needed to establish the feasibility of a 100 kton liquid argon detector is underway at Fermilab, with good communication with a parallel effort being implemented in Europe. The leading challenges are establishing sufficient argon purity to achieve long drifts in an industrial rather than a laboratory environment; acquiring the ionization signal on very long, high capacity electrodes; and developing realistic cost and schedule estimates. Studies of argon purity and signal to noise on long wires are underway. If these tests are successful, the liquid argon collaboration proposes to build a large prototype detector in the one kiloton range.

A large liquid argon detector for an off-axis beam would be deployed at or near the earth's surface. In this case, it is essential that the large data rate from cosmic rays be demonstrated to be tractable and that rejection of cosmic ray induced background be demonstrated. A liquid argon detector might also be deployed underground in a laboratory such as DUSEL. For underground deployment there will be additional cost and safety issues that must be understood.

In studying nucleon decay, the liquid argon detector is not as good a general purpose detector as the water Cherenkov detector because it is less massive. Nonetheless, for the decay mode $p \to K^+\overline{\nu}_\tau$ favored in supersymmetric theories, the high efficiency of the liquid argon detector should allow good detection efficiency for all particles in the $K^+ \to \mu^+ \to e^+$ chain. For this important decay mode, the liquid argon detector may be more sensitive than the water Cherenkov detector.

3.5 Comparison of approaches to neutrino oscillation experiments

Comparisons of the approaches to future long baseline neutrino oscillation experiments are made using the work performed by members of the Brookhaven-Fermilab study group on future long baseline experiments. The summary that is presented here is abstracted from the full report of the study group [10].

To make meaningful comparisons of experimental approaches the same beam exposures are used, specifically 30×10^{20} protons on target (POT) for neutrinos and 30×10^{20} POT for antineutrinos. To put this in context, 1 MW at 120 GeV corresponds to 18.8×10^{16} protons/hour. If the accelerator produces a neutrino beam for 130 hours per week for 42 weeks each year, the number of targeted protons is 10.3×10^{20} POT/year. Baseline calculations have used 6.5×10^{20} POT/year. Thus 30×10^{20} POT corresponds to a five year exposure, or, optimistically, a three year exposure. For the studies reported here, equal time is spent with neutrino and antineutrino running. Optimization of the $\nu/\overline{\nu}$ split may be performed in the future.

The proponents of the wide-band beam and the proponents of the off-axis beam used different analysis packages. The wide-band beam group used the GLoBES software package [11]. The procedures are documented in Ref. [12] where similar calculations were performed for a beam derived from the Brookhaven AGS. The off-axis group developed their own software and checked it by comparing calculations for the NOνA detector in the NuMI beamline with those done independently by the NOνA collaboration.

For liquid argon detectors both groups used an overall detection efficiency of 80% on electron neutrino charged current events with an energy resolution of $\sigma(E)/E = 5\%/\sqrt{E(GeV)}$ for quasi-elastic events and $\sigma(E)/E = 20\%/\sqrt{E(GeV)}$ for other charged current events. For the water Cherenkov detector, the efficiency for electron neutrino charged current events is 15-20% after application of the π^0 rejection algorithm. The energy resolution used is approximately 10% at 1 GeV and improves at higher energy, but has significant non-Gaussian tails. Calculations for the liquid argon detector assume a complete rejection of all but the irreducible beam ν_e background. The systematic uncertainty on the irreducible background is taken to be 5%. For the water Cherenkov detector, the systematic uncertainty on the beam plus detector backgrounds is taken to be 10%.

3.5.1 Experimental configurations

Many beam-detector configurations have been studied by the BNL-FNAL Study Group. Four configurations that are promising are compared in this subsection. The detectors considered provide more than one order of magnitude in sensitive mass times efficiency beyond that of the NOνA detector. The detector masses below correspond to fiducial mass. The beam-detector configurations considered by NuSAG are:

Option 1: A 100 kiloton liquid argon detector located at the site of the NOνA detector 810 km from Fermilab and 0.9° off-axis using the NuMI medium energy beam. Data from the NOνA detector is included. This configuration samples the first oscillation appearance maximum.

Option 2: A 50 kiloton liquid argon detector located 810 km from Fermilab and 0.9° off-axis using the NuMI low energy beam operated in conjunction with an additional 50 kiloton liquid argon detector to be located 700 km from Fermilab and 3.3° off-axis. This configuration splits the detector mass equally between the first and second oscillation maxima.

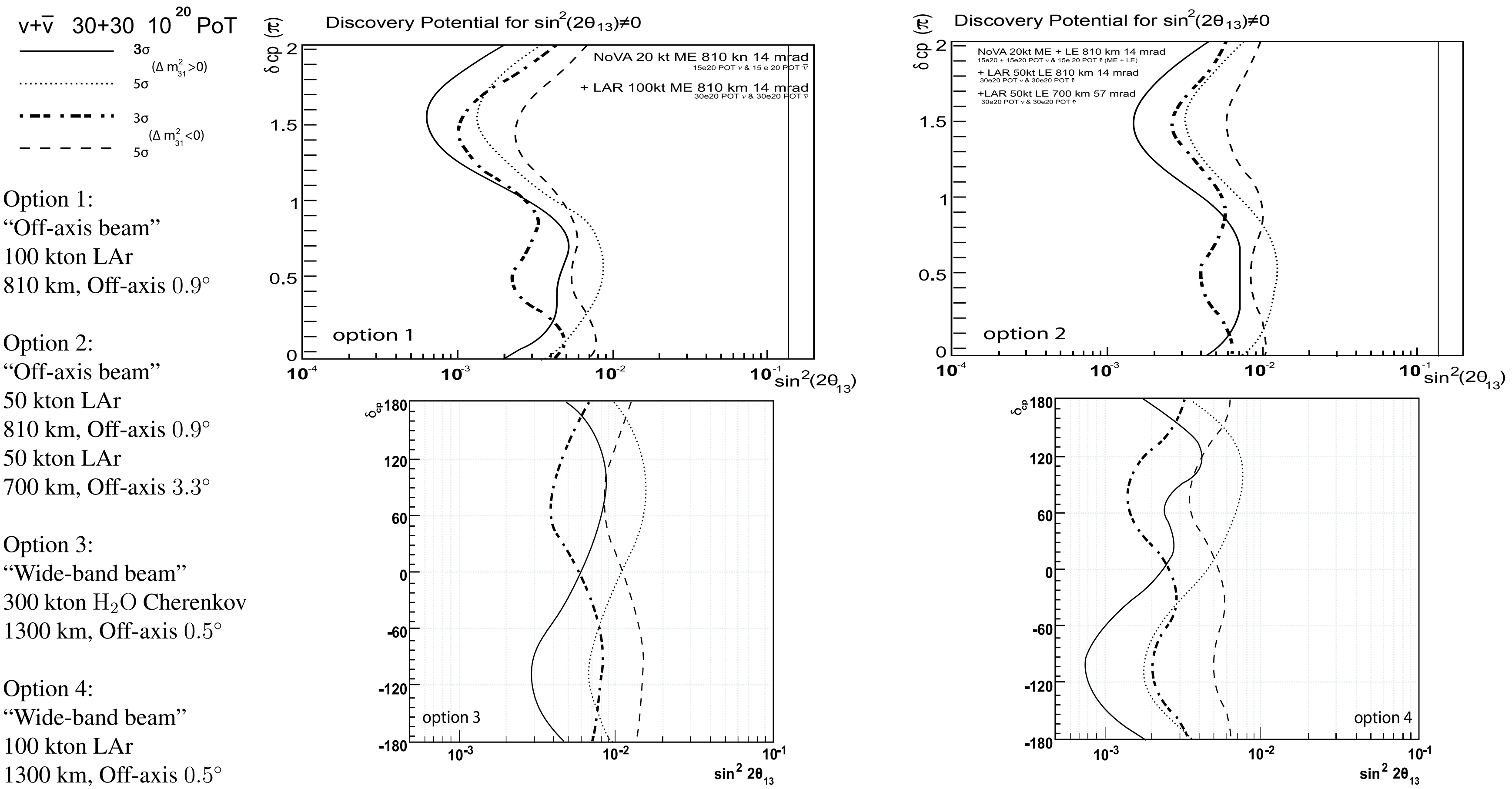
Option 3: A 300 kiloton water Cherenkov detector located in a wide-band beam 1300 km from Fermilab and 0.5° off-axis. This is near the optimum distance for the wide-band approach, but the sensitivity varies slowly between 1000 and 2600 km.

