Recommendations to the Department of Energy and the National Science Foundation on a United States Program in Neutrino-less Double Beta Decay

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

Submitted by the Neutrino Scientific Assessment Group

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Contents

Summary of Report

Experiments in neutrino-less double beta decay address two fundamental problems about the physical world - whether neutrinos are their own anti-particles, and the absolute scale of the masses of neutrinos. This report from the Neutrino Scientific Assessment Group offers a plan for a United States program in neutrino-less double beta decay. The report discusses the science addressed by these experiments, the proposed experiments, and in Section 4.2 recommends a prioritized program for participation in this important area of research.

1 Introduction

Discoveries in neutrino physics during the past decade have advanced fundamental physics in dramatic and unexpected ways. United States physicists have made important contributions to international collaborations at several locations. The Super-Kamiokande and K2K collaborations, working in Japan, have demonstrated that the different types of neutrinos mix with each other as described by a quantum mechanical phenomenon called neutrino oscillations. The Sudbury Neutrino Observatory collaboration, working in Canada, resolved a long standing puzzle about the flux of solar neutrinos by observing that those neutrinos transform from the type emitted by the sun to other types on their trajectory to terrestrial detectors. The KamLAND collaboration in Japan showed that anti-neutrinos produced in terrestrial nuclear power reactors behave similarly to solar neutrinos, thereby demonstrating that matter-induced neutrino oscillations are responsible for the transformation of the solar neutrinos.

As a result of this research, it is now understood that neutrinos have mass, that the mass of all the neutrinos in the universe is comparable to the mass of all the stars in the universe, and that the standard model of electro-weak interactions that accounts for almost all the phenomena we observe must be extended to account for the new data from the neutrino experiments. This research involves nuclear physicists, high energy physicists and chemists. It is sponsored by the Department of Energy through the Office of Nuclear Physics and the Office of High Energy Physics in the Office of Science, and by the Nuclear and Elementary Particle Physics offices in the Mathematics and Physical Sciences Directorate of the National Science Foundation.

Neutrino science will make more contributions to our understanding of the physical universe. The experiments considered in the initial charges to the Neutrino Scientific Assessment Group (NuSAG) are part of a two-pronged thrust. The first area to be considered is the absolute mass scale of neutrinos. The observation of neutrino oscillations determines mass squared differences of neutrino types and thereby sets a lower bound on the largest of the neutrino masses. Precision beta decay experiments set laboratory upper limits on the absolute mass, and these limits are of the same order of magnitude as those derived from observational cosmology.

Neutrino-less double beta decay experiments are needed to understand the absolute mass scale of neutrinos and to answer the fundamental question of whether neutrinos are their own anti-particles, that is, whether they are Majorana or Dirac particles. The laboratory precision beta decay experiments are limited in sensitivity to $0.2 - 0.3$ eV. Neutrino-less double beta decay experiments considered in this report may have sensitivity to an "effective" neutrino mass an order of magnitude smaller. Observation of neutrino-less double beta decay requires that neutrinos are their own anti-particles, or Majorana type, which gives direction to the understanding of physics beyond the present standard model of electro-weak interactions. Complementary information on the absolute mass scale from experiments in observational cosmology cannot address the question of the Majorana nature of the neutrinos. This report addresses experiments in neutrino-less double beta decay.

The second area of research on the fundamental properties of neutrinos addresses questions of neutrino mixing, the phenomenon that leads to neutrino oscillation. From solar and atmospheric neutrino experiments, later confirmed by accelerator and reactor experiments, we know that of the three neutrino mass states, two of them, ν_1 and ν_2, have masses that differ by only $|m_2^2 - m_1^2| = 7.9 \times 10^{-5}$ eV^2, with $m_2 > m_1$. The third mass state, ν_3, is separated from these two by a larger amount $|m_3^2 - m_1^2| \approx |m_3^2 - m_2^2| = 2.4 \times 10^{-3}$ eV^2[1]. Note that oscillation experiments only determine absolute mass squared differences. Two questions related to masses therefore remain to be answered:

a) Is m_3 larger or smaller than the other two masses? These two scenarios are referred to as the normal and inverted hierarchies, respectively.

b) Does the neutrino mass spectrum start at or near zero mass or is it shifted upwards by a significant amount, albeit bounded by present direct and cosmological mass measurements? The latter case is referred to as the degenerate scenario.

We have also learned that neutrino oscillations can be described by a mixing matrix that includes three angles, two of which, θ_{12} and θ_{23}, have already been measured by solar and atmospheric neutrino experiments and found to be large. Only an upper limit, set by reactor experiments, has been established for the third angle, θ_{13}, and it appears to be much smaller than the other two.

