Recommendations to the Department of Energy and the National Science Foundation on a U.S. Program of Reactor- and Accelerator-based Neutrino Oscillation Experiments

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

Submitted by the Neutrino Scientific Assessment Group

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1 An experimental program in neutrino oscillations

During the past decade, we have found compelling evidence that neutrinos can oscillate between one "flavor" and another, which implies that they have nonzero masses. The Standard Model (SM) of particle physics is constructed with massless neutrinos. Though a more fundamental theory is desired, the SM, which has been under experimental challenge since its full formulation in the 1970's, has proved to be consistent with all experimental data — until massive neutrinos. Thus, neutrino experiments are the only demonstrated experimental window on physics beyond the Standard Model.

Neutrino oscillation also implies that neutrinos mix, just as quarks do. As with the mixing of quarks, the mixing of three or more flavors of neutrino can generate a violation of the combined symmetry of the exchange of particles with antiparticles (Charge conjugation) and mirror inversion (Parity). This phenomenon, called "CP violation," is a key requirement of theories that try to generate the imbalance of matter over antimatter observed in the current universe from an initially symmetric state. In neutrino oscillation, the presence and magnitude of CP violation are controlled by two as-yet-unmeasured parameters.

The discovery of neutrino mass and mixing has raised a number of intriguing questions. Especially interesting are several qualitative questions about the nature of the neutrinos and their relations to the rest of physics and to astrophysics-cosmology. The new questions, and how they may be answered through future experiments, are discussed in Section 2. A global effort to pursue the answers has come up with a well-developed experimental program that, subject only to the constraints imposed by the magnitudes of the unknown parameters, can completely fill out our knowledge of three-neutrino mixing. There is a striking convergence in this program: access to all the relevant physics, including CP violation, comes from studying $\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e$, and $\bar{\nu}_e \to$ Not $\bar{\nu}_e$ flavor transitions at or near the peak of an expected oscillating contribution with a wavelength equal to that of the observed oscillation of atmospheric neutrinos.

The proposed program assumes that Nature contains only the three known neutrino types. With one unconfirmed exception, the LSND experiment, all present observations are consistent with this assumption. However, we must be alert to surprises. Confirmation of the LSND oscillation evidence would require re-evaluation of the interpretation and priority of the proposed experiments. The LSND result is currently being tested, and it is anticipated that resolution of this issue will take place early enough to allow such re-evaluation if needed.

The United States has been a leader of the field of neutrino oscillations from the beginning, discovering the neutrino flavors themselves and the first evidence for solar neutrino disappearance, later confirmed as neutrino oscillations. U.S. physicists have played important roles in the milestone experiments Super-K, KamLAND, and K2K in Japan and SNO in Canada. It is likely that the next important neutrino oscillation results will come from two current U.S.-based experiments, MiniBooNE and MINOS, both at Fermilab. This leadership represents a wealth of experience and a substantial investment, which together position the U.S. program to continue its leading role.

NuSAG, the Neutrino Scientific Assessment Group, has been charged by the High Energy Physics Advisory Panel and the Nuclear Science Advisory Committee of the Department of Energy and National Science Foundation "to make recommendations on the specific experiments that should form part of the broad U.S. neutrino science program." One of the charges, dealing with a program in neutrino-less double beta decay, was the subject of NuSAG's first report.[1] The experiments before NuSAG under the remaining two charges, both of which are addressed in this report, are proposals for U.S. participation in the next phase of the worldwide program in neutrino oscillations. This program includes both accelerator- and reactor-based experiments, and its goal is the complete exploration of three-neutrino mixing. In the next section, we describe the physics of neutrino oscillations and the specific aims of the worldwide program. Section 3 describes the charge to NuSAG in more detail and reviews the procedures NuSAG followed to arrive at the recommendations in this report. The experiments NuSAG considered are discussed in Section 4. NuSAG's conclusions are reported in Section 5, and our recommendations for a U.S. program in neutrino oscillations are presented in the final section. NuSAG strongly endorses the scientific goals of the worldwide program and recommends that the U.S. mount key experiments necessary to advance this science.

2 The science of neutrino oscillation

2.1 The goals

Through future experiments on neutrino oscillation, we would like to answer the following questions:

1. *What is the approximate size of the small mixing angle θ_{13}? With what kinds of underlying theories is it compatible?*

2. *Is the atmospheric mixing angle maximal? If not, is the heaviest neutrino more ν_τ than ν_μ, as naively expected, or more ν_μ than ν_τ?*

3. *Does the neutrino mass spectrum resemble the charged lepton and quark spectra, or is it an inverted version of those other spectra?*

4. *Do neutrinos violate CP?*

In the past few years, dramatic insights into the nature of neutrinos have been gained from experiments with naturally-occurring neutrinos. Answering these new questions will require experiments with man-made neutrinos, from accelerators and reactors.

The other critical questions of neutrino physics, whether neutrinos are their own antiparticles and the absolute scale of neutrino mass, are not addressed by oscillation experiments, but by neutrino-less double beta decay. As already mentioned, the latter process was the topic of NuSAG's first report.

In this section, we first briefly review what has been learned so far about the neutrinos, then discuss the importance of the open questions to be addressed by oscillation experiments, and then consider how these questions can be answered.

2.2 What we have learned so far

Neutrinos come in three "flavors": ν_e, ν_μ, and ν_τ. Each of these is coupled only to the charged lepton of the same flavor: ν_e to the e, ν_μ to the μ, and ν_τ to the τ. If there are additional neutrino flavors, they must be very massive or have non-Standard-Model couplings. Neutrino oscillation is the remarkable morphing of a neutrino of one flavor into that of another. That this occurs implies that neutrinos have nonzero masses and mix. That they mix means that each neutrino of definite flavor, ν_α, is not a neutrino of definite mass, ν_i, but a superposition of such neutrinos. This superposition is given by $\nu_\alpha = \sum_i U^*_{\alpha i}\nu_i$, where U is the unitary *leptonic mixing matrix*. Conversely, each neutrino of definite mass is a superposition of the neutrinos of definite flavor, given by $\nu_i = \sum_\alpha U_{\alpha i}\nu_\alpha$.

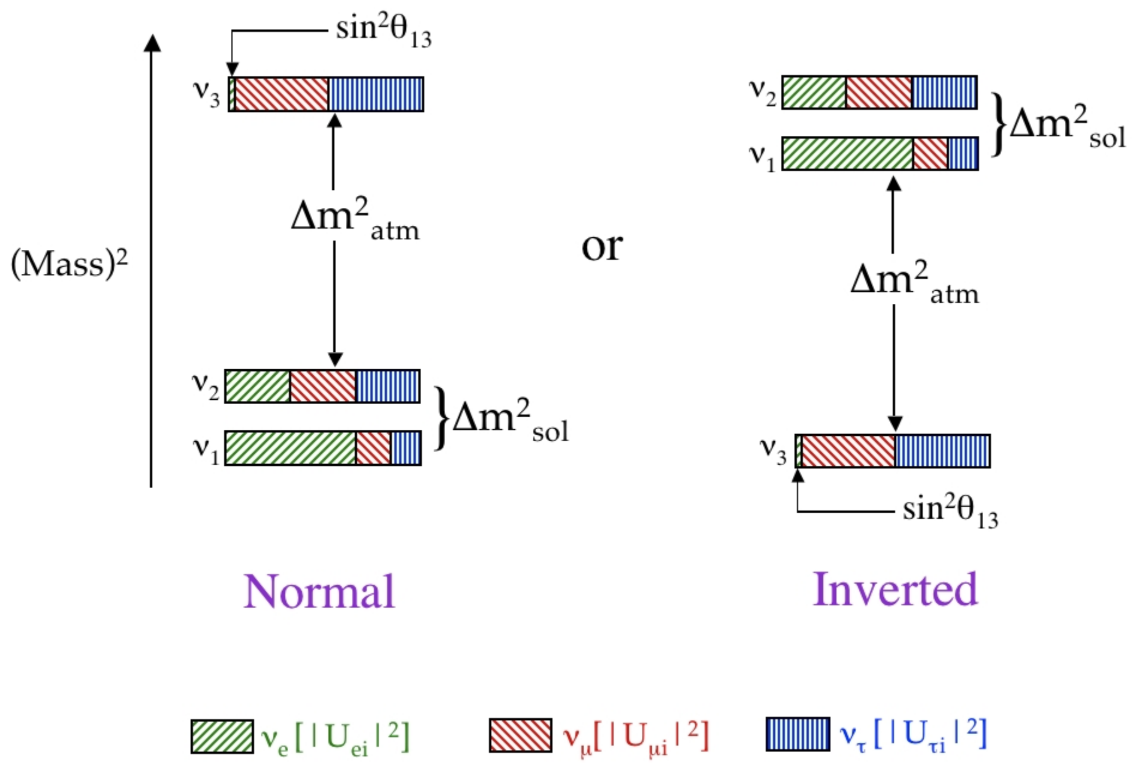

Figure 1. The neutrino $(\text{Mass})^2$ spectrum.

Since there are three neutrinos of definite flavor, there must be at least three of definite mass: ν_1, ν_2, and ν_3. Oscillation data tell us that the $(\text{Mass})^2$ spectrum of these neutrinos is one of the two spectra shown in Fig. 1. The spectrum on the left, with the closely-spaced pair at the bottom, resembles the charged lepton and quark spectra, and so is referred to as a "normal" spectrum or hierarchy, while the very unusual one on the right, with the closely-spaced pair at the top, is referred to as an "inverted" spectrum or hierarchy.