Option 4: A 100 kiloton liquid argon detector located in the wide-band beam 1300 km from Fermilab and 0.5° off-axis. The difference between this case and the preceding case 3 is entirely due to the detector response. The difference between this case and case 1 is the effect of the wide-band beam versus the off-axis beam.

The sensitivity to $\sin^2 2\theta_{13}$, CP violation, and the mass hierarchy is presented in Figures 1-3 for each of the options. These plots were produced by the BNL-FNAL Study Group. Note that these contours represent high-level summaries of complicated data. Much more can be understood by studying the low-level information such as the event rates and the energy spectra of the signals for different input parameters and the event rates and energy spectra of the backgrounds. This information is available in the Study Group report [10] and in plots linked to the Study Group web site: http://nwg.phy.bnl.gov/~diwan/nwg/fnal-bnl/.

The plots in Figures 1-3 show contours for Monte Carlo data generated with the normal mass hierarchy and the inverted mass hierarchy, with rejection of the null hypothesis for each hierarchy for 3σ C.L. and 5σ C.L. indicated as the region to the right of the particular curve. In each figure, the option numbers are labeled and the key is given in the left-hand sidebar. Briefly, the two upper panels in each figure represent the response of the off-axis option 1 and option 2, and the two lower panels show the 1300 km wide-band beam option 3 and option 4. In Figure 1, the ability to reject the null hypothesis $\sin^2 2\theta_{13} = 0$ is displayed, in Figure 2, the ability to reject the null hypothesis $\delta_{CP} = 0, \pi$ is displayed, and in Figure 3, the ability to reject the wrong mass hierarchy is displayed. Note that the horizontal scales have been stretched and aligned and that the vertical scale in the upper figures goes from 0 to 2π while the vertical scale in the lower figures goes from $-\pi$ to π.

The complicated information presented in the plots is reduced further in Table 1 and Table 2. The three right-hand columns in Table 1 show, respectively, the values of $\sin^2 2\theta_{13}$ for which 50%



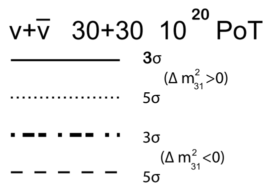
Option 1:
"Off-axis beam"
100 kton LAr
810 km, Off-axis $0.9°$

Option 2:
"Off-axis beam"
50 kton LAr
810 km, Off-axis $0.9°$
50 kton LAr
700 km, Off-axis $3.3°$

Option 3:
"Wide-band beam"
300 kton H_2O Cherenkov
1300 km, Off-axis $0.5°$

Option 4:
"Wide-band beam"
100 kton LAr
1300 km, Off-axis $0.5°$

Figure 1: Plots showing the rejection of the null hypothesis $\sin^2 2\theta_{13} = 0$ for the four detector-beam options discussed in the text. For each hierarchy the rejection is shown as a function of $\sin^2 2\theta_{13}$ for 3σ and 5σ C.L. The key to the graphs and the summary of the options are given in the left-hand side-bar. Note that the vertical scale goes from 0 to 2π on the upper figures and from $-\pi$ to π on the lower figures.



Option 1:
"Off-axis beam"
100 kton LAr
810 km, Off-axis 0.9°

Option 2:
"Off-axis beam"
50 kton LAr
810 km, Off-axis 0.9°
50 kton LAr
700 km, Off-axis 3.3°

Option 3:
"Wide-band beam"
300 kton $\mathrm{H_2O}$ Cherenkov
1300 km, Off-axis 0.5°

Option 4:
"Wide-band beam"
100 kton LAr
1300 km, Off-axis 0.5°

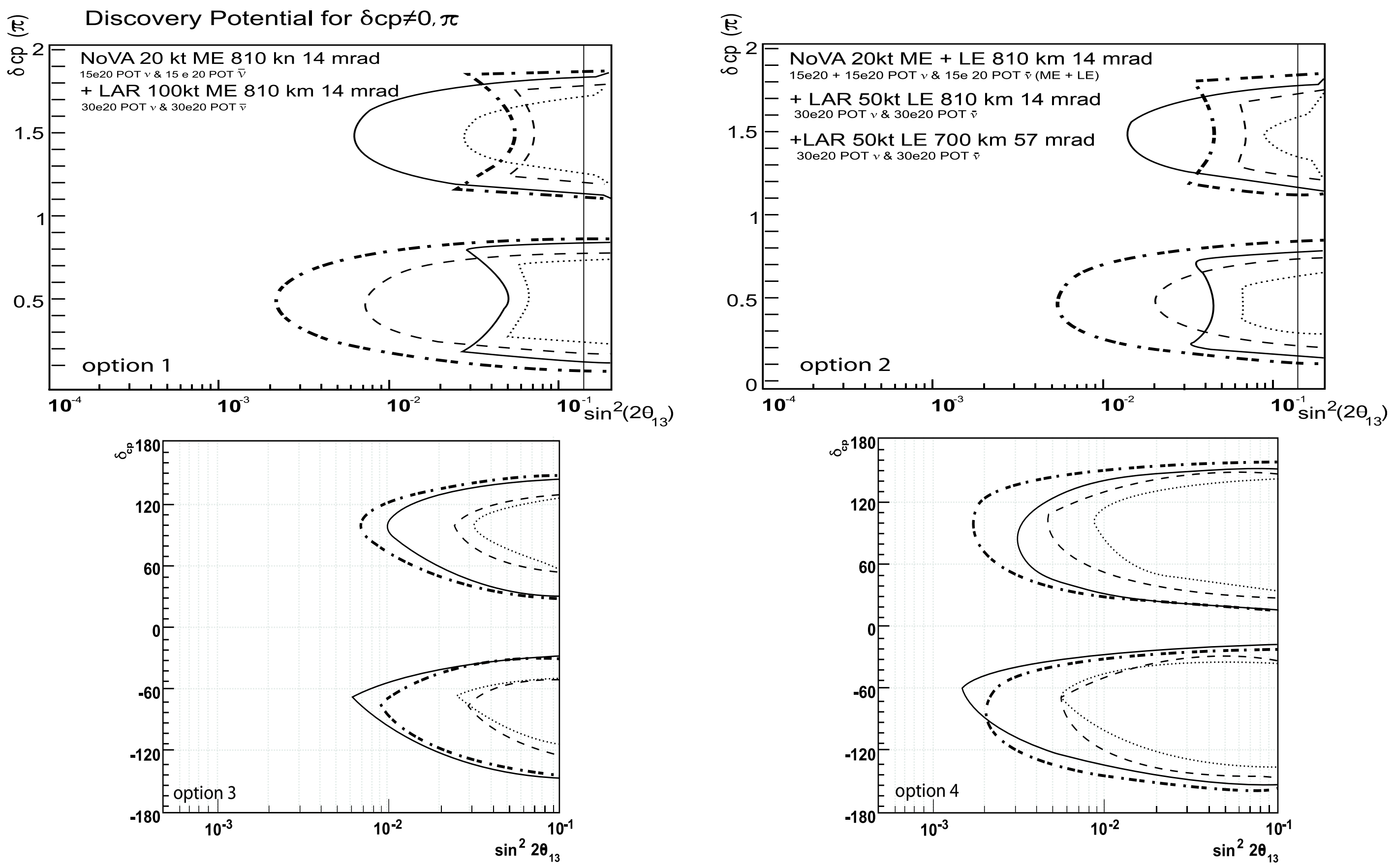
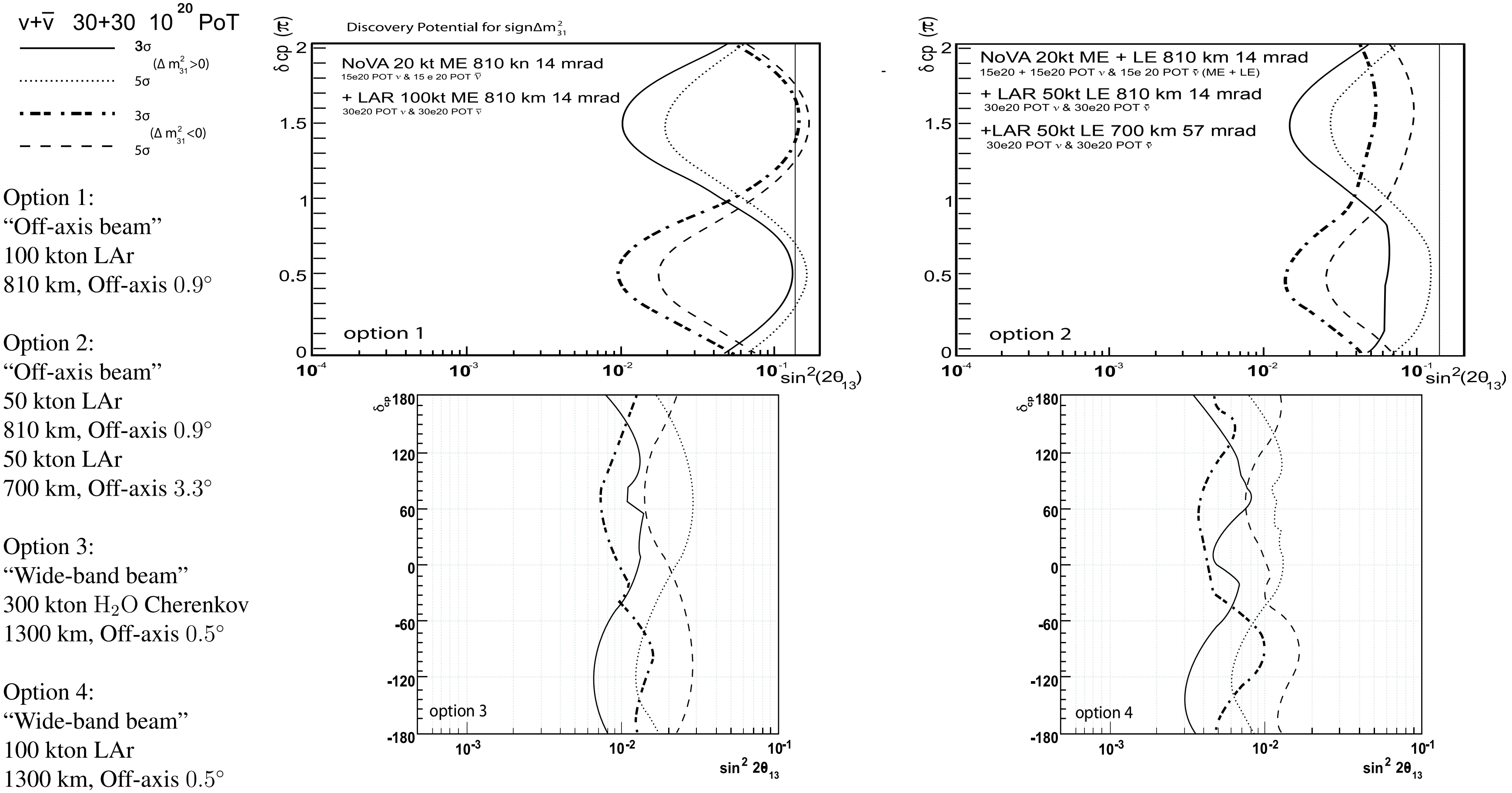