The mixing matrix also includes a phase angle that, if non-zero, could cause neutrinos to behave differently from anti-neutrinos through the mechanism called CP violation. If neutrinos are Majorana particles, as would be the case if neutrino-less double beta decay occurs, there are two more phases that could lead to CP violation.

In further exploration of neutrino mixing, an important milestone is the measurement of θ_{13}. Not only would observation of non-zero θ_{13} confirm the overall pattern of neutrino mixing, but, if θ_{13} is not too small, it may be possible to determine one phase angle in the mixing matrix. This in turn could lead to the beginning of an explanation of why our universe is made from matter and not from equal proportions of matter and anti-matter. Certain experiments designed to measure θ_{13} could also distinguish the mass hierarchy of neutrinos. Recommendations on experiments on neutrino mixing will appear in a subsequent report from NuSAG.

The following sections of this report discuss the charge to the panel and the process followed, the nature and importance of the scientific questions involved in establishing a plan for neutrino-less double beta decay for the United States, a short description of each of the experiments under consideration, the criteria used to establish a plan, and the recommendations of the panel.

1.1 The Charges

The Department of Energy (DOE) and the National Science Foundation (NSF) requested in March, 2005, that the Nuclear Science Advisory Committee (NSAC) and the High Energy Physics Advisory Panel (HEPAP) 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). The latter study identified a set of important issues but did not make recommendations on specific experiments.

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 the 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."*

Options for experiments 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. 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 charge letter requests that NuSAG report to HEPAP and NSAC by the end of June, 2005. A subsequent agreement between the panel co-chairs, the heads of the funding offices, and the NSAC and HEPAP chairs revised the target dates for responses to be the end of July 2005 for the neutrino-less double beta decay charge, and the end of September 2005 for the two charges on neutrino mixing experiments.

1.2 The Process

The panel, whose members are listed in Appendix B, was organized in April and May 2005. 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: http://www.hep.net/nusag_pub/May2005talks.html. The panel did not solicit input from experiments that were not mentioned in the charge, but the process was sufficiently open that three additional experiments have contacted the panel chairs. One of those experiments was invited to make a presentation to the panel, a second has no collaborators from the United States at this time and was not invited, and discussions with the third are ongoing.

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. Prior to this meeting, information was requested from GERDA, a European neutrino-less double beta decay experiment that uses techniques similar to one of the experiments under consideration here.

2 The Science of Neutrino-less Double Beta Decay

Revolution in neutrino science

The standard model of electroweak interactions (SM), developed in the late 1960's, incorporates neutrinos as left-handed partners to the charged leptons. The subsequent discovery of charmed quarks and the third generation of quarks and leptons completed the modern version of the standard model of electroweak interactions. Later, detailed study of the decay of the Z-boson showed that indeed three, and only three, neutrino "flavors" with the SM interactions exist. In the standard model the three neutrinos are massless, and the individual lepton flavor numbers,

$$L_\alpha(\nu_\alpha) = L_\alpha(\ell_\alpha^-) = -L_\alpha(\bar{\nu}_\alpha) = -L_\alpha(\ell_\alpha^+) = 1 \ , \tag{1}$$

are strictly conserved. Here the index α labels the electron and its neutrino, the muon and its neutrino, and the tau and its neutrino.

Following the success of big-bang nucleosynthesis, which describes the observed abundance of the lightest elements, and the discovery of the cosmic microwave photon background, it also became clear that neutrinos were major players in the history of the early universe. This set the stage for an experimental assault on the issue of neutrino mass and its role in cosmology and provided substantial impetus to a worldwide program of experiments addressing the issues of finite neutrino mass and the possibility of mixing between flavors.

Convincing evidence for neutrino mass has been obtained now in experiments that observe neutrino oscillations. Neutrino oscillations, transformations of one neutrino flavor into another, can occur only if neutrinos have finite mass that is not the same for the different states (so-called "mass eigenstates"). The oscillation length, i.e., the distance over which one flavor could be transformed into another one, depends on the difference of the squares of these masses, quantities usually denoted as Δm^2_{ji}. The phenomenon of neutrino oscillation is a purely quantum-mechanical interference effect that exists over macroscopic distances. It is extremely satisfying, even though perhaps not surprising, that such phenomena are so well described by the basic machinery of quantum physics.