The atmospheric (Mass)^2 splitting in Fig. 1, $\Delta m^2_{atm} \cong 2.4 \times 10^{-3}$ eV^2, drives the observed behavior of atmospheric neutrinos, while the thirty-times smaller solar (Mass)^2 splitting, $\Delta m^2_{sol} \cong 8.0 \times 10^{-5}$ eV^2, drives the behavior of solar neutrinos. The approximate ν_e, ν_μ, and ν_τ fractions of each neutrino are shown by different color/hatching. However, the ν_e fraction shown for the isolated neutrino ν_3 is just an illustration of the possibilities. At present, we know only that, at 2σ, this fraction, whose size is the mixing parameter $\sin^2\theta_{13}$, is no larger than 0.032.

The leptonic mixing matrix can be written in the form

$$U = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}_{\text{Atmospheric}} \times \underbrace{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}}_{\text{Cross-Mixing}} \times \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Solar}} \tag{1}$$

Here, $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$. The first, "Atmospheric," matrix factor dominates atmospheric neutrino oscillation, and from the atmospheric neutrino data, $37^\circ \leq \theta_{23} \leq 53^\circ$ at 90% CL. The last, "Solar," factor dominates solar neutrino flavor change, and from the solar (and to some extent the KamLAND reactor) data, $\theta_{12} = (33.9^{+2.4}_{-2.2})^\circ$. In striking contrast to the small quark-mixing angles, the atmospheric and solar neutrino mixing angles, θ_{23} and θ_{12}, are both very large. Indeed, the value of θ_{23} that fits the data best is 45° — maximal mixing. The middle, "Cross-Mixing," factor involves the mixing angle θ_{13}, which is constrained by upper limits from reactor data to $\leq 10^\circ$ (evaluated at Δm^2_{atm}), corresponding to $\sin^2 2\theta_{13} \leq 0.12$. The Cross-Mixing factor also contains the CP-violating phase δ, which, if not 0° or 180°, leads to a CP-violating difference between the probabilities for corresponding neutrino and antineutrino oscillations. However, as the expression above for U makes clear, δ enters neutrino mixing only in combination with $s_{13} \equiv \sin\theta_{13}$. Thus, the CP-violating effects of δ depend on θ_{13}. Consequently, the physics reach that facilities must have in order to look for these effects depends on the order of magnitude of θ_{13}.

2.3 The importance of the open questions

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

While we know that the mixing angle θ_{13} is small, we do not know *how* small. Learning its actual size will discriminate between models of neutrino mass. For example, in one class of models, $\sin\theta_{13}$ is naturally of order $\Delta m^2_{sol}/\Delta m^2_{atm} \cong 1/30$, so that $\sin^2 2\theta_{13} \sim 0.004$. In contrast, in a second class of models, $\sin\theta_{13}$ is of order $(\Delta m^2_{sol}/\Delta m^2_{atm})^{1/2} \cong 1/6$, so that $\sin^2 2\theta_{13} \sim 0.1$, very close to the present upper bound. Thus, finding out whether $\sin^2 2\theta_{13}$ lies above or below, say, 0.01 will discriminate between these two classes of models. Quite apart from specific models, the mathematics of mixing makes it 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.

It has already been noted that CP violation depends on θ_{13}. As we shall see, 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 neutrinos violate CP and determine whether the mass spectrum is normal or inverted, using intense but conventionally produced accelerator neutrino and antineutrino beams (sometimes called "super beams"). But if $\sin^2 2\theta_{13} < 0.01$, a neutrino factory or beta beam will be needed 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. What is the atmospheric mixing angle, θ_{23}?

The atmospheric mixing angle θ_{23} mixes ν_μ and ν_τ. Should this $\nu_\mu - \nu_\tau$ mixing, already known to be very large, prove to be maximal (say, $\sin^2 2\theta_{23} > 0.99$), then very likely an underlying symmetry is responsible, just as (near) CP invariance is responsible for the (near) maximal $K^\circ - \overline{K^\circ}$ mixing. If precision measurements reveal that θ_{23} is not maximal, then it will be important to know whether it lies below or above 45º. When combined with other information, this will determine whether the heaviest neutrino of definite mass is more ν_τ than ν_μ, as naively expected, or more ν_μ than ν_τ. In addition, if θ_{23} is uncertain, then the measurement of the CP-violating phase δ will be uncertain as well, though it should be pointed out that the establishment of CP violation in the accelerator experiments can be unambiguous even with an ambiguity in the value of the phase.

3. 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 at the grand unification energy scale, $\sim 10^{15}$ GeV. Needless to say, such physics is way 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 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. 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 potentially 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 has reported an unconfirmed $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillation whose short wavelength calls for a (Mass)^2 splitting much larger than either of those in the spectra of Fig. 1. Thus, if the MiniBooNE experiment, aimed at testing LSND, should confirm the reported oscillation, the neutrino spectrum would have to be revised altogether to include one or more additional states, and we would have to re-determine the optimum strategy for future neutrino experiments.

4. Do neutrinos violate CP?

We would like to know why the universe contains matter but almost no antimatter, so that living creatures made of matter can exist without getting annihilated. 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 entirely 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. Interestingly, for this scenario, known as Leptogenesis, to work, the light neutrinos must have masses in the range actually suggested by the experimental data. 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.

2.4 How the questions can be answered

So long as $\sin^2 2\theta_{13} > (0.01 - 0.02)$, all of the open questions we are discussing, except perhaps the question of whether θ_{23} lies below or above 45°, can be answered by a program of experiments using conventionally generated accelerator neutrino and antineutrino beams, and reactor antineutrinos. However, most measurable quantities depend simultaneously on several of the underlying neutrino properties one would like to determine. As a result, one must make a variety of complementary measurements to unravel the physics.

In pursuit of θ_{13}

The first target of the next generation of oscillation experiments will be θ_{13}. As shown in Fig. 1, $\sin^2\theta_{13}$ is the small ν_e fraction of the isolated neutrino ν_3. The latter neutrino lies at one end of the atmospheric (Mass)^2 splitting, Δm^2_{atm}. As a result, an oscillation experiment that is sensitive to Δm^2_{atm} will probe the properties of ν_3. In particular, if the experiment involves an oscillation either from or into a ν_e (or $\bar{\nu}_e$), then it will probe the ν_e fraction of ν_3, $\sin^2\theta_{13}$.

Two complementary approaches are proposed: One would look for the disappearance of some of the $\bar{\nu}_e$ flux from a reactor. The other would look for the appearance of ν_e in a long-baseline accelerator ν_μ beam. In both cases, at least one detector would be situated at or near the first maximum of the oscillation induced by Δm^2_{atm}.

When matter effects may be neglected, neutrino oscillation is a sinusoidal function of *L*/*E*, the distance traveled by the neutrinos divided by their energy. To describe this oscillation, we shall use the abbreviations

$$m_{\nu_i} \equiv Mass(\nu_i),\;\; \Delta m^2_{ij} \equiv m^2_{\nu_i} - m^2_{\nu_j},\; \text{ and }\; \Delta_{ij} \equiv 1.27\Delta m^2_{ij}(\text{eV}^2)L(\text{km})/E(\text{GeV})\,.$$

Then the oscillation induced by $|\Delta m^2_{atm}|$, which to a good approximation may be identified with either $|\Delta m^2_{31}|$ or $|\Delta m^2_{32}|$, involves the oscillatory factor $\sin^2\Delta_{31} \cong \sin^2\Delta_{32}$. The first oscillation maximum occurs where $|\Delta_{31}| \cong |\Delta_{32}| = \pi/2$. For the ~ 3 MeV antineutrinos from a reactor, this is at L ~ 1.5 km. For the ~ 2 GeV (~ 0.6 GeV) neutrinos in the NOvA (T2K) accelerator neutrino experiment, it is at L ~ 1000 km (~ 300 km).

The disappearance probability that would be measured by a reactor experiment is given by

$$P[\overline{\nu_e} \rightarrow \text{Not } \overline{\nu_e}] \cong \sin^2 2\theta_{13}\sin^2\Delta_{31} + \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \qquad (2)$$

For $\sin^2 2\theta_{13} > 0.01$, the first term dominates near $|\Delta_{31}| = \pi/2$. Thus, given a measured value of Δm^2_{31} (expected with ~ 10% accuracy from MINOS), an observed value of the disappearance probability would yield a clean determination of θ_{13}.

In contrast to the reactor $\bar{\nu}_e$ disappearance probability, the ν_e and $\bar{\nu}_e$ appearance probabilities to be studied in long-baseline accelerator neutrino experiments depend on θ_{13} and θ_{23}, on whether the spectrum is normal or inverted, and on whether – and how much – CP is violated through the phase δ. Thus, the accelerator experiments can access everything that we would like to know. However, as already mentioned, most measurable quantities depend on more than one underlying neutrino property. Even if one omits non-negligible matter effects, the ν_e and $\bar{\nu}_e$ appearance probabilities are given by the already rather complicated expressions

$$\begin{aligned} P[\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e] \cong\; & \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\Delta_{31} \\ & + \sin 2\theta_{13}\cos\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\sin\Delta_{31}\sin\Delta_{21}\cos(\Delta_{32} \pm \delta) \qquad (3) \\ & + \sin^2 2\theta_{12}\cos^2\theta_{23}\cos^2\theta_{13}\sin^2\Delta_{21} \end{aligned}$$

Here, the plus (minus) δ on the second line is for neutrinos (antineutrinos). If δ is present and different from 0° or 180°, then clearly there will be a CP-violating difference between the $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation probabilities.

In view of the intertwining of neutrino parameters in accelerator neutrino experiments, obtaining via a reactor experiment a clean value of θ_{13} that is independent of the other parameters is very useful.