Figure 2: Plots showing the rejection of the null hypothesis that CP is conserved, $\delta_{CP} = 0, \pi$ for the four detector-beam options discussed in the text. For each hierarchy the rejection is shown as a function of $\sin^2 2\theta_{13}$ for 3σ and 5σ C.L. The key to the graphs and the summary of the options are given in the left-hand side-bar. Note that the vertical scale goes from 0 to 2π on the upper figures and from $-\pi$ to π on the lower figures.



Option 1:
"Off-axis beam"
100 kton LAr
810 km, Off-axis $0.9°$

Option 2:
"Off-axis beam"
50 kton LAr
810 km, Off-axis $0.9°$
50 kton LAr
700 km, Off-axis $3.3°$

Option 3:
"Wide-band beam"
300 kton $\mathrm{H_2O}$ Cherenkov
1300 km, Off-axis $0.5°$

Option 4:
"Wide-band beam"
100 kton LAr
1300 km, Off-axis $0.5°$

Figure 3: Plots showing the rejection of the wrong mass hierarchy. For each hierarchy the rejection is shown as a function of $\sin^2 2\theta_{13}$ for 3σ and 5σ C.L. The key to the graphs and the summary of the options are given in the left-hand side-bar. Note that the vertical scale goes from 0 to 2π on the upper figures and from $-\pi$ to π on the lower figures.

Option	Beam	Exposure (POT)	Baseline(s)	Detector	$\sin^2 2\theta_{13}$	δ_{CP}	sgn(Δm^2_{31})
1	NuMI ME, 0.9°	30ν+$30\overline{\nu}$	810 km	LAr 100 kton	0.002	0.02	0.05
2	NuMI LE, 0.9°/3.3°	30ν+$30\overline{\nu}$	810/700 km	LAr 2×50 kton	0.004	0.05	0.04
3	WBB 0.5°	30ν+$30\overline{\nu}$	1300 km	H_2O Ch 300 kton	0.006	0.02	0.01
4	WBB 0.5°	30ν+$30\overline{\nu}$	1300 km	LAr 100 kton	0.002	0.005	0.006

Table 1: Summary of the sensitivity for the four experiments shown in Figures 1-3. All experiments are for exposures of 60×10^{20} protons on target split equally between neutrino and antineutrino running. The numerical values in the three right-hand columns are the values of $\sin^2 2\theta_{13}$ for which the null hypothesis is rejected at $\geq 3\sigma$ confidence level for 50% of the δ_{CP} angles.

Option	Beam	Exposure (POT)	Baseline(s)	Detector	$\sin^2 2\theta_{13}$	δ_{CP}	sgn(Δm^2_{31})
1	NuMI ME, 0.9°	30ν+$30\overline{\nu}$	810 km	LAr 100 kton	0.008	0.08	0.18
2	NuMI LE, 0.9°/3.3°	30ν+$30\overline{\nu}$	810/700 km	LAr 2×50 kton	0.011	>0.10	0.15
2A	NuMI LE, 0.9°/3.3°	30ν+$30\overline{\nu}$	810/700 km	LAr 2×100 kton	0.009	0.08	0.08
3	WBB 0.5°	30ν+$30\overline{\nu}$	1300 km	H_2O Ch 300 kton	0.015	>0.10	0.032
3A	WBB 0.5°	60ν+$60\overline{\nu}$	1300 km	H_2O Ch 300 kton	0.012	0.08	0.022
4	WBB 0.5°	30ν+$30\overline{\nu}$	1300 km	LAr 100 kton	0.008	0.035	0.019

Table 2: Summary of the sensitivity for the four experiments shown in Figures 1-3. Options 1-4 are the same as in Table 1 except that the NuSAG standard for sensitivity is presented. The numerical values in the $\sin^2 2\theta_{13}$ column and the sgn(Δm^2_{31}) column are the values of $\sin^2 2\theta_{13}$ for which $\sin^2 2\theta_{13} = 0$ and the incorrect mass hierarchy are rejected at 5σ for 100% of δ_{CP}. The δ_{CP} column displays the value of $\sin^2 2\theta_{13}$ for which the null hypothesis of no CP violation is rejected at $\geq 5\sigma$ confidence level for 50% of the δ_{CP}. Option 2A shows the effect of doubling the detector mass in option 2 and option 3A shows the effect of doubling the exposure for option 3.

of the values of δ_{CP} will reject the hypotheses $\sin^2 2\theta_{13} = 0$, $\delta_{CP} = 0$ or π, and the wrong hierarchy, at $\geq 3\sigma$ confidence level, respectively. Options 1-4 in Table 2 are derived from the same plots as the information in Table 1, but the null hypotheses $\sin^2 2\theta_{13} = 0$ and the wrong mass hierarchy are rejected at 5σ for all values (100%) of δ_{CP}, and the null hypothesis $\delta_{CP} = 0$ or π is rejected at $\geq 5\sigma$ for 50% of the values of δ_{CP}. The study group report also indicates the response for twice the exposure for two of the configurations. Option 2A doubles the detector size for the two-detector off-axis configuration, and option 3A doubles the beam exposure for the water Cherenkov detector in the wide-band beam. (The entries in Table 2 were estimated from the figures in the study group report using Table XI in the study group report as a reference.)