The first hints that neutrino oscillations occur were found serendipitously. Recent studies definitively establish that the solar electron neutrino flux observed on earth is reduced due to flavor oscillations, and so it is now clear that the first real signal of neutrino oscillations was the long-standing deficit of solar neutrinos observed by Ray Davis and collaborators in the Chlorine radiochemical experiment in the Homestake mine. (R. Davis, together with M. Koshiba, were recipients in 2002 of the physics Nobel Prize for their pioneering role in observing the neutrinos.) Evidence that neutrinos produced in the atmosphere by cosmic rays ("atmospheric neutrinos") oscillate was a byproduct of the search for proton decay using large water Cherenkov counters.

While the revolutionary discoveries of neutrino oscillations were obtained with natural, and thus difficult to control, neutrino sources, more recent experiments have succeeded in establishing the existence of these phenomena with man made and better understood neutrino sources, nuclear power reactors and particle accelerators. It is now known that the standard electroweak model is incomplete, and that, among other things, the individual lepton numbers L_α are not conserved.

In order to explore further this window to physics beyond the SM the physics community worldwide is embarking on an ambitious program of neutrino studies, concentrating in particular on the intrinsic properties of neutrinos.

The Neutrino-Antineutrino Relation[*]

One of the most interesting questions about the intrinsic nature of neutrinos, raised by the discovery of neutrino mass, is the question of whether neutrinos are their own antiparticles. Is each neutrino mass eigenstate ν_i identical to its antiparticle $\overline{\nu_i}$, or distinct from it? If $\overline{\nu_i} = \nu_i$, we call the neutrinos Majorana particles, while, if $\overline{\nu_i} \neq \nu_i$, we call them Dirac particles.

Of course, we know that the electron is distinct from its antiparticle, the positron, because these two particles carry opposite electric charge. However, a neutrino carries no electric charge, and may not carry any other conserved charge-like quantum number. It might be thought that there is a conserved total lepton number L, defined in analogy to Eq.(1), but independent of lepton flavor, by

$$L(\nu) = L(\ell^-) = -L(\bar{\nu}) = -L(\ell^+) = 1 \ . \tag{2}$$

This total lepton number simply distinguishes neutrinos ν and charged leptons ℓ^- on the one hand from antineutrinos $\bar{\nu}$ and anti-charged leptons ℓ^+ on the other hand. Even though violation of the total lepton number L has not been observed so far, there is no deep reason known for the existence of such a conserved quantum number. If it does not exist, then nothing distinguishes $\overline{\nu_i}$ from ν_i. The neutrino mass eigenstates are then Majorana particles, identical to their antiparticles.

Many theorists believe that, indeed, the lepton number L defined by Eq.(2) is not conserved. One reason for this belief is the nature of the very successful standard model that, as mentioned above, contains no neutrino masses. Nor does it contain, by definition, any chirally right-handed neutrino fields, ν_R, but only left-handed ones, ν_L. Now that we know neutrinos have masses, we must extend the SM to accommodate them. Suppose that we try to do this in a manner that will preserve the conservation of L. Then, for a neutrino ν, we add to the SM Lagrangian a "Dirac mass term" of the form

$$\mathcal{L} = -m_D \overline{\nu}_L \nu_R + h.c. \ \ . \tag{3}$$

Here, m_D is a constant, and ν_R is a right-handed neutrino field that we were obliged to add to the SM in order to construct the Dirac mass term. A Dirac mass term does not mix neutrinos and antineutrinos, so it conserves L. The masses of the charged leptons, electron, muon, and tau, which are Dirac particles, are determined by analogous Dirac mass terms. Of course, it is somewhat disturbing that the constants m_D for neutrinos have to be more than a million times smaller than the analogous constants for the electron, muon, and tau.

In the SM, left-handed fermion fields belong to electroweak-isospin doublets, but right-handed ones are isospin singlets. Once ν_R is present, all the SM principles, including electroweak-isospin conservation and renormalizability, allow the occurrence of the "Majorana mass term"

$$\mathcal{L}_M = -m_M \overline{\nu_R}^c \nu_R + h.c. \ \ . \tag{4}$$

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[*] Text in the following several sections is taken from "Neutrino Intrinsic Properties: The Neutrino-Antineutrino Relation," by Boris Kayser, to appear in the Proceedings of the Nobel Symposium 2004, Enköping, Sweden, August 19-24, 2004. (The publisher's permission has been obtained.)

Here, m_M is a constant, and ν_R^c is the charge conjugate of ν_R. Any Majorana mass term of this form converts a ν into a $\bar{\nu}$, or a $\bar{\nu}$ into a ν. Thus, it does not conserve L.

If we insist that the SM, extended to accommodate neutrino masses, remain L conserving, Majorana mass terms are forbidden. The only allowed mass terms are then Dirac mass terms like the one in Eq. (3), and we must accept the extremely small constants m_D that these would entail. However, if we do not impose L conservation by hand, but require only the general SM principles, such as electroweak-isospin conservation and renormalizability, then Majorana mass terms such as the one in Eq.(4) are allowed. It is then very natural to expect that they are present in nature, so that L is not conserved and the neutrinos are Majorana particles.