In pursuit of θ_{23}

The probability for accelerator ν_μ disappearance is given by the very simple expression

$$P[\nu_\mu \to \text{Not}\,\nu_\mu] \cong \sin^2 2\theta_{23} \sin^2 \Delta_{atm} \tag{4}$$

Here, Δ_{atm} lies somewhere between the very nearly equal Δ_{31} and Δ_{32}. Clearly, a measurement of this disappearance probability would yield a clean determination of $\sin^2 2\theta_{23}$. However, if $\theta_{23} \neq 45°$, then this measurement will leave two possibilities for this mixing angle: θ_{23} and $90° - \theta_{23}$. From Eq. 3, we see that if θ_{23} is left uncertain in this way, θ_{13} and δ will be uncertain as well. Comparison with a reactor measurement may be able to resolve the $\theta_{23} \Leftrightarrow 90° - \theta_{23}$ ambiguity, with beneficial consequences for our knowledge of other parameters as well.

Determining whether the mass spectrum is normal or inverted

In earth matter, coherent forward scattering from electrons raises the effective mass of ν_e and lowers that of $\bar{\nu}_e$. The consequences of this change depend on whether the ν_e flavor content, which is heavily concentrated in the neutrinos ν_1 and ν_2 (see Fig. 1), is at the bottom of the spectrum (a normal spectrum), or at the top (an inverted spectrum). At accelerator neutrino energies of ~1 GeV, the matter effect changes θ_{13} into an effective mixing angle θ_M that is different for antineutrinos and neutrinos, and is given by

$$\sin^2 2\theta_M \cong \sin^2 2\theta_{13}\left[1 \pm S\frac{E}{6\,\text{GeV}}\right]. \tag{5}$$

In this expression, the positive (negative) sign is for a neutrino (antineutrino) beam, and $S = +1$ (-1) for a normal (inverted) spectrum. At oscillation maximum, the $\nu_\mu \to \nu_e$ or $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation probability is proportional to the value of $\sin^2 2\theta_M$. Thus, at oscillation maximum, $P[\nu_\mu \to \nu_e]/P[\bar{\nu}_\mu \to \bar{\nu}_e]$ is greater (less) than unity if the spectrum is normal (inverted). From the expression for $\sin^2 2\theta_M$, we see that the deviation from unity is much larger at $E \sim 2$ GeV, the proposed energy of the NOvA experiment, than at $E \sim 0.6$ GeV, the energy of the T2K experiment. As a consequence, T2K has no sensitivity to the mass hierarchy.

As already mentioned, this approach to ascertaining whether the spectrum is normal or inverted depends on θ_{13}. As $\theta_{13} \to 0$, so does θ_M, and the sensitivity to the character of the spectrum is lost.

Searching for CP violation

To find out whether neutrinos violate CP, one can search for a CP-violating difference between the probability for the neutrino oscillation $\nu_\alpha \to \nu_\beta$, and that for its antineutrino CP-mirror image, $\bar{\nu}_\alpha \to \bar{\nu}_\beta$. However, as long as CPT invariance holds, the probabilities for the CPT-mirror-image processes $\nu_\alpha \to \nu_\alpha$ and $\bar{\nu}_\alpha \to \bar{\nu}_\alpha$ must be identical. That is, there can be no CP-violating difference between neutrino and antineutrino *disappearance* probabilities. Violation of CP must be sought in *appearance* experiments. It is proposed that, in due course, it be sought in the contemplated long-baseline accelerator experiments on $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations. The ν_e and $\bar{\nu}_e$ would be observed via a detector located near or at the first peak of the "atmospheric" oscillation — the oscillation induced by the atmospheric $(\mathrm{Mass})^2$ splitting, $\Delta m^2_{atm} \cong \Delta m^2_{31} \cong \Delta m^2_{32}$. However, as perusal of Eq. 3 reveals, the CP-violating difference between $P[\nu_\mu \to \nu_e]$ and $P[\bar{\nu}_\mu \to \bar{\nu}_e]$ arising from the phase δ comes about through an interference between the relatively short-wavelength atmospheric oscillation and the thirty-fold longer-wavelength "solar" oscillation — the oscillation induced by the solar $(\mathrm{Mass})^2$ splitting, $\Delta m^2_{sol} \cong \Delta m^2_{21}$. Of course, at the first peak of the atmospheric oscillation, the solar-atmospheric interference term is suppressed by the smallness of $\Delta m^2_{21} / \Delta m^2_{31}$ (see Eq. 3). However, the atmospheric oscillation term is itself suppressed by the smallness of θ_{13}. As a result, the CP-violating difference $P[\nu_\mu \to \nu_e] - P[\bar{\nu}_\mu \to \bar{\nu}_e]$ can easily be as large as $P[\nu_\mu \to \nu_e]$ and $P[\bar{\nu}_\mu \to \bar{\nu}_e]$ themselves.

In finding out whether neutrinos violate CP, and in determining whether the neutrino mass spectrum is normal or inverted, the proposed U.S. and Japanese accelerator neutrino programs would play powerfully complementary roles. The key distinction between these programs is that in the U.S. the neutrino and antineutrino energies would be three times higher than in Japan, making the spectrum-dependent matter effect much larger. As we have discussed, both genuine CP violation and the matter effect contribute to the difference between neutrino and antineutrino oscillation probabilities. Both will be sought by looking for this difference. However, to determine the nature of the neutrino mass spectrum via the matter effect, and to establish the presence of CP violation in neutrino oscillation, it will be necessary to disentangle the matter effect from CP violation in the neutrino-antineutrino difference that is actually observed. To determine two quantities, one needs two measurements, and a program based on the combination of U.S. and Japanese experiments before NuSAG can provide these measurements over much of the region $\sin^2 2\theta_{13} > 0.01$.

3 NuSAG and the process leading to this report

In March, 2005, the Nuclear Science Advisory Committee (NSAC) and the High Energy Physics Advisory Panel (HEPAP) were requested by the Department of Energy (DOE) and the National Science Foundation (NSF) to establish a Neutrino Scientific Assessment Group (NuSAG) to advise on issues in neutrino science. The letter charging NSAC and HEPAP is reproduced in

Appendix A. This letter notes that the importance of research in neutrino science has been addressed by two panels of the National Research Council and by a multi-disciplinary study sponsored by the American Physical Society (APS). Key points in the charges to NuSAG are:

Charge 1: We request that NuSAG address the APS Study's suggestion that the U.S. participate in "*An expeditiously deployed multi-detector reactor experiment with sensitivity to* ν_e *disappearance down to* $\sin^2 2\theta_{13} = 0.01$, *an order of magnitude below present limits.*"

Charge 2: NuSAG is requested to address the APS Study's recommendation of a phased program of sensitive searches for neutrino-less nuclear double beta decay. In particular, a timely assessment of the scientific opportunities and the resources needed should be performed of the initiatives that are presently under discussion in the research community.

Charge 3: We request that NuSAG address the APS Study's suggestion that the U.S. participate in "*A timely accelerator experiment with comparable* $\sin^2 2\theta_{13}$ *sensitivity [to the recommended reactor experiment, i.e.* $\sin^2 2\theta_{13} = 0.01$*] and sensitivity to the mass-hierarchy through matter effects.*"

Specific experiments to be considered are listed for each charge, but other experiments may be included. NuSAG is to consider scientific potential, timeliness of the scientific output, likely costs, and the international context of the experiments. For the third charge NuSAG is to consider what may be learned from other experiments and also the extensibility of the experiments as part of an evolving U.S. neutrino program. For all three charges, NuSAG is to recommend a strategy of one, or perhaps more than one, experiment which should be pursued as part of a U.S. program.

The reactor options listed in the charge were:

- A U.S. experiment (in Diablo Canyon CA, Braidwood, IL, or elsewhere)
- U.S. participation in a European reactor experiment (Double Chooz or elsewhere)
- U.S. participation in a Japanese reactor experiment
- U.S. participation in a reactor experiment at Daya Bay, China

NuSAG found that the Diablo Canyon effort had been discontinued, with proponents joining Daya Bay, and that there were no proposed U.S. collaborators in the Japanese experiment, so these two options were not considered further.

The accelerator-based options listed in the charge were:

- U.S. participation in the T2K experiment in Japan
- Construction of a new off-axis detector to exploit the existing NuMI beamline from Fermilab to Soudan, as proposed by the NOvA collaboration
- As above but using a large liquid argon detector

NuSAG found that there were two distinct U.S. collaborations forming around different aspects of T2K. Both were evaluated. At Fermilab, the liquid argon effort is clearly in an R&D phase – it was not presented as a substitute for NOvA, but rather as a technology for use in later phases of an ongoing neutrino program.

The NuSAG chairs were contacted by two groups not included in the charge letter. The first of these was a Brazilian reactor experiment. As it has only minimal U.S. participation, NuSAG considered it only as part of the international context. Brookhaven National Laboratory contacted NuSAG about an accelerator-based long-baseline program that uses an approach different from the off-axis, narrow-band experiments mentioned in the charge and described in Section 4.1. Though this approach avoids some of the limitations of the off-axis experiments, its very long baseline requires the initial deployment of a megawatt-class beam and a megaton-class detector. This places it in a longer time frame than the experiments in the charge. Without passing judgment on the BNL approach, NuSAG concluded that the experiments in the charge should be evaluated on their own scientific merit.

The panel was organized in April and May 2005. Its members are listed in Appendix B. In addition to the panel co-chairs and the NSAC and HEPAP chairs who are *ex-officio* members, there are five experimentalists and one theorist each from the nuclear physics community and from the high energy physics community. There is one European representative and one Japanese representative to assure that the international context is accurate. The panel was chosen to have some members with backgrounds in neutrino physics and to have other members who have more general experience and can assure that the role of neutrino physics in the context of the larger programs in nuclear and high energy physics is kept in perspective. All panel members have stated their possible association with work under discussion, and the conflicts have been documented.