Using the figures and the summaries in Table 1 and Table 2, it is seen that the best sensitivity to CP violation and to the mass hierarchy is obtained for Option 4, the 100 kiloton liquid argon detector placed at the 1300 km location in the wide-band beam. This is partly because the liquid argon detector is assumed to reject all background events that are not charged current electron neutrino events. At 1300 km, the matter effect gives good separation of the mass hierarchies for appearance probabilities above $P = 0.01$.

The 100 kiloton liquid argon detector located at 810 km off-axis from the NuMI beam (Option 1) has somewhat better reach in CP sensitivity than the 300 kiloton water Cherenkov detector located at 1300 km in the wide-band beam (Option 3). A detector at 810 km is not sufficiently distant from the neutrino source to distinguish the neutrino mass hierarchy well for all values of δ_{CP}, while a water Cherenkov detector at 1300 km resolves the mass hierarchy for all values of δ_{CP} down to $\sin^2 2\theta_{13} \cong 0.03$ and the liquid argon detector at the same location does slightly better.

The final option (Option 2) is the off-axis option with 50 kilotons of liquid argon at each of the first and second oscillation maxima. It is less sensitive to CP violation than the single 100 kiloton off-axis detector at 810 km (Option 1) and is slightly better than Option 1 for 3σ resolution of the mass hierarchy.

Particle physicists usually describe a 3σ effect as “evidence for” a hypothesis and reserve “discovery” for a 5σ effect. Given the order of magnitude increase in detector mass in the experiments described here, the next level of improvement might be achieved with more intense proton beams. This would allow the 3σ effects to be obtained more rapidly and might permit 5σ to be realized within a decade if $\sin^2 2\theta_{13} \cong 0.03$. For this $\sin^2 2\theta_{13}$, and without a significant beam upgrade from 1 MW, the plots show that the 100 kiloton liquid argon detector in the wide-band beam is the only option with 5σ sensitivity to δ_{CP}.

The discussion above has focused on the beam-detector configurations with the maximum sensitivity to the neutrino oscillation parameters. In the case that $\sin^2 2\theta_{13}$ is close to the present limit, it may be possible to make good progress with a smaller detector at the NOνA site. The study group has explored five and twenty kiloton liquid argon detectors at the NOνA site. For a twenty kiloton detector, the CP coverage at three standard deviations rejection of the null hypothesis is significant, but there is no rejection at five standard deviations. Also, the mass hierarchy is not resolved for all values of δ_{CP}. It has been noted [13] that if T2K and NOνA are operated at the same values of $\langle E_\nu \rangle / L$ so that the kinematic oscillation parameters are the same, the differences in response are due to the matter effect. This improves the sensitivity to the mass hierarchy, but the sensitivity of a global analysis has not been calculated for a second phase of long baseline neutrino oscillation experiments.

3.6 Estimated timeline

The decision to proceed with construction of a next generation long baseline experiment depends on knowledge of the value of $\sin^2 2\theta_{13}$. If $\sin^2 2\theta_{13}$ is in the range of values that motivate a new experiment, there follows the time to form a collaboration that can produce a proposal to proceed, the time for the project approval process (CD-0 to CD-3 in the case of DOE), and the actual construction time.

Knowledge of $\sin^2 2\theta_{13}$

NuSAG collected information on the expected sensitivity as a function of time from principals involved in each of the current generation neutrino oscillation experiments that search for non-zero θ_{13}. The responses are presented in the following paragraph. Although the responses presented parameters and sensitivities that differed from those requested in some cases, a reasonable picture of the future is discernible.

The first new information on $\sin^2 2\theta_{13}$ will come from the Double Chooz experiment, which is expected to reach a $\sin^2 2\theta_{13}$ sensitivity of 0.05 at 3σ C.L. at the end of 2012 after a three year run. T2K/JPARC will begin operation in 2009, and the JPARC beam power is expected to reach 0.75 MW by 2012. T2K is expected to have sensitivity to $P(\nu_\mu \to \nu_e) \sim 0.01 - 0.015$ at 90% C.L. by the end of 2012. The Daya Bay reactor experiment is scheduled to begin operation in 2010 and reach sensitivity of $\sin^2 2\theta_{13} = 0.02$ at three standard deviation confidence level in three years. The NOνA experiment will commence data taking when 25% of the detector is installed at the end of 2011 and expects to have three standard deviation sensitivity for $\sin^2 2\theta_{13} = 0.02$ in 2014 and similar sensitivity to $\sin^2 2\theta_{13} = 0.01$ at the end of 2017.

In order to proceed with the construction of the major project under consideration in this report, it will be necessary to have a high level of confidence that $\sin^2 2\theta_{13}$ is large enough that the search for CP violation and measurement of the mass hierarchy will be successful. While a five standard deviation confidence level that $\sin^2 2\theta_{13} > 0.01 - 0.02$ would be desirable for a single experiment, it may be that three standard deviation measurements by two experiments will be sufficient and be available sooner. The earliest that this information will be available is likely to be 2012. If $\sin^2 2\theta_{13}$ is small, the decision might not be made until a few years later.

Approval and construction time

Formation of a collaboration of interested scientists and generation of a proposal typically takes two to three years in particle physics. For the purposes of this report, we will assume that all of this work occurs before $\sin^2 2\theta_{13}$ is known, and therefore does not contribute to the timeline. The approval process for new initiatives (Critical Decisions) in the Department of Energy requires three to four years [14].

It is relatively straight-forward to estimate the time required to construct the water Cherenkov detectors under consideration here. The proponents of both the modular and monolithic approaches have identified manufacture of the large number of photo-multiplier tubes as the critical path item. The presentation on the UNO (monolithic, 440 kton fiducial volume) water Cherenkov detector lists the construction time as nine to ten years with photo-multiplier tube construction a limiting factor. The three module (3 times 100 kton fiducial volume) water Cherenkov detector group estimates seven to eight years to produce 150,000 10 to 13 inch photo-multiplier tubes. These times could be reduced if optimization of the number of photo-multiplier tubes required makes a significant reduction in that number, or if more than one vendor could be engaged as a supplier.

It is not possible to estimate the construction time for a large liquid argon detector at this time because there is no design for a large detector. Assuming that all R&D associated with the development of a large liquid argon detector is complete at the beginning of construction, a guess gives four to six years construction time.

NuSAG estimates that knowledge of $\sin^2 2\theta_{13}$ could motivate a decision to proceed with a long baseline experiment capable of determining the neutrino mass spectrum ordering and investigating CP violation in the neutrino sector around 2012 or shortly thereafter. Approval and construction will require roughly a decade beyond that time. To reduce the total time, it would be necessary to start the approval process before $\sin^2 2\theta_{13}$ is known. It will also be necessary to reassess the international program in neutrino oscillations at that time.

3.7 Cost estimates

The crude cost estimates provided here are based on rough estimates of the proponents and have not been subjected to formal review. In the case of the liquid argon detector, the R&D is not yet to the point where a conceptual design report could be produced. The water Cherenkov detector concept is well established, and a conceptual design could be produced in a much shorter time than for liquid argon. Either of these detectors could be located at the Deep Underground Science and Engineering Laboratory site. Due to the requirement of a deep site, the water Cherenkov detector is not considered for a site in the NuMI beam line.