The neutrino ν appearing in the mass terms of Eqs. (3) and (4) is not a mass eigenstate, but one of the underlying states in terms of which the theory is written. Like a K^0, ν is distinct from its antiparticle. However, once the Majorana mass term of Eq (4) that mixes ν and $\bar{\nu}$ is present, L is not conserved. As a result, the mass-eigenstate neutrinos ν_i that diagonalize the theory are identical to their antiparticles, just as are K_S and K_L.

The most popular explanation of why neutrinos are so light is the see-saw mechanism. This mechanism includes Majorana mass terms. Hence, it predicts that L is not conserved and that neutrinos are Majorana particles. The see-saw mechanism introduces very heavy right-handed neutrinos ν_R. If that idea could be confirmed, it would allow us to explore a particle mass range many orders of magnitude larger than anything observed so far.

In testing L conservation we are assuming that the interactions of neutrinos are correctly described by the SM. There is no experimental evidence that would suggest that this is not so, and plenty of evidence supporting this assumption. Since the SM interactions conserve L, the L non-conservation that we seek can only come from Majorana neutrino mass terms. Thus, it must vanish when the neutrino masses vanish. Consequently, any attempt to demonstrate that $\overline{\nu_i} = \nu_i$ or, equivalently, that L is not conserved will be challenged by the smallness of neutrino masses. The only approach that shows considerable promise of being able to meet this challenge is the search for neutrino-less double beta decay, which allows us to use very many potentially decaying nuclei and observe just the very few that decay in the apparatus.

Proving that L is not conserved, and hence that neutrinos are massive Majorana particles, would be of fundamental significance. It would demonstrate that neutrinos are very different from the other fermion constituents of matter - the quarks and charged leptons. In addition, it would, we hope, pave the way to the proper generalization of the SM model and a better understanding of the whole field of particle physics.

Neutrino-less double beta decay

Neutrino-less double beta decay $(0\nu\beta\beta)$ is the spontaneously occurring process Nucl $\rightarrow$ Nucl$'+$ $e^- + e^-$, in which two neutrons embedded in the ground state of the initial nucleus decay simultaneously into two protons in the final nucleus, two electrons, and nothing else. Since the nuclei are so much heavier than the energy available for the decay, the electrons carry *all the decay energy,* which depends only on the well-measured nuclear masses. Observing a sharp feature in the summed electron energy spectrum is then an indication that the $(0\nu\beta\beta)$ decay occurred. Several nuclei exist in nature in which this process is energetically possible with the energy release of a few MeV.

Manifestly, this reaction would not conserve L. Thus, observing it at any nonzero level would establish that neutrinos are identical to their antiparticles. Like any L-nonconserving process, $0\nu\beta\beta$ decay is suppressed by the smallness of neutrino masses. However, if we choose as our parent nucleus one that cannot decay by α or single β emission and wait long enough, we might see it decay by $0\nu\beta\beta$ emission. To be sure, any nucleus that can decay in this L-nonconserving way can also decay via the L-conserving process Nucl $\rightarrow$ Nucl$'$ $+ e^- + e^- + \bar{\nu} + \bar{\nu}$, the so-called $2\nu\beta\beta$ decay that has been observed now in many isotopes. However, this two-neutrino double beta decay is phase-space suppressed, and its summed electron energy spectrum is continuous, peaking near the half its maximum allowed value and thus giving the neutrino-less mode a chance to be observed.

The dominant mechanism for $0\nu\beta\beta$ is expected to be the light neutrino-exchange diagram in Figure 1, in which one or another of the neutrino mass eigenstates ν_i is exchanged. The neutrino-electron-W-boson vertices in this diagram are assumed to be SM weak vertices, which conserve L. Thus, if $\overline{\nu}_i$ is distinct from ν_i, the exchanged particle emitted by the leptonic weak vertex on the left side of the diagram must be a $\overline{\nu}_i$. When this same exchanged particle is absorbed by the leptonic weak vertex on the right side of the diagram, it must be a ν_i. Thus, this diagram does not exist unless $\overline{\nu}_i = \nu_i$.