A three day open meeting was held in Gaithersburg, MD, May 31 through June 2, 2005, to collect information on experiments to be considered under each of the three charges. The agenda for this meeting is shown in Appendix C. The presentations from this meeting are posted on a public web site.[2]

Using the information from presentations at the open meeting and the materials submitted to NuSAG before the meeting, the panel discussed each experiment. Additional questions were sent to the experiments and informative responses were received. A second meeting was held in Chicago, IL, July 17-18, 2005. This was a closed meeting focused on the neutrino-less double beta decay charge although information on the other two charges was reviewed. NuSAG's first report, on neutrino-less double beta decay, was approved by NSAC and HEPAP in late-August 2005. NuSAG held another closed meeting on the remaining two charges in Chicago on September 6-7, 2005.

4 The experiments

4.1 Accelerator experiments

The accelerator experiments T2K in Japan and NOvA in the U.S. are searches for ν_e appearance in a beam that is initially ν_μ. They look for this appearance at a distance and energy corresponding to the oscillation maximum of atmospheric ν_μ's, that is, L/E~500 km/GeV, as predicted by the three-neutrino mixing model. The most important backgrounds in such a search are the intrinsic beam ν_e's and ν neutral-current π^0 production. The intrinsic beam ν_e's are produced in the beam initially, primarily from muon and kaon decay, and are thus not due to oscillation. Neutral-current π^0 production is a background because, like the signal, it will have an electromagnetic-shower final state with no muon. Both experiments use large far detectors several hundred kilometers from the neutrino source to detect the oscillated neutrinos. They also deploy smaller near detectors to measure the properties of the beam, including the flux, spectrum, and intrinsic ν_e content prior to oscillation and to measure the cross sections needed to predict the rate of backgrounds such as NC π^0 production in the far detector. In both experiments, the detectors are located away from the beam axis. In this "off-axis" configuration, the two-body pion decay kinematics results in a relatively narrow spread of neutrino energies at the detector. By the appropriate choice of off-axis angle, the peak neutrino flux can be at the oscillation maximum, and the reduced high-energy neutrino flux results in reduced π^0 production. The proposed off-axis beams have estimated ν_e contamination $\leq$1%, and the intrinsic ν_e spectrum is not peaked in energy as the off-axis ν_μ beam is, allowing further reductions with simple energy cuts. The long decay path of pions is a line source of neutrinos for the near detector and a point source for the far detector. Further, in an off-axis beam the near detector sees a much broader range of off-axis angles than the far detector. This necessitates corrections, and thus reliable Monte Carlos.

Each experiment in its initially proposed configuration is designed to have sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillation down to $\sin^2 2\theta_{13}$~0.01. If ν_e appearance is discovered in this range, a series of upgrades can bring a determination of the mass hierarchy and observation of CP violation, if present. The T2K and NOvA experiments are themselves later phases of earlier programs, with T2K reusing Super-K as its far detector and NOvA reusing the existing Fermilab NuMI beam, currently used in the MINOS experiment. The different baseline-energy combinations in the two experiments make their combination considerably more sensitive to CP violation and the mass hierarchy than either experiment alone.

4.1.1 NOvA

The NOvA experiment will use the existing Fermilab neutrino beam facility (NuMI). The far detector will be located on the surface near Ash River, MN at a baseline of approximately 810 km and 12 km (~15 mRad or ~0.8°) off-axis resulting in a narrow-band neutrino beam peaked at an energy of ~2 GeV. In the era after Run II at Fermilab ends, it is estimated that the Main Injector will be able to deliver 6.5×10^{20} protons per year to the NuMI target, corresponding to ~0.6 MW of protons at 120 GeV. Fermilab contemplates upgrades to this beam power. Under consideration is a Proton Driver replacing the lower-energy accelerators feeding the Main Injector, perhaps with a superconducting linac using technology similar to that proposed for the International Linear Collider. With upgrades to the Main Injector to handle the increased flux, the power to the neutrino production target would increase to 2 MW. As an alternative, if priorities and budgets do not allow a Proton Driver, Fermilab could pursue a more incremental path that might yield 1 MW or more.

Both the NOvA near and far detectors are composed of liquid scintillator in PVC extrusions with a longitudinal sampling of 0.15 radiation lengths, read out with wavelength shifting fiber and avalanche photodiodes. The common technology of the two detectors reduces systematic uncertainties. The far detector has an 80% active volume with a total mass of 30 kilotons and is 15.7 m × 15.7 m × 132 m in size. The far detector is on the surface. Cosmic-muon-induced events are not thought to be a problem; however the gamma-ray component of cosmics may make a few meters of overburden necessary. The near detector will have a total mass of 262 tons with an active mass of 145 tons and a fiducial mass of 20.4 tons. The near detector will also have 1 meter of steel interspersed with additional planes of liquid scintillator as a muon catcher. The near detector is also placed off-axis from the neutrino beam at Fermilab, about 1000 m from the production target. As no single location for the near detector matches the neutrino spectrum at the far detector very well, the near detector is designed to be moved to several different positions. Possible locations in the existing tunnels have been found that are optimized to reproduce the simulated far-detector spectra of unoscillated ν_μ's (relevant for measuring the NC π^0 background), or, at a different location, the intrinsic ν_e's. The entire near detector can also be placed in the Fermilab test beam for energy calibration. Improved neutrino cross sections from the MINERvA experiment and measurements of pion production from MINOS (and thus NOvA) targets in the MIPP experiment will be combined with near-detector data to reduce the systematic error on backgrounds to an estimated 5%.

For a five year run of NOvA with 6.5×10^{20} protons on target per year, the 3-sigma discovery sensitivity for $\sin^2 2\theta_{13}$ extends to approximately 0.01. The simulation studies in the proposal indicate that for $\sin^2 2\theta_{13}$~0.01, a five year run would give an expected signal of ~14 events on a predicted background of ~19.5 events. Once $\nu_\mu \rightarrow \nu_e$ oscillations are observed, NOvA's long baseline and corresponding high energy give it sensitivity to the mass hierarchy through matter effects. If $\sin^2 2\theta_{13}$ is close to the current limit, NOvA has a chance to resolve the mass hierarchy in its initial beam and detector configuration. For mass-hierarchy sensitivity at lower $\sin^2 2\theta_{13}$, or for sensitivity to CP violation at any $\sin^2 2\theta_{13}$, upgrades are necessary. The most likely second phase would be increased beam power, as discussed above. If ambiguities prevent extraction of the mass hierarchy and CP violation, either alone or in combination with results from (an upgraded) T2K, a second far detector, located further off axis to lower the beam energy and place it at the second oscillation maximum, is an option.

The fully burdened cost estimate for the NOvA experiment, as calculated by the experimenters with 50% contingency included, is $165M. NOvA has Stage 1 (scientific) approval from Fermilab and would like an FY2007 start for construction. Completion of the far detector would be in 2011 with data taking beginning in 2010 after completion of the first 5 kiloton of the far detector.

4.1.2 T2K

The T2K experiment will send a 2.5°-off-axis neutrino beam with average energy of ~0.6 GeV from the new J-PARC accelerator under construction at Tokai in Japan to the existing 50 kiloton Super-K detector, which is 295 km away and under a 2700 m.w.e. overburden. The initial project, approved in Japan and under construction, will have a beam power of 0.75 MW at 40 GeV, delivering an estimated 10^{21} protons per year to the neutrino production target. Later upgrades to 4 MW are under consideration. The T2K project includes the new neutrino beam, the suite of near detectors, and the Super-K far detector. U.S. groups have proposed to contribute to all of these areas. U.S. groups played an important role in the construction of the Super-K detector and have participated actively in the extraordinary experimental program built around it.

Commissioning of the J-PARC neutrino beam is scheduled to take place in 2009. Current plans expect the beam to reach its initial design power of 0.75 MW by 2011-12.

For $\sin^2 2\theta_{13}$~0.01, in a five year run with 10^{21} protons per year, 10.3 signal events with a background of 23 events is expected.

Before NuSAG are two proposals for U.S. participation in the T2K experiment. A collaboration of U.S. groups proposes to take part in the construction of the B280 project, an effort that includes the beamline, an on-axis detector to monitor the beam direction, and an off-axis near detector 280 m from the production target. The B280 project itself is approved in Japan. A separate collaboration of U.S. groups proposes to join with European and Japanese groups to extend the T2K project beyond its currently-approved scope to include detectors at 2 km.

T2K B280

U.S. groups have already been involved in the R&D for most aspects of the beam-near detector complex. They now seek funding to take part in the construction project, including aspects of the primary and secondary beams and portions of the off-axis near detector. The off-axis near detector consists of a π^0 detector, the PØD, and a fine-grained tracking detector, surrounded by an EM calorimeter and a re-instrumented version of the old UA1/Nomad magnet. The U.S. groups would focus on the PØD and new scintillation counters for the magnet.

The PØD is needed to measure the rate of NC π^0 production. The rate must be measured on an oxygen (water) target to match that of the far detector, and a precision of at least 10% is needed to keep this from dominating the uncertainty in the first-phase measurement, that is, the currently approved project with the initial T2K beam power. At 280 m from the production target, a large, unsegmented water Cherenkov detector would have too high a neutrino event rate, so a fine-grained scintillator tracker/calorimeter, like Minerva or the K2K Scibar, but with thin lead layers to convert photons, is proposed, with interspersed water layers for the oxygen measurement. While the neutrino beam subtended by the near detector has a considerably different spectrum than that at the far detector, the claim is made that the π^0 spectra are similar, so that a measurement of the overall π^0 rate in the near detector gives a good prediction for the rate in the far detector. Current estimates indicate that this detector can meet the 10% goal for the total systematic error.