The large single detector concept for the water Cherenkov approach has a cost estimate based principally on scaling the costs of the Super-Kamiokande detector. The rough number presented to NuSAG for the total cost is $500 M for a 440 kton fiducial volume detector, with the largest single item being photo-multiplier tube and related electronics, corresponding to about 40% of the total cost. For the modular approach to a water Cherenkov detector, the total estimated cost is $335 M based on building three 100 kton fiducial volume modules. Approximately 60% of the cost of these three detectors is photo-multiplier tubes based on 25% of the surface area being covered by photo-cathode.

For a liquid argon detector, the cost of the liquid argon is $1M per kiloton. Estimates for containers to hold the liquid argon are available up to about 50 ktons. At 50 ktons the cost of a tank is roughly $18 M. The project is not advanced enough to project other costs such as refrigeration and electronics. The goal is to reduce the cost per kiloton by one order of magnitude relative to the existing T600 liquid argon detector. A very rough guess would put the lower bound on the cost of a 100 kton liquid argon detector at $200 M. No estimates have been made for actual siting and safety. If the liquid argon detector is sited underground, these costs could be significant.

For the off-axis approach, the infrastructure of the NuMI beam would be reused. For a detector located at a DUSEL site, a new neutrino beam must be constructed. A rough estimate of the cost of a new beam is $100M to $200M, based on the $109M cost of the NuMI project.

3.8 International context

3.8.1 Neutrino oscillation physics in Japan

Neutrino programs in Japan are very successful and productive, with several running experiments and preparations for future experiments. Super-Kamiokande (Super-K) is collecting the world's largest data sample of atmospheric neutrinos and ^{8}B solar neutrinos, and monitors for possible supernova neutrinos continuously. KamLAND is being upgraded to lower the energy threshold to observe ^{7}Be solar neutrinos, and will start solar neutrino observation in 2007. In addition KamLAND is also accumulating more geo-neutrino data. The accelerator-based long baseline neutrino experiment, T2K, is under construction and will start taking data in April 2009. T2K is expected to get the designed intensity of J-PARC (750kW) a few years after the start.

For the longer term future neutrino program in Japan, several proposals are being seriously considered. For a Super-K upgrade, an option with gadolinium (Gd) loading is being investigated to extend the performance to identifying anti-neutrino events by tagging the neutron produced in the reaction. With Gd loading of Super-K, the first observation of relic supernova neutrinos is expected. Study of the relic supernova neutrinos provides information about the era of star formation in the early universe. A high precision and high statistics measurement of neutrino oscillation with reactor neutrinos is another goal of Gd loaded Super-K.

For T2K, there is a plan to increase the proton intensity of J-PARC for neutrino operation. If electron neutrino appearance $\nu_\mu \to \nu_e$ is observed, another extension of T2K is to study neutrino oscillations using an anti-neutrino beam. This would make T2K the first experiment to look into CP violation in neutrino oscillation. At this stage, combined analysis of T2K with reactor neutrino data, atmospheric neutrino data, and the NOνA results is expected.

Building of the next generation Megaton-scale neutrino detector, Hyper-Kamiokande (Hyper-K), as a successor to Super-K is a long-cherished idea in Japan. Hyper-K would be the far detector of T2K Phase-II. In order to realize Hyper-K, intensive R&D work is on-going in Japan. The development of a new photo-sensor, the Hybrid Avalanche Photo-Diode, could result in reducing the cost of photo-sensors and shortening the production time, both of which are also issues for Hyper-K. In parallel, the site selection for Hyper-K is being investigated together with analysis of geology, the cavity and cavern structures issues. This R&D work will continue until evidence of proton decay is obtained or the path to the study of CP violation in T2K is opened by the discovery of $\nu_\mu \to \nu_e$ oscillation.

3.8.2 Neutrino oscillation physics in Europe

The current European neutrino oscillation program is centered on the CNGS beam from CERN to the Gran Sasso laboratory. This is a high energy beam intended to study ν_τ appearance in a ν_μ beam using the OPERA hybrid emulsion detector. This experiment has also a marginally better sensitivity than Chooz to $\sin^2 2\theta_{13}$ through the search for ν_e appearance. The scope of this facility will be increased with the installation at Gran Sasso of the 600 ton ICARUS liquid argon detector which will also search for oscillations.

The next neutrino oscillation experiment to come on line in Europe will most probably be the Double Chooz experiment. This reactor experiment will reuse the cavern used by Chooz as their location for a far detector. However, in addition, a near detector will be installed at a distance of 280m from the reactor to essentially eliminate systematic uncertainties due to reactor flux and interaction cross sections, as well as some arising from detector performance. This, together with a larger mass of 10.2 tons relative to Chooz, will allow this experiment to have a 90% CL limit on $\sin^2 2\theta_{13}$ of 0.03 and a 3σ discovery level of 0.05.

There have been discussions on a possible reuse of the CNGS beam line with lower energy neutrinos and off-axis detectors. One such possibility was to build an underwater Cherenkov detector with a mass of one megaton in the Gulf of Taranto. Another one was to use a large liquid argon detector off-axis.

Further into the future, there have been extensive studies on a use of a low energy neutrino beam produced with a Superconducting Proton Linac (SPL) at CERN and directed to MEMPHYS, a future 500 kton water Cerenkov detector located in a new cavern off the Fréjus road tunnel at a distance of 130 km from CERN. Running two years of neutrinos and eight years of antineutrinos, the sensitivity to $\sin^2 2\theta_{13}$ could be at the level of 0.0015 at 90% CL[15].

CP violation is searched for by comparing oscillations of neutrinos and antineutrinos. Two approaches, going much further in scope than the above, are being considered: beta beams and a neutrino factory.

In a beta beam complex, electron neutrinos or antineutrinos would be produced through beta decays of radioactive ions accelerated in the CERN SPS. Neutrinos would be obtained from the decays of ^{18}Ne and antineutrinos from ^{6}He. This study is proceeding in the context of a design study for EURISOL, a radioactive beam facility for nuclear physics experiments, with which the beta beams have a large synergy. This facility would also use MEMPHYS and could also run concurrently with SPL beams.

In a neutrino factory, pions are produced using an SPL, and the muons produced in their decays are cooled, accelerated to about 20 GeV and stored in a storage ring. Decays of positive muons produce ν_e which can be observed in detectors placed in line with the storage ring straight sections. Oscillations of ν_e to ν_μ can be identified and distinguished from the $\overline{\nu}_\mu$ also produced in muon decays using their charged current interactions in a magnetized detector. Oscillations of antineutrinos are studied by storing negative muons.

The International Scoping Study is currently evaluating the relative merits of the two approaches. Preliminary results indicate that a combination of SPL and beta beams could discover CP violation at 3σ if δ_{CP} differs from 0 or π by more than 25^o for values of $\sin^2 2\theta_{13}$ greater than 0.0035. The corresponding value of $\sin^2 2\theta_{13}$ for a neutrino factory is 0.0015. Whereas the neutrino factory reach in CP violation is definitely better for small values of $\sin^2 2\theta_{13}$, there is no firm conclusion yet for large values of this angle.

3.8.3 The United States role in the world program

Once the value of $\sin^2 2\theta_{13}$ is determined, the search for CP violation in the neutrino sector is the next step in neutrino oscillation physics. The program of measurement addressed in this report is an important contribution to science and complements the program of physics at the energy frontier.

The present program in the United States parallels but does not duplicate the program in Japan. The unique feature of the next generation US program is the potential ability to determine the order of the neutrino mass spectrum using a thousand kilometer baseline available in the U.S. For the Japanese program to compete here would require an investment of a large detector in another country such as Korea.

The neutrino oscillation program in Europe looks beyond the current generation of experiments and could make important contributions with new neutrino source technology, especially if $\sin^2 2\theta_{13} \lesssim 0.01 - 0.02$. European neutrino physicists are pursuing the same detector technologies as physicists in the United States. Given the long lead times to approve and construct the next generation detectors in the U.S. that were discussed in Section 3.6, it may be possible for a European neutrino program to compete with the U.S. neutrino program.

In preparation for the possible implementation of the program discussed in this report, it is important for US scientists to participate in the world program of photo-sensor development, and in the world program of liquid argon detector development. If the expense of a program at this level of sensitivity is determined to be in the range estimated in this report, and there is a strong focus in particle physics on the energy frontier, physicists worldwide may need to work toward the successful implementation of a single neutrino physics program. Should $\sin^2 2\theta_{13}$ be smaller than can be addressed by the program considered in this report, the US should be an active participant in the world program to develop the technology to extend the reach of experiments that investigate CP violation in the neutrino sector.