The proposed cost to the U.S. of the T2K B280 project, as estimated by the experimenters, is \$4.7M, including 39% contingency. The proposed schedule, based on an April, 2009 date for first protons on target, has the beamline components ready by that date, but the near detector installation extending to Spring 2010.

T2K 2KM

The 2KM collaboration proposes to build a further near detector to monitor the off-axis neutrino beam for the T2K experiment. By virtue of its greater distance from the neutrino source, the 2KM detector sees an off-axis energy spectrum very much like the one seen by Super-K. The lower beam intensity at 2KM makes it possible to use an unsegmented water Cerenkov detector, the same technology employed by Super-K. The addition of a large liquid argon detector provides fine-grained event reconstruction, enabling separate measurements of intrinsic ν_e beam contamination and of neutral current ν_μ interactions producing a single π^0 which can mimic a ν_e interaction. The 2KM detector will also measure the beam intensity and energy distribution. The 2KM goal is to determine the systematic error on the total backgrounds to ν_e appearance to less than 10%. Their current estimate is about 7.5%, which may be reduced further by improved calibration schemes and detailed understanding of the differences in efficiency between 2KM and Super-K. This results in a very modest improvement to the T2K sensitivity in $\sin^2 2\theta_{13}$ for the planned five-year exposure. However, if T2K were to detect a signal for ν_e appearance, measurements from the 2KM detector would enhance the credibility of the detection. In the future, a possible follow-on Hyper-K experiment, with forty times the detector volume, would be systematics-limited within a year of turn-on at the upgraded 4 MW beam power, unless the total background uncertainty can be held to 5% or less.

The proposed 2KM detector consists of a 150-ton liquid argon detector, followed by a 1-kiloton water Cerenkov detector and a steel/scintillator muon range-out detector. The 2KM water Cerenkov detector is designed as a scaled-down version of the Super-K detector, with smaller photo-tubes, but identical readout electronics and energy response. The liquid argon detector will have a frozen water or CO_2 target. The 2KM detector will be located 50 m underground along a line that is 0.75 degrees south of the neutrino beam axis, in line with a site for Hyper-K. The Super-K detector is located symmetrically, along a line that is 0.75 degrees north of the neutrino beam axis. Thus 2KM is not monitoring the actual beam en route to Super-K, but relies on the azimuthal beam symmetry, measured by the near detector. Improvements in the detectors at 280 m are needed to extend the azimuthal beam monitoring far enough to check this symmetry.

The collaboration consists of Japanese, European and U.S. institutions, and they propose to share the costs approximately equally among the three geographical regions. The proposed U.S. contribution, roughly $12M without contingency, is for one-half of the water Cerenkov detector, one-half of the civil construction, and 15% of the liquid argon detector. The schedule calls for construction beginning in 2008 and data-taking commencing in 2011. The design allows for the liquid argon detector to be installed later if necessary, since it may be more challenging to complete it on this schedule than for the other, more conventional detectors.

4.1.3 Liquid Argon Detector R&D

A promising emergent technology for the detection of ν_e appearance is the Liquid Argon Time Projection Chamber (LArTPC). A 600 ton module with 1.5 m drift length has been successfully built and operated by the Icarus collaboration in Europe. The high spatial resolution of LArTPC's (pixels 3mm on a side) allows clear separation of electron neutrino interactions from most hadronic backgrounds. Simulations indicate that signal efficiencies of up to 80% are achievable for electron neutrinos while 99% of hadronic events can be rejected. Efficiencies for scintillator and Čerenkov detectors are far lower at 30-40%. A collaboration centered at Fermilab has submitted an R&D proposal outlining a path to a 15 kiloton LArTPC.

NuSAG's charge suggested that we consider this technology as an alternative to NOvA. This was not the case presented to NuSAG by the proponents or by Fermilab. Instead, use of a liquid argon neutrino detector in later phases of the program is contemplated, possibly for a second detector in the NOvA program.

To make LArTPC's an attractive technology for a next-generation experiment, the technology must be industrialized and scaled to 10-30 kiloton fiducial mass. The proposal consists of an engineering phase to establish basic design principles such as long wires and drift distances and low cost electronics, followed by two large-scale prototypes: a 130 ton prototype detector with full instrumentation to run in existing neutrino beams and a partially instrumented 1 kiloton tank system to validate scaling of the technology to larger scales. At the same time, U.S. groups are exploring collaboration with the Icarus group in Europe on large detectors and with the T2K experiment in Japan on a significant LArTPC near detector.

Besides dealing with longer wires, higher voltage, and longer drift times than the existing Icarus modules, cost reduction by about an order of magnitude will be required to make a 10-30 kiloton detector feasible.

4.2 Reactor experiments

The most stringent limit on $\sin^2 2\theta_{13}$ has been set by the CHOOZ reactor experiment. A limit of $\sin^2 2\theta_{13} < 0.14$ for a Δm^2 of 2.5×10^{-3} eV^2 was obtained using a single detector located about 1050 m from two reactor cores. The limit was determined in part by the uncertainty on the detector mass, the reactor flux, and the neutrino interaction cross sections. All three experiments being considered in the present report, Double Chooz, Braidwood, and Daya Bay intend to improve on this limit by using two or more identical liquid scintillator detectors located at different distances from the reactors. The measurement then reduces to a ratio in the observed number and distribution of events (after background subtraction) between the different locations, thus considerably reducing the uncertainties related to detector performance, reactor power, and the neutrino energy spectrum and cross sections. This is the main reason that this uncertainty is reduced from 2.7% in CHOOZ to 0.3-0.6%.

Antineutrino interactions are observed through the inverse beta decay (IBD) reaction:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

The neutron is captured either in the hydrogen of the scintillator or in gadolinium mixed into the scintillator with subsequent emission of gamma rays. The signal is therefore a delayed coincidence between the positron and gamma rays, each of which would deposit a few MeV.

There are three main sources of background.

1) Random coincidences simulating a positron-gamma coincidence. This is reduced by controlling the amount of radioactive material near the detectors which is the major source of singles rate, a measurement of which leads to an estimate of this background.
2) Neutron production from cosmic ray muons traversing the detector or the nearby rock. This can be reduced with a large muon veto detector which would reject any coincidence in time with a muon passage and with a neutron-absorbing buffer surrounding the target.
3) The production by muons of ^{8}He and ^{9}Li radioactive isotopes which subsequently decay to a positron and a neutron. This is the exact signature of an inverse beta decay event. They cannot be vetoed upon the passage of a muon because of the long life time (119 ms and 178 ms respectively) of these isotopes, which would result in unacceptably large dead time. However these isotopes are predominantly produced in muon-generated events containing high energy showers or multiple neutron interactions. Their number can therefore be reduced by selectively vetoing muon events with such features. Their impact can also be estimated through measurement in the near detector, and through fitting of the positron energy spectrum above the IBD region.

The CHOOZ scintillator had a light attenuation length of about 5 m and the unpleasant feature of aging at the rate of 0.4%/day. This should no longer be a problem as new scintillators now being developed have attenuation lengths of about 15 m which are stable over at least 100 days and light yields which are constant over at least 220 days.

4.2.1 Double Chooz

The Double Chooz collaboration will use the same reactor complex in northern France and the same far detector location as the original CHOOZ experiment. The improvement will come from the use of a near detector, a larger far detector mass, and more integrated flux from the two 4.2 GW reactors as they will no longer be in a commissioning phase as they were during the CHOOZ experiment.

The near detector will be located 100 m from the reactors and will have an overburden of 60 m.w.e. The equivalent numbers for the far detector are 1050 m and 330 m.w.e. The near detector overburden is chosen to keep the signal/background level above 100.

The detectors are cylindrical and each consists of an inner tank containing the target of 0.1%-gadolinium-loaded scintillator with a total mass of 12.7 tons, a diameter of 2.4 m, and a height of 2.8 m. A 60-cm “gamma catcher” of scintillator without gadolinium surrounds the target. Its purpose is to observe photons from neutron captures near the edge of the target and positron annihilations and to reduce the fast neutron background. This gamma catcher is itself surrounded by a second non-scintillating buffer 95 cm thick designed to reduce fast neutrons. A 60-cm inner veto (100 cm for the near detector) and an outer veto of four layers of proportional tubes are used to flag traversing muons. A total of 512 8" photomultipliers are used in each detector.

	CHOOZ	Double Chooz
Reactor fuel cross sections	1.9%	------
Reactor power	0.7%	------
Energy per fission	0.6%	------
Number of protons	0.8%	0.2%
Detection efficiency	1.5%	0.5%

The table outlines the reduction in systematic uncertainties expected in Double Chooz relative to those achieved in CHOOZ. As can be seen, the use of the near detector eliminates the reactor related uncertainties. The use of a non-scintillating buffer reduces the singles rate to such an extent that the positron threshold can be decreased to 0.5 MeV, less than half the 1.022 MeV physical threshold, and localization cuts can also be made less stringent. As a consequence, the detection efficiency uncertainty is also greatly improved. Unlike in Braidwood and Daya Bay the swapping of detectors is not planned in Double Chooz. The total systematic uncertainty is 0.6%.

A total of 10^6 events/detector/year and 20 000 events/detector/year are expected respectively at the near and far locations. A 5-year run should yield a sensitivity on $\sin^2 2\theta_{13}$ of 0.02 at 90% CL and a discovery limit of 0.03 at 3 σ.

The experiment is in its final approval process and could start with just the far detector as early as 2007. The near detector needs civil engineering and would start 16 months later.

The cost to the U.S. would be $4.9M, to be spent mostly on photomultipliers and the outer veto.

The advantages of Double Chooz are its quick start and its low investment from the U.S. Its lower mass and hence modest statistical uncertainty makes it less dependent on the final systematic uncertainties achieved; a worsening of these errors by 50% would result in a negligible worsening of its limits. However its sensitivity is limited when compared to Braidwood and Daya Bay.

4.2.2 Braidwood

This experiment intends to use two contiguous reactors of 3.6 GW each situated near Braidwood, Illinois, as the source of antineutrinos. The collaboration proposes to build four identical detectors, two of which would be located at the near location, 270 m from the reactors and the other two at the far location, 1510 m from the reactors. The two reactors are located symmetrically about the line connecting the near and far detectors thus considerably reducing uncertainties related to reactor power.

Each detector is spherical and consists of an inner sphere of 5.2 m diameter containing the gadolinium-loaded scintillator, resulting in a target fiducial mass of 65 tons per detector. The target is surrounded by an outer buffer of 7 m diameter containing oil. Unlike the other two proposals, no gamma catcher is envisaged. The proponents argue that this allows a larger inner detector and therefore reduced uncertainties due to edge effects and a more efficient detection of multiple neutron interactions. Each detector is viewed by 1000 photomultipliers. The whole set up is surrounded by a 2 m.w.e. concrete shield which is itself surrounded by an active muon detector.

Both the near and far detectors are located in underground caverns accessed through 180-m-deep shafts. The overburden corresponds to 450 m.w.e. and is identical at the near and far location. This allows a direct subtraction of the cosmic ray background, in particular of the 131 ^{8}He and 1045 ^{9}Li background events expected per detector per year.

For cross-calibration of the detectors and to reduce detector-related systematic uncertainties to the desired 0.3%, three of the four detectors would in turn be positioned next to the fourth one at the near location. Moving detectors between sites would entail raising the detectors to the surface and moving them along surface roads. In addition, the relatively modest overburden allows 50 000 cosmogenic ^{12}B events/ detector/year to be recorded. Counting the β decays (20 ms life time) of these isotopes in conjunction with a tagging muon allows the measurement of the fiducial mass to 0.45%, a useful cross-check.

A total of 3.6×10^6 events/detector/year and 123 000 events/detector/year are expected respectively at the near and far locations. This results in a statistical uncertainty of 0.04% and 0.2% at the two locations. The systematic uncertainties amount to 0.3% detector-related uncertainty for each detector pair and 0.14% for the background. For a 3-year run, a sensitivity on $\sin^2 2\theta_{13}$ of 0.005 at 90% CL, and a discovery limit of 0.01 at 3σ can be reached.

Braidwood can also address the measurement of $\sin^2 \theta_W$. This is particularly topical in view of the discrepancy relative to standard model expectations observed by NuTeV. The measurement would be made through the observation of about 10 000 $\bar{\nu}_e + e$ elastic scattering events in the near detectors. An accuracy of 1% on g_L^2, comparable to the NuTeV accuracy, could be achieved, by normalizing the observed rate to IBD events. Of the three experiments, Braidwood is best suited to make this measurement because of the high mass, reactor proximity, and high shielding of their near detectors.

The estimated cost of the experiment is \$34M + \$8.5M contingency for the civil engineering and infrastructure part and \$18M + \$5M contingency for the four detectors for a total of \$52M + \$13.5M.

With a full approval and a start of construction in 2007, data-taking could start in 2010.

4.2.3 Daya Bay

The U.S. collaborators in this proposal initially intended to use the Diablo Canyon reactors in California, but switched to the Daya Bay site in southern China after difficulties in getting approval to use the U.S. site. The Daya Bay reactor complex has two contiguous reactors at Daya Bay and two more at Ling Ao, for a total of 11.6 GW. Two additional reactors currently being planned for a second Ling Ao site would raise the total power to 17 GW.

The proposal is to build a total of 6 detectors which would be spread over 4 sites: a near site 500 m from the Daya Bay reactors, a second near site 500 m from the Ling Ao reactors, a mid-distance site 1111 m from Daya Bay and 796 m from Ling Ao and a far site 2227 m from Daya Bay and 1801 m from Ling Ao. The detectors are cylindrical and each consists of an inner tank containing the target gadolinium-loaded scintillator with a fiducial mass which has not been decided yet but would be between 20 and 60 tons. The 40 ton version would have a diameter of 3.38 m and a length of 7.14 m. A gamma catcher surrounds the target, and has a diameter of 4 m and a length of 8.1 m. A cylindrical neutron-absorbing buffer surrounds the two inner cylinders. A total of 631 photomultipliers are used in each detector. The setup is surrounded by a water shield, which could be active and used as a Čerenkov counter and, outside this, by a muon tracker consisting of RPC's or scintillators. All detectors are located in underground galleries connected by a system of tunnels.

The respective overburdens are 330 m.w.e. at the two near sites, 560 m.w.e. at the mid site and 1143 m.w.e at the far site. This large overburden at the far site reduces the cosmogenic ^{8}He and ^{9}Li radioactive isotopes production at this site to a negligible level.

Several schemes involving moving detectors between sites to cross-calibrate them and reduce systematic uncertainties are being proposed. Moving detectors between locations would be done underground through the tunnels.

In the near-far configuration the reactor-related and background-related uncertainties are estimated to be 0.1% and 0.4% respectively. The corresponding numbers for the mid-far configuration are 0.2% and 0.18%. Combining these uncertainties with a detector-related uncertainty of 0.36%, a 90% CL sensitivity of 0.009 in $\sin^2 2\theta_{13}$ in a mid-far configuration and 0.008 in a near-far configuration can be reached after 3 years of data-taking. The corresponding 3 σ discovery limit is about 0.014. A more aggressive scheme to reduce the detector-related uncertainty to 0.12% would improve the near-far sensitivity to 0.006.

With construction starting in 2006, data-taking in a near-mid configuration could start in mid 2007, and the far detector could be included as of January 2009.

The civil engineering and infrastructure costs amount to $12.5M and would likely be borne by China. The cost of the detectors is currently being worked out, but for the Diablo Canyon site it had been calculated at $25M + $12.5M contingency.

4.2.4 Comparing reactor experiments

The three reactor experiments before NuSAG are summarized in the following table. There are other reactor experiments being discussed, notably KASKA in Japan, RENO in Korea, and Angra in Brazil. They have not requested U.S. resources and do not appear to be as ambitious in sensitivity as Braidwood or Daya Bay. NuSAG did not consider them in detail, but it is likely that Braidwood and Daya Bay are the only ones aimed at the full range of $\sin^2 2\theta_{13}$ consistent with the reach of accelerator experiments.

	Double Chooz	**Braidwood**	**Daya Bay**
Reactor Power	8.4 GW_{th}	7.2 GW_{th}	11.6 $\rightarrow$ 17.4 GW_{th}
Near Dist/Depth	100 m/60 m.w.e.	270 m/450 m.w.e.	500 m/330 m.w.e.
Mid Dist/Depth	---	---	1111-796 m/560m.w.e
Far Dist/Depth	1100 m/330 m.w.e.	1510 m/450 m.w.e.	2227-1801 m/1143 m.w.e
Mass (Near-Far)	12.7-12.7 tons	2 × 65 - 2 × 65 tons	2 × 40 - 3 × 40 tons
Geometry	Cylindrical	Spherical	Cylindrical
Gamma catcher	Yes	No	Yes
Detector systematics	0.6%	0.3%	0.36% $\rightarrow$ 0.12%
$\sin^2 2\theta_{13}$ at 90% CL	0.02	0.005	0.008 $\rightarrow$ 0.006
Approval/Start	2006/2007 Far	2007/2010	2006/2007 Near-Mid.
	2006/2008 Near		2006/2009 Near-Far
Detector swapping	No	Yes	Yes

The two large reactor proposals, Braidwood and Daya Bay, are scientifically very similar. Both claim comparable total systematic errors and experimental sensitivity, and this sensitivity is consistent with the scientific goals of ambiguity-free coverage down to $\sin^2 2\theta_{13} \sim 0.01$. Both proposals are at a fairly early stage, with the broad experimental layout defined, but many details of the civil construction and detector design still to be determined. The present proposals do not have extensive engineering studies to back up their cost and schedule estimates. It must be emphasized that a full technical review is a necessary precursor to approval for either experiment.

The committee did not find any obvious weakness in either proposal, and concluded that both experiments are likely to achieve most of their claimed scientific reach. In the absence of more detailed technical proposals and simulation studies, it is difficult to predict which experiment will ultimately do a better job. NuSAG did conclude that the symmetric arrangement of detectors with respect to reactor cores in Braidwood allows straightforward cancellation of reactor-based errors. The more complicated arrangement of detectors with respect to three reactor sites at Daya Bay leaves a residual flux error due to uncorrelated power changes that is not negligible compared to other sources of error.

The non-technical differences between Braidwood and Daya Bay are considerable. These primarily have to do with the siting of Daya Bay in China. This brings with it both potential benefits and potential risks. NuSAG discussed some of these, but most are well outside NuSAG's expertise. It is likely that the cost of Daya Bay to the U.S. program would be less than the (~all-U.S.) cost of Braidwood. The difference could be substantial, but neither cost estimate is final. Further, Daya Bay's cost is not as developed as Braidwood's, and the details of the division of costs between the U.S. and China are not yet worked out.

This brings another dimension to the Braidwood-Daya Bay decision. To what extent do the costs to the U.S. program and the non-technical issues make one experiment more likely to reach and successfully execute its construction phase? To address this requires an understanding of expected budgets, sufficient understanding of the costs, absolute and relative, to the U.S. program, and the weights to be attached to the non-technical issues.