3.9 Section summary

This section has presented the information gathered by NuSAG on its charge to examine the experimental techniques available for a future long baseline neutrino oscillation program designed to measure the neutrino mass hierarchy and to search for CP violation in the neutrino sector. The following section presents the findings and recommendations of NuSAG.

4 Findings and recommendations for a continuing United States program in neutrino oscillations

This subsection presents a summary and discussion of the principal issues raised in Section 3 with respect to long baseline neutrino oscillation experiments. It concludes with a set of recommendations for the next steps in a program that could lead to a realization of this ambitious program.

Two approaches to long baseline neutrino oscillation experiments and two detector technologies have been reviewed by NuSAG. The comparisons use equal exposures of 30×10^{20} protons on target, or three to five years of a one megawatt beam, for neutrino operation and an equal exposure for antineutrino running. The standard detectors are either a 100 kiloton liquid argon time projection chamber or a 300 kiloton water Cherenkov detector.

The discussions of NuSAG on these topics are summarized in a series of findings, enumerated below. The findings are followed by four recommendations.

4.1 Findings

Scientific Findings

S1 The scientific goals of a program of long baseline neutrino oscillation experiments are to measure the mixing parameter $\sin^2 2\theta_{13}$, to determine the order of the states of the neutrino mass spectrum, and to determine whether there is CP violation in the neutrino sector. Measurement of these quantities is an important goal of elementary particle physics.

S2 The cost of the experiment and the impact of the discovery of CP violation in the neutrino sector on our view of the universe demand a high standard of confidence in the result. For this reason, NuSAG has adopted a standard of five standard deviation rejection of the null hypothesis to establish the discovery of CP violation and the determination of the neutrino mass spectrum. The quantitative comparisons in Table 2 show the value of $\sin^2 2\theta_{13}$ such that the hypothesis of no CP violation is rejected at a confidence level corresponding to five standard deviations for 50% of the values of δ_{CP}.

S3 The neutrino oscillation experiments that are presently under construction or in the final stages of approval (Daya Bay and Double Chooz measuring $\overline{\nu}_e$ disappearance and NOνA and T2K measuring ν_μ disappearance and ν_e appearance) are designed to determine whether the important but unknown mixing parameter $\sin^2 2\theta_{13}$ is non-zero. The accelerator experiments may provide some additional information on the neutrino mass spectrum and CP violation if $\sin^2 2\theta_{13}$ is near the present limit determined by a global fit, $\sin^2 2\theta_{13} < 0.19$ at 90% C.L.[1], but they do not have the sensitivity to reach the five standard deviation discovery level.

S4 Determination of the ordering of the neutrino mass spectrum, searching for CP violation, and resolution of parameter degeneracies with sensitivity down to $\sin^2 2\theta_{13} \sim 0.03$ will require a new generation of experiments with detectors with masses of 100 kilotons or more. This represents an increase in sensitivity of more than one order of magnitude over the experiments that will begin to acquire data in the next few years.

S5 The optimal strategy for the next generation of neutrino oscillation experiments requires experimental information on the value of $\sin^2 2\theta_{13}$.

The strategy for a future experiment will be quite different if $\sin^2 2\theta_{13}$ is just below the present limit from what it will be if $\sin^2 2\theta_{13}$ is below the sensitivity of T2K or NOνA. The panel identified three regimes of $\sin^2 2\theta_{13}$ that lead to different strategies.

(a) **Large $\mathbf{\sin^2 2\theta_{13}}$:** If $\sin^2 2\theta_{13}$ is near the present limit, say $\sin^2 2\theta_{13} \gtrsim 0.1$, it may be possible to establish CP violation with a detector of fiducial mass smaller than 100 kilotons at the off-axis NOνA site. Such an experiment may not resolve the neutrino mass hierarchy by itself. If such an experiment is operated at the same $\langle E_\nu \rangle / L$ as an upgraded T2K experiment so that the oscillation parameters are the same and the difference is dominated by the matter effect, improved sensitivity to the mass hierarchy can be achieved [13]. This speculation should be quantified in future studies.

(b) **Medium $\mathbf{\sin^2 2\theta_{13}}$:** If $\sin^2 2\theta_{13} \gtrsim 0.03$, an experiment of the type discussed in this report should be built. It would have a large reach in the exploration of CP violation and—with a baseline greater than 1000 km—it could determine the neutrino mass spectrum ordering. Again, a cooperative program with T2K could extend the mass hierarchy sensitivity for an experiment with a baseline less than 1000 km, but this option needs further study. The scientific capabilities of experiments discussed by NuSAG are discussed in Section 3.5 of this report.

(c) **Small $\mathbf{\sin^2 2\theta_{13}}$:** If $\sin^2 2\theta_{13} \lesssim 0.03$, the experiments that are considered in this report may not be able to resolve the neutrino mass hierarchy and establish CP violation with certainty. In this case, a new approach will be needed such as the beta beam source under study in Europe, or a neutrino factory. Should one of these technologies prove feasible, it would provide a neutrino source with a well understood spectrum and minimal irreducible background from beam neutrinos with the same flavor as the neutrinos of the appearance channel.

S6 The wide-band beam approach to neutrino oscillation physics can, in principle, utilize either a liquid argon detector or a water Cherenkov detector. If located more than 1000 km from Fermilab, the mass hierarchy resolution is quite good. At a baseline of 1300 km, a 100 kiloton liquid argon detector can discover CP violation for 50% of δ_{CP} values at $\sin^2 2\theta_{13} = 0.035$ and determine the mass hierarchy down to $\sin^2 2\theta_{13} = 0.019$.

The water Cherenkov detector has worse sensitivity, but can determine the mass hierarchy to $\sin^2 2\theta_{13} \cong 0.03$.

S7 The off-axis beam approach to neutrino oscillation physics has good sensitivity to $\sin^2 2\theta_{13}$. The sensitivity to CP violation is reasonable with 50% of δ_{CP} values providing 5σ rejection of the no CP violation hypothesis at $\sin^2 2\theta_{13} = 0.08$. Working only at the first oscillation appearance maximum, the sensitivity to the mass hierarchy is poor.

An off-axis approach that uses 50 kilotons of liquid argon at each of the first and second oscillation appearance maxima suffers from low interaction rate at the second oscillation maximum location chosen. It gives slightly better mass hierarchy response but loses some CP sensitivity due to the lower rate in the detector at the first maximum.

S8 The study of the instability of matter through the search for nucleon decay is an important physics goal. Although the study of neutrino oscillations is the primary motivation for the program under consideration here, including a capability to study nucleon decay in a future program adds important scientific value to the program. If a nucleon decay signal is observed in Super-Kamiokande in the near future, the nucleon decay motivation for a large detector would equal the motivation from long baseline neutrino oscillations. A nucleon decay detector must be located at a site with significant overburden.

S9 Neutrino astrophysics, especially the detection of neutrinos from a possible galactic supernova and the detection of the diffuse supernova neutrinos, would be advanced by the deployment of a large detector in an underground laboratory.

Detector Technology Findings

D1 The off-axis beam approaches considered in the US are based on a detector technology that is to be deployed on or near the earth's surface. An ability to acquire data at a high rate, an ability to process the large volume of data originating from cosmic rays, and an ability to reject background to neutrino oscillation induced by cosmic rays or their secondary products must be demonstrated for this detector technology to be feasible for an experiment sited near the earth's surface. Water Cherenkov detectors do not satisfy this criterion; it remains to be demonstrated that liquid argon time projection chambers do.

D2 The wide-band beam approach could be implemented with the established water Cherenkov detector technology or with a liquid argon detector, if that technology proves successful. Water Cherenkov detectors must be deployed underground for the cosmic ray event rate to be manageable. If liquid argon is deployed underground, there are additional cost and safety issues that are presently not addressed.