5 Conclusions

5.1 Global Conclusions

The worldwide program to study neutrino oscillations is in progress. The U.S. has been a major participant in this from the beginning, and is currently at the forefront, with running experiments that will bring the next major results. A global planning effort has developed a comprehensive set of proposed measurements that together have the potential to fully determine the mixing matrix that parametrizes 3-neutrino mixing. The experiments before NuSAG are the first phase of a program designed to perform all of these measurements, subject only to the limitation imposed by $\sin^2 2\theta_{13}$. Accelerator and reactor experiments play complementary roles in this comprehensive study of neutrino mixing, and currently proposed reactor- and accelerator-based experiments have similar reach in sensitivity to oscillations. Conventional neutrino beams, pushed to the maximum feasible power (so-called "super beams"), are believed to allow a quite thorough exploration of oscillations, CP violation, and the mass hierarchy down to $\sin^2 2\theta_{13}$~0.01. The proposed program of experiments is meant to cover this region, initially with sensitivity to observe the oscillations, and, with upgrades, to measure CP violation and the mass hierarchy.

Construction of experiments in the next round of the global program has begun: in Japan, on a new accelerator-based neutrino beam aimed at the existing Super-K detector (T2K), and in France on an improved reactor experiment (Double Chooz). The U.S. has the opportunity to share the leading role in the global effort with Japan, both by mounting critical experiments and by playing a major role in experiments abroad. The Double Chooz and T2K experiments now under construction will extend the sensitivity to non-zero $\sin^2 2\theta_{13}$ by factors of six and 20, respectively. However, they will be unable to observe CP violation or determine the mass hierarchy, and, even if $\overline{\nu}_e$ disappearance or $\nu_\mu \rightarrow \nu_e$ oscillation is seen, would be unable to determine the value of $\sin^2 2\theta_{13}$ precisely or resolve the two-fold ambiguity in θ_{23}. Even if the beam power in T2K is increased, there is only limited potential for observing CP violation and none for determining the mass hierarchy. The NOvA and Braidwood or Daya Bay experiments could bring all of these capabilities for a substantial range of the unknown parameters.

The neutrino oscillation program can proceed step-by-step. Accelerator-based experiments re-use an existing large detector (T2K with Super-K) and neutrino beam (NOvA with the NuMI beam), each of which represents an enormous investment. First-round observations would indicate if and how beams or detectors should be upgraded. While additional sensitivity is possible with upgraded accelerator beams and detectors, the reactor proposals already push systematic errors using all the tricks they can muster, and no second phase for them is anticipated.

5.2 Accelerator

Leading the global program in neutrino oscillations means supporting a program that can advance oscillation physics on a broad front. While reactor experiments can establish that θ_{13} is non-zero by observing $\overline{\nu}_e$ disappearance, only long-baseline accelerator experiments can address CP violation and the mass hierarchy.

The NOvA experiment would give the U.S. a leading role in the program of neutrino oscillations. It is a natural extension of the existing NuMI program at Fermilab and provides a pathway towards more ambitious experiments in the future. The collaboration has put together a detailed proposal and cost estimate, both of which have been thoroughly reviewed by Fermilab. The collaboration is strong, and they are ready for a 2007 construction start. NOvA in its first phase would operate using the existing NuMI beam with intensity improvements estimated to approach a factor of two, primarily from flexibility in using the Fermilab accelerator complex after Run II ends. In this configuration, NOvA's sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillations is comparable to T2K. Although a new detector would have to be understood, NOvA would have the advantage of starting with a fully commissioned beam. Consequently, if initiated soon, NOvA's results would be on about the same time scale as T2K's. With their initial beam power, NOvA and T2K would establish that θ_{13} is non-zero if $\sin^2 2\theta_{13}$ is greater than about 0.01. This observation would demonstrate that the determination of the mass hierarchy and sensitive searches for CP violation are within the reach of conventional, albeit megawatt or higher power, neutrino beams. NOvA also has a modest chance of resolving the mass hierarchy in Phase 1, if $\sin^2 2\theta_{13}$ is not too far below current limits. Combining measurements with T2K adds to this sensitivity.

The T2K experiment in Japan will have, with the currently designed beam power, sensitivity to $\nu_\mu \rightarrow \nu_e$ appearance comparable in $\sin^2 2\theta_{13}$ reach to that of a large reactor experiment. The U.S. has had a long-standing role in this very successful program using the Super-K detector, and this can continue with a modest further investment. The B280 project, containing necessary components to run the experiment, naturally has a higher priority than the 2KM effort. While the systematic precision of 2KM detectors is nominally not required in the first phase of the T2K program, the credibility of a first-phase appearance signal would be substantially enhanced by the 2KM detectors.

NOvA and T2K are also steps in a larger program. With the currently designed beam power, neither T2K nor NOvA has any significant sensitivity to CP violation. The upgrade path to the accelerator experiments starts with the establishment of non-zero $\sin^2 2\theta_{13}$ by either the accelerator or reactor experiments. Then, the most effective next step is increasing the beam power. The upgrade considered for T2K brings its beam power to 4 MW. At Fermilab, a "Proton Driver" could bring the power to 2 MW. Also under consideration at Fermilab are a series of incremental improvements that might bring a substantial fraction of this power.

With beam power upgraded, T2K and NOvA each has a modest sensitivity to CP violation. Combined, the experiments have considerably more CP sensitivity. However, at T2K's low energy, determined by its 295-km baseline, T2K cannot determine the mass hierarchy. NOvA alone with a Proton Driver enhances its reach in the mass hierarchy substantially. As with CP violation, the comparison of the two different baselines makes the combination of NOvA and T2K considerably more sensitive.

Further reach in both CP violation and the mass hierarchy is possible through additional upgrades. This third phase would most likely involve additional large detectors. The Japanese program is considering Hyper-K, a one-megaton detector near Super-K, while in the U.S. more emphasis is placed on a ~50 kiloton detector at the second oscillation maximum.

Experiments beyond the first phase of NOvA or T2K will require both high intensity beams and improved sensitivity. LArTPC's are a promising technology for a new generation of detector, but the ability to industrialize and scale the technology to >10 kiloton levels must be demonstrated before a commitment to the technology can be made.

Even if a higher priority for the International Linear Collider (ILC) precludes building a Proton Driver, the NOvA program, once established with the existing beam, can develop with incremental beam improvements and, possibly, a second detector. There are scenarios that would delay or skip NOvA, waiting for ILC siting and approval to be resolved. Though such an approach would save money in the short term and might have more information on $\sin^2 2\theta_{13}$ prior to further investment, it would cede leadership of the field to Japan and direct U.S. physicists to pursue their interest elsewhere. If the time came to revive the program in the U.S., the buy-in cost in an era where megawatt beams would be a prerequisite would be multiplied by a large factor. Further, there would be years with no U.S.-accelerator-based high energy physics, including the time between a decision to return to accelerator-based neutrino physics and the approval of any construction project. The U.S. infrastructure of accelerators and accelerator expertise would degrade during this period, and it is not clear when, where, or by whom a competitive U.S. accelerator neutrino program would develop.

5.3 Reactor

A reactor neutrino experiment determines, or sets a limit on, $\sin^2 2\theta_{13}$ independent of other parameters. The proposed large reactor experiments will not be significantly faster than accelerator experiments in reaching sensitivities approaching $\sin^2 2\theta_{13} \sim 0.01$.

However, the reactor determination of $\sin^2 2\theta_{13}$ helps disentangle the combination of parameters measured by an accelerator ν_e appearance experiment by eliminating some of the ambiguities. A reactor experiment is therefore valuable regardless of its timing with respect to an accelerator experiment.

Double Chooz gives the earliest improvement over current sensitivities in the search for $\bar{\nu}_e$ disappearance, but it cannot cover the full range of interest to accelerator experiments, and it cannot provide measurements of precision sufficient to resolve ambiguities. A larger reactor experiment is therefore an important part of the global program. The Braidwood and Daya Bay collaborations propose experiments reaching similar sensitivities that cover this interesting region.

The large reactor experiments are challenging and are limited by systematic uncertainties. While this would make a second such experiment attractive as a cross check, one would be sufficient since there would be general confirmation available in the accelerator experiments. This, and the fact that the large reactor experiments are expensive, suggest that the U.S. program should include only one such experiment. The present proposals do not have extensive engineering studies to back up their cost and schedule estimates, although Braidwood is more advanced in this respect. A full technical review is a necessary precursor to approval for either experiment.

Braidwood and Daya Bay are scientifically very similar. NuSAG concludes that Braidwood has an advantage in the control of systematic errors due to its simpler arrangement of reactor cores and detectors and the symmetry in background between near and far sites. However, it is likely that both experiments could reach similar sensitivities, and these sensitivities probe the scientifically interesting region $\sin^2 2\theta_{13}{\sim}0.01$.

It is likely that Daya Bay could be mounted at a cost to the U.S. program that would be less than the cost of Braidwood, but this has not been reliably established. Doing so would require an understanding of how costs would be shared between China and the U.S. and commitments from all parties to stand by that arrangement. The decision between Braidwood and Daya Bay has other important components, notably those having to do with Daya Bay being in China. These can cut both ways, and the ones that could be decisive are generally outside the expertise of NuSAG.

6 Recommendations for the U.S. program in neutrino oscillations

6.1 General recommendations

6.1.1 The United States can and should be a leader of the worldwide experimental program in neutrino oscillations.

6.1.2 The U.S. program should include both accelerator- and reactor-based experiments.

6.2 Recommendations on accelerator-based experiments

6.2.1 The U.S. should conduct the NOvA experiment at Fermilab. The first phase of this experiment can compete successfully with the Japanese T2K program. If justified by Phase-1 results, both NOvA and T2K have potential later phases. The combination of the two programs is considerably more powerful than either alone, due to their different baselines. Particularly notable is NOvA's sensitivity to the mass hierarchy, unique among the experiments studied for this report.

6.2.2 The U.S. should continue to play an important role in the Japanese neutrino program. This is a cost-effective element of the U.S. program and beneficial to the worldwide program. The U.S. participation in the T2K program should focus in the short term on the B280 effort. This is crucial to bringing the T2K experiment on line. The T2K 2KM project brings improved systematics that would be necessary in later phases of the T2K program. In the initial oscillation search, it would bolster confidence in an observation, especially if NOvA were not underway. U.S. participation on an appropriate time scale is supported if possible.

6.2.3 The U.S. R&D program in Liquid Argon TPC's should be supported at a level that can establish if the technology is scalable to the 10-30 kiloton range. If workable, this technology will come into its own in the later phases of the long-baseline program.

6.3 Recommendations on reactor experiments

6.3.1 The United States should mount one multi-detector reactor experiment sensitive to $\bar{\nu}_e$ disappearance down to $\sin^2 2\theta_{13}$~0.01.

6.3.2 Braidwood and Daya Bay have both made a good case that they could achieve the desired sensitivity, given their current level of technical maturity. The Braidwood experiment has somewhat more sensitivity due to the reduced systematic limitations associated with its simpler geometry. NuSAG did not carry out any detailed review of the costs presented by the two collaborations. Based on the information given us, the Braidwood estimate is further developed than Daya Bay's. It is likely that the cost sharing between the U.S. and China will lead to a lower cost to the U.S. program for Daya Bay. However, until this cost sharing is better defined, it is impossible to determine the relative cost of the two experiments.

Understanding that such a determination is necessary, NuSAG strongly recommends that this happen as quickly as possible, with timely R&D funding to further understanding of costs and schedules.

6.3.3 Although it cannot perform its measurements to the sensitivity required by the broader program and thus has lower scientific priority than the larger reactor experiment, U.S. participation in Double Chooz is encouraged because of its relatively low cost and the opportunity to make early improvements in sensitivity to $\bar{\nu}_e$ disappearance.

Appendix A: The NuSAG Charge

March 7, 2005

Professor Frederick Gilman
Chair, HEPAP
Carnegie-Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213

Professor Richard F. Casten
Chairman, NSAC
Wright Nuclear Structure Laboratory
Yale University
New Haven, CT 06520

Dear Professors Gilman and Casten:

This letter is to request that, in response to the Office of Science & Technology Policy led interagency working group report on a federal strategy for the Physics of the Universe, you form a subcommittee to address issues involving neutrinos that cross disciplinary and agency boundaries. Specifically, we ask that the High Energy Physics Advisory Panel (HEPAP) and the Nuclear Science Advisory Committee (NSAC) establish a Neutrino Scientific Assessment Group (NuSAG) as a joint sub-committee to advise the Department of Energy (DOE) Offices of Nuclear and High Energy Physics and National Science Foundation Programs of Nuclear Physics and Elementary Particle Physics on specific questions concerning the U.S. neutrino physics program.

There has been a growing recognition of the important role played by neutrinos in answering some of the most compelling questions in subatomic physics. Two National Research Council studies (*Quarks to the Cosmos, Neutrinos and Beyond*), two long range planning exercises (HEPAP and NSAC), and most recently a multi-divisional year-long American Physical Society (APS) study have all identified compelling discovery opportunities involving neutrinos. These studies laid the scientific groundwork for the choices that must be made during the next few years. They did an excellent job of explaining the new paradigm of neutrino science, why this science is filled with important and interesting questions, and why the time is right to address these questions.

It is clear that a number of experimental directions should be pursued, but none of the studies mentioned made recommendations on particular projects. For those directions where the timescale is long-term, we will wait to take advantage of additional input, such as from the National Academy Sciences study on Elementary Particle Physics (EPP2010). However, for those directions where expeditious action is appropriate, we ask the NuSAG to make recommendations on the specific experiments that should form part of the broad U.S. neutrino science program. In addition, on a similar time line to NuSAG, the NSAC will be reviewing the full DOE Nuclear Physics program. Timely recommendations from NuSAG will be important input for this review.

NuSAG will be constituted for a fixed period of two years as a joint subpanel of HEPAP and NSAC. It will report to the agencies though HEPAP and NSAC who will consider its recommendations for approval and transmittal to the agencies.

The recommendations of the APS Neutrino Study form the basis for the first three charges for NuSAG listed below.

Charge 1

We request that NuSAG address the APS Study's suggestion that the U.S. participate in *"An expeditiously deployed multidetector reactor experiment with sensitivity to* ν_e *disappearance down to* $sin^2 2\theta_{13}=0.01$*, an order of magnitude below present limits."*

The options to be considered should include, but need not be limited to:

- A U.S. experiment (in Diablo Canyon, CA, Braidwood, IL, or elsewhere)
- U.S. participation in a European reactor experiment (Double Chooz or elsewhere)
- U.S. participation in a Japanese reactor experiment
- U.S. participation in a reactor experiment at Daya Bay, China.

Charge 2

NuSAG is requested to address the APS Study's recommendation of a phased program of sensitive searches for neutrino-less nuclear double beta decay. In particular, a timely assessment of the scientific opportunities and resources needed should be performed of the initiatives that are presently under discussion in the research community. These include, but should not be limited to:

- U.S. experiments (Majorana, EXO, others)
- U.S. participation in an Italian experiment (Cuoricino/Cuore)
- U.S. participation in a Japanese experiment (Moon).

Charge 3

We request that NuSAG address the APS Study's suggestion that the U.S. participate in *"A timely accelerator experiment with comparable* $sin^2 2\theta_{13}$ *sensitivity [to the recommended reactor experiment, i.e.* $sin^2 2\theta_{13}=0.01$*]* and sensitivity to the mass-hierarchy through matter effects."

The options to be considered should include, but not be limited to:

- U.S. participation in the T2K experiment in Japan
- Construction of a new off-axis detector to exploit the existing NUMI beamline from Fermilab to Soudan, as proposed by the Nova collaboration
- As above but using a large liquid argon detector.

Within each of these three charges, NuSAG should consider the various initiatives that have been proposed. NuSAG should look at the scientific potential of each initiative, the timeliness of its scientific output together with the likely costs to the U.S., and its place in the broad international context. In addition, for the off-axis initiatives (charge 3), the context should include a consideration of what is likely to be learned from other experiments, and the likely future extensibility of each option as part of an evolving U.S. neutrino program. For all three charges NuSAG should then recommend a strategy of one (or perhaps more than one) experiment in that direction, which in its opinion should be pursued as part of the U.S. program.

It is requested that the NuSAG Report be sent to HEPAP and NSAC by no later than the end of June 2005.

We thank you for your help in establishing this advisory group; its input is very important. We look forward to working with you in this endeavor.

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

Appendix B: Members of the DOE/NSF Neutrino Scientific Assessment Group (NuSAG)

Eugene Beier (University of Pennsylvania and Co-Chair)

Peter Meyers (Princeton University and Co-Chair)

Leslie Camilleri (European Organization for Nuclear Research, CERN)

Rick Casten (Yale University) NSAC Chair ex-officio

Fred Gilman (Carnegie-Mellon University) HEPAP Chair ex-officio

John Hardy (Texas A\&M) from July 1 to September 1, 2005

Boris Kayser (Fermi National Accelerator Laboratory)

Naomi Makins (University of Illinois)

Art McDonald (Queens's University) until July 1, 2005

Tsuyoshi Nakaya (Kyoto University)

Natalie Roe (Lawrence Berkeley National Laboratory)

Guy Savard (Argonne National Laboratory)

Heidi Schellman (Northwestern University)

Gregory Sullivan (University of Maryland)

Petr Vogel (California Institute of Technology)

Bruce Vogelaar (Virginia Tech)

Glenn Young (Oak Ridge National Laboratory)

Appendix C: Agenda of the Open NuSAG Meeting

First NuSAG Meeting -- Gaithersburg, MD -- May 31-June 2, 2005

Agenda -- Draft 3

Tuesday, May 31

9:00 Executive session	
10:45 Break	
11:00 Introduction to neutrino oscillations	Boris Kayser
11:45 Introduction to double beta decay	Petr Vogel
12:30 Lunch	
Presentations: double beta decay	
1:30 CUORE	Rick Norman, *LBL*
2:15 EXO	Giorgio Gratta, *Stanford*
3:00 Majorana	John Wilkerson, *U.Washington*
3:45 Break	
4:15 Moon	Hamish Robertson, *U.Washington*
4:45 Super-NEMO	Xavier Sarazin, *LAL, Orsay*
	Karol Lang, *U.Texas*
5:30 Executive session	
6:00 End	

Wednesday, June 1

9:00 Executive Session	
10:00 Break	
Presentations: accelerator long baseline experiments	
10:15 NOvA	Gary Feldman, *Harvard*
11:00 Liquid Argon Detectors	Bonnie Fleming, *Yale*
11:45 T2K	Chang Kee Jung, *Stony Brook*
	Chris Walter, *Duke*
12:40 Lunch	

2:00 Executive Session

Presentations: Reactor θ_{13} experiments

2:30 Double CHOOZ	Bob Svboda, *LSU*
	Maury Goodman, *ANL*
3:15 Braidwood	Mike Shaevitz, *Columbia*
4:00 Break	
4:30 Daya Bay	Stuart Freedman, *LBL*
5:15 Executive session	
6:00 End	

Thursday, June 2

9:00 Executive session

1:00 End

References

[1] Neutrino Scientific Assessment Group, "Recommendations to the Department of Energy and the National Science Foundation on a United States Program in Neutrino-less Double Beta Decay," September 1, 2005, http://www.science.doe.gov/hep/NuSAGReport1final.pdf and http://www.sc.doe.gov/np/nsac/docs/NuSAG_report_final_version.pdf

[2] http://www.hep.net/nusag_pub/May2005talks.html