D3 LIQUID ARGON DETECTOR:

LAr-1 The principal advantage of a liquid argon detector for neutrino oscillation physics is excellent spatial resolution that results in good rejection of neutral current induced π^0 background. This property results in an estimated factor of four to five greater detection efficiency per unit mass relative to the water Cherenkov approach. The liquid argon detector is highly suited to the study of the decay mode $p \to K^+\overline{\nu}$ favored in supersymmetric models of nucleon decay.

LAr-2 Initiation of construction of liquid argon detectors of 50-100 kton fiducial mass on the time scale of a decision to proceed with a long baseline neutrino oscillation program requires the success of an aggressive R&D program.

LAr-3 Liquid argon detectors are an attractive option for the wide-band beam approach if all R&D is successfully completed and the cost per unit effective mass is competitive.

D4 WATER CHERENKOV DETECTOR:

- WC-1 Water Cherenkov detectors are an established technology for neutrino oscillation and nucleon decay physics. Adequate rejection of background π^0 events in neutrino oscillation experiments has been demonstrated in detailed simulations using the full reconstruction made available by the Super-Kamiokande experiment.
- WC-2 The water Cherenkov detector wide-band beam neutrino oscillation experiment could be ready to proceed at the time $\sin^2 2\theta_{13}$ is determined. The cost of this option is driven by the cost of photo-multiplier tubes, and the schedule is driven by the time to manufacture the photo-multiplier tubes.
- WC-3 The water Cherenkov detector technology has been demonstrated to be a suitable technology for a general purpose search for nucleon decay.
- WC-4 Water Cherenkov detectors are not suitable for deployment at or near the earth's surface due to the large rate of cosmic ray events.

4.2 Recommendations

The Neutrino Scientific Assessment Group finds that a continuing program designed to study CP violation in the neutrino sector and to determine the hierarchy of the neutrino mass spectrum is scientifically compelling. The US program may be unique in the world in its ability to measure the neutrino mass spectrum ordering.

The optimum approach to this science depends on the value of the mixing parameter $\sin^2 2\theta_{13}$. The wide-band beam approach has a greater scientific reach for neutrino oscillations when located at a distance that permits resolution of the neutrino mass hierarchy, and further scope if located at a depth that permits the study of nucleon decay, but greater cost due to the need to construct a new neutrino beam. If technically feasible, a wide-band beam experiment with a LAr detector would have the greatest scientific reach for neutrino oscillations of the options currently under consideration, while the water Cherenkov option provides a practicable alternative with known technology. The off-axis approach studied here has moderate reach for CP violation, but has only fair reach for resolving the mass hierarchy due to the shorter baseline. It depends on the successful development of a liquid argon technology that requires an aggressive R&D program.

There is a tension between the desire to exploit the existing NuMI beam infrastructure using an off-axis beam and the need to go to distances significantly greater than 800 km in order to maximize matter effects to resolve the mass hierarchy. Presuming that the Deep Underground Science and Engineering Laboratory will exist at an appropriate distance, an underground detector there would have good sensitivity to all the parameters of neutrino oscillations and would also extend the search for nucleon decay.

In the following recommendations, NuSAG supports continuation of R&D on intense beams and on both the liquid argon and water Cherenkov detector options.

Recommendation 1. The US should prepare to proceed with a long baseline neutrino oscillation program to extend sensitivity to $\sin^2 2\theta_{13}$, to determine the mass ordering of the neutrino spectrum, and to search for CP violation in the neutrino sector. Planning and R&D should be ready for a technology decision and a decision to proceed when the next round of results on $\sin^2 2\theta_{13}$ becomes available, which could be as early as 2012. A review of the international program in neutrino oscillations and the opportunities for international collaboration should be included in the decision to proceed.

Recommendation 2. Research and development towards an intense, conventional neutrino beam suitable for these experiments should be supported. This R&D may be to support intensity upgrades to the existing NuMI beam, as well as development of a new beam directed towards DUSEL, which would likely employ the wide-band beam approach.

Recommendation 3. Research and development required to build a large water Cherenkov detector should be supported, particularly addressing questions of minimum required photocathode coverage, cost, and timescale.

Recommendation 4. A phased R&D program with milestones and using a technology suitable for a 50-100 kton detector is recommended for the liquid argon detector option. Upon completion of the existing R&D project to achieve purity sufficient for long drift times, to design low noise electronics, and to qualify materials, construction of a test module that could be exposed to a neutrino beam is recommended.

References

[1] Particle Data Group: W.-M. Yao et al., J. Phys.G **33**, 1 (2006).

[2] C. Albright and M.-C. Chen, phys. Rev. D **74** 113006 (2006)

[3] C. Albright, Phys.Lett.B **599**, 285 (2004)

[4] A. Cervera, *et al.*, Nucl. Phys.B **579**, 17 (2000), hep-ph/0002108, and M. Freund, Phys. Rev. D **64** 053003 (2001), hep-ph/0103300.

[5] P. Nath and P. Fileviez Perez, arXiv.org:hep-ph/0601023.

[6] S.T.Clark, Ph.D. Thesis, Boston University, 2006.

[7] Super-Kamiokande Collaboration, Phys.Rev. D **72** 052007 (2005).

[8] Brookhaven AGS Proposal E889, Brookhaven Report BNL-52459, April 1995.

[9] William J. Marciano, arXiv.org:hep-ph/0108181.

[10] Report of the U.S. long baseline neutrino experiment study, Fermilab report 0801-AD-E, May 30, 2007, arXiv:0705.4396.

[11] P. Huber, M. Lindner and W. Winter, Comput.Phys.Commun. **167** 195 (2005), arXiv:hep-ph/0407333, and Patrick Huber, Joachim Kopp, Manfred Lindner, Mark Rolinec and Walter Winter, arXiv:hep-ph/0701187.

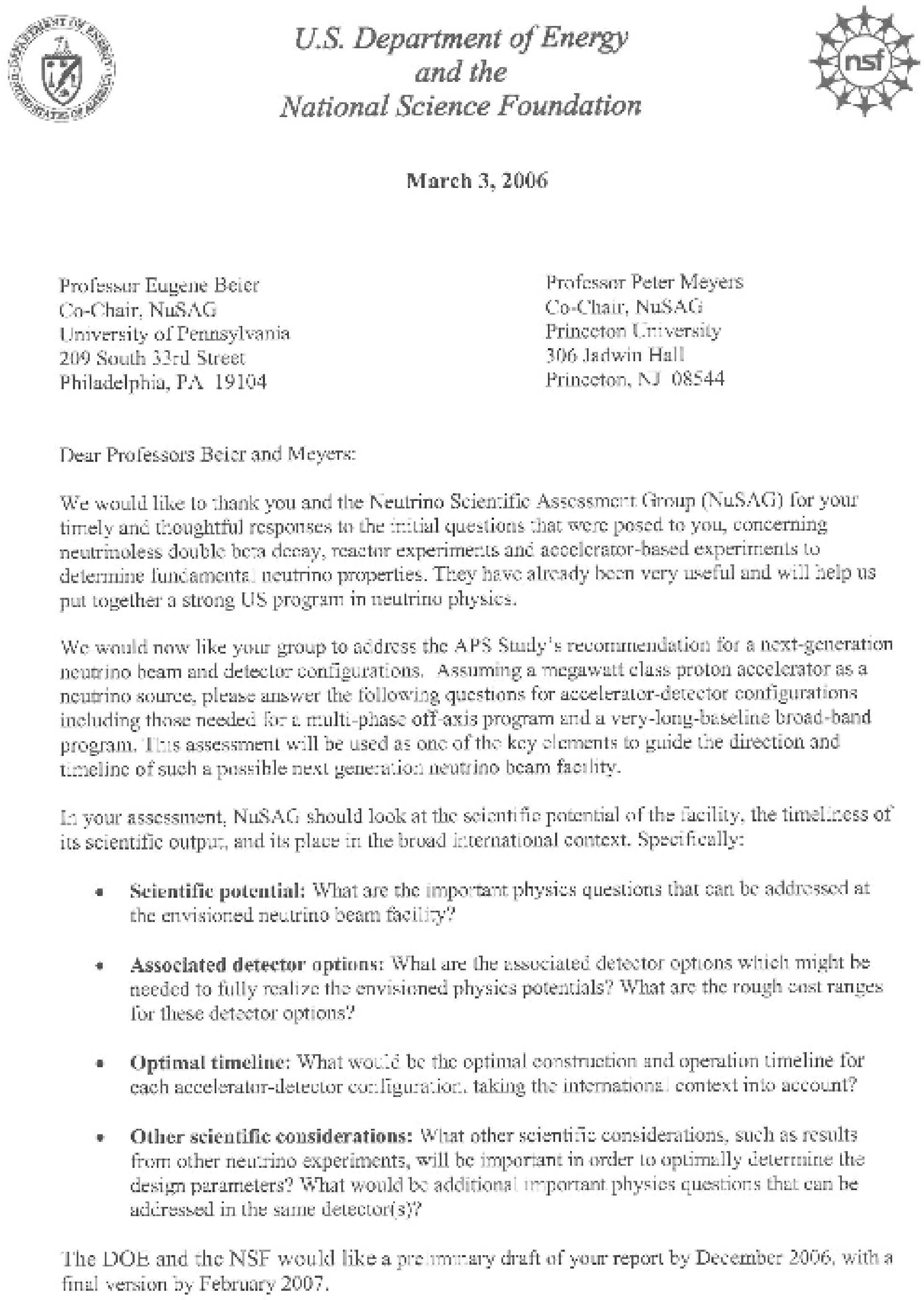
[12] V. Barger, M. Dierckxsens, M.Diwan, P. Huber, C. Lewis, D. Marfatia, and B. Viren, Physical Review D **74** 073004 (2006).

[13] O. Mena, Proceedings of Neutrino 2006, Santa Fe, NM, June 2007; arXiv.org:hep-ph/0609031.

[14] Aesook Byon-Wagner, HEPAP Orientation talk at HEPAP meeting of March 3-4, 2006, slides available at: http://www.er.doe.gov/hep/HEPAP/Mar2006/Aesook_DOE_orientation.pdf

[15] J.E.Campagne and Antoine Cazes, arXiv.org:hep-ex/0411062.

A Charge



U.S. Department of Energy
and the
National Science Foundation

March 3, 2006

Professor Eugene Beier
Co-Chair, NuSAG
University of Pennsylvania
209 South 33rd Street
Philadelphia, PA 19104

Professor Peter Meyers
Co-Chair, NuSAG
Princeton University
306 Jadwin Hall
Princeton, NJ 08544

Dear Professors Beier and Meyers:

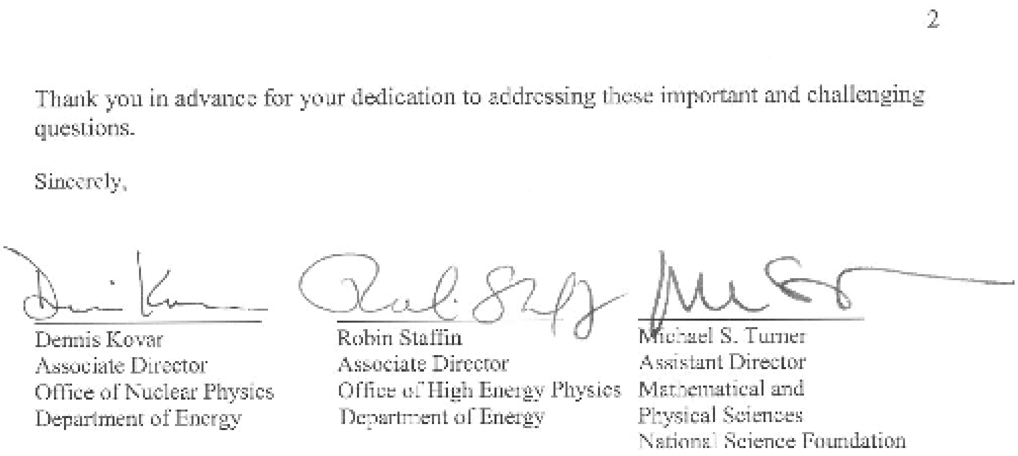
We would like to thank you and the Neutrino Scientific Assessment Group (NuSAG) for your timely and thoughtful responses to the initial questions that were posed to you, concerning neutrinoless double beta decay, reactor experiments and accelerator-based experiments to determine fundamental neutrino properties. They have already been very useful and will help us put together a strong US program in neutrino physics.

We would now like your group to address the APS Study's recommendation for a next-generation neutrino beam and detector configurations. Assuming a megawatt class proton accelerator as a neutrino source, please answer the following questions for accelerator-detector configurations including those needed for a multi-phase off-axis program and a very-long-baseline broad-band program. This assessment will be used as one of the key elements to guide the direction and timeline of such a possible next generation neutrino beam facility.

In your assessment, NuSAG should look at the scientific potential of the facility, the timeliness of its scientific output, and its place in the broad international context. Specifically:

- **Scientific potential:** What are the important physics questions that can be addressed at the envisioned neutrino beam facility?
- **Associated detector options:** What are the associated detector options which might be needed to fully realize the envisioned physics potentials? What are the rough cost ranges for these detector options?
- **Optimal timeline:** What would be the optimal construction and operation timeline for each accelerator-detector configuration, taking the international context into account?
- **Other scientific considerations:** What other scientific considerations, such as results from other neutrino experiments, will be important in order to optimally determine the design parameters? What would be additional important physics questions that can be addressed in the same detector(s)?

The DOE and the NSF would like a preliminary draft of your report by December 2006, with a final version by February 2007.



2

Thank you in advance for your dedication to addressing these important and challenging questions.

Sincerely,

Dennis Kovar
Associate Director
Office of Nuclear Physics
Department of Energy

Robin Staffin
Associate Director
Office of High Energy Physics
Department of Energy

Michael S. Turner
Assistant Director
Mathematical and
Physical Sciences
National Science Foundation

B Members of DOE/NSF Neutrino Scientific Assessment Group (NuSAG) Subpanel

Eugene Beier (University of Pennsylvania and Co-Chair)
Peter Meyers (Princeton University and Co-Chair)

Leslie Camilleri (European Organization for Nuclear Research, CERN)
Boris Kayser (Fermi National Accelerator Laboratory)
Ed Kearns (Boston University)
William Louis (Los Alamos National Laboratory)
Naomi Makins (University of Illinois)
Tsuyoshi Nakaya (Kyoto University)
Guy Savard (Argonne National Laboratory)
Heidi Schellman (Northwestern University)
Mel Shochet (University of Chicago) ex-officio
Gregory Sullivan (University of Maryland)
Robert Tribble (Texas A&M) ex-officio
Petr Vogel (California Institute of Technology)
Bruce Vogelaar (Virginia Tech)
Glenn Young (Oak Ridge National Laboratory)

C May 2006 Meeting Agenda

NuSAG Meeting
Vendome and Louvre Rooms
Sofitel Chicago O'Hare
Rosemont, IL
May 20-May 21, 2006
Agenda

Saturday, May 20, 2006

8:30 Executive session

9:30 Neutrino physics and other physics	Andre De Gouvea, *Northwestern U.*
10:10 EPP2010 report	Sally Dawson, *BNL*
10:20 BNL/FNAL LBL Workshop	Sally Dawson, *BNL*

10:30 Break

10:50 Off-axis technique	Gina Rameika, *FNAL*
11:35 Wideband technique	Milind Diwan, *BNL*
12:20 Discussion	

12:45 Lunch

1:45 Accelerator and beam requirements	Alberto Marchionni, *FNAL*
2:30 H2O Modular detector	Kenneth Lande, *U. Pennsylvania*
3:15 H2O Monolithic detector	Chang Kee Jung, *SUNY-SB*

4:00 Break

4:15 Liquid Argon	Bonnie Fleming, *Yale*
5:00 European activities	Leslie Camilleri, *CERN*
5:30 Asian activities	Tsuyoshi Nakaya, *Kyoto U.*

6:00 Executive session
6:30 Adjourn

Sunday, May 21, 2006

9:00 Executive Session

10:30 Break

12:30 Lunch

2:30 Break

4:30 Adjourn