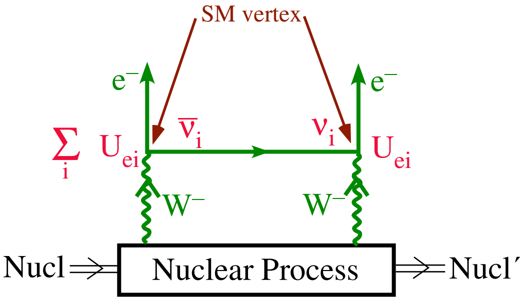

Figure 1: The neutrino-exchange mechanism for $0\nu\beta\beta$.

Apart from an overall coupling strength, the amplitude for a ν_i to create a charged lepton of flavor α at a SM weak vertex is $U_{\alpha i}$, where U is the unitary leptonic mixing matrix. Hence, there is a factor of U_{ei} at each of the leptonic weak vertices in Figure 1. As indicated in that figure, the amplitude for $0\nu\beta\beta$, Amp $[0\nu\beta\beta]$, is a coherent sum over the contributions of the different ν_i. Just as if it had been born in an e^--producing β decay, the exchanged ν_i in Figure 1 is emitted in a state which is almost totally of right-handed helicity, but which contains a small piece, of order m_i/E_{ν_i}, having left-handed helicity. Here m_i is the mass of ν_i, and E_{ν_i} is its energy. When the exchanged ν_i is absorbed, the absorbing SM left-handed current can only absorb its left-handed component without further suppression. Since this component is $\mathcal{O}[m_i/E_{\nu_i}]$, the contribution of ν_i exchange to $0\nu\beta\beta$ is proportional to m_i. Hence, recalling the two factors of U_{ei} in Figure 1, and summing over all the ν_i contributions,

$$\mathrm{Amp}[0\nu\beta\beta] \propto \left| \sum_i m_i U_{ei}^2 \right| \equiv \langle m_{\beta\beta} \rangle \quad . \tag{5}$$

Since the two emitted electrons are identical particles, U_{ei}^2 appears rather than $|U_{ei}|^2$. Thus the amplitude depends on the phases of the complex numbers U_{ei}. The quantity $\langle m_{\beta\beta} \rangle$ is known as the effective Majorana neutrino mass for neutrino-less double beta decay.

As we have stressed, if neutrino interactions are governed by the SM, then any L nonconservation in nature must vanish with the neutrino masses. Eq.(5) makes this vanishing explicit for the case of $0\nu\beta\beta$. The fact that Amp [$0\nu\beta\beta$] depends on neutrino masses means that a measurement of the rate for $0\nu\beta\beta$ would provide information on these masses. Naturally, at the same time, it means that the actual observation of the process will be challenging since the neutrino masses are so tiny.

From $\langle m_{\beta\beta} \rangle$ to absolute neutrino mass

In the effective Majorana mass $\langle m_{\beta\beta} \rangle$ defined by Eq. (5), the neutrino masses m_i depend on the mass of the lightest mass eigenstate m_{min}, which reflects the absolute neutrino mass scale, and on the neutrino mass square differences $\Delta m^2_{ji} = |m^2_j - m^2_i|$. The mass square differences, as well as the absolute values of the mixing matrix elements U_{ei} appearing in Eq. (5), can be determined in the oscillation experiments, and are in fact known, within experimental uncertainties. However, the absolute neutrino mass scale is presently unknown and is constrained only from above by the laboratory studies of tritium beta decay, and independently by the analysis of the Cosmic Microwave Background (CMB) combined with the observation of galaxy distributions and other astrophysical data.

Moreover, as pointed out above, $\langle m_{\beta\beta} \rangle$ depends on the "Majorana phases" of the U_{ei} that are totally unknown. These phases do not affect the usual flavor changing neutrino oscillations and appear only in processes where the total lepton number L could change, none of which have been observed so far. However, independent of the values of these phases, one can always find upper and lower limits of $\langle m_{\beta\beta} \rangle$ which are independent of the phases and depend only on quantities known from the flavor oscillation experiments and on the absolute neutrino mass scale. Thus, for any value of the absolute mass, we can evaluate the maximum and minimum allowed $\langle m_{\beta\beta} \rangle$. Similarly, for any possible $\langle m_{\beta\beta} \rangle$, there is only a finite, and relatively narrow, interval of the allowed absolute neutrino masses.

We plot these quantities in Figures 2 and 3. In Figure 2 we use the mass of the lightest mass eigenstate, m_{min}, as the independent variable, while in Figure 3 we use the sum of neutrino masses $M = m_1 + m_2 + m_3$ as the independent variable. In both cases we use the current best fit to the oscillation parameters [1], $\sin^2\theta_{12} = 0.314^{+0.056}_{-0.047}$, $\sin^2\theta_{13} = 0.9^{+2.3}_{-0.9} \times 10^{-2}$, $\Delta m^2_{21} = (7.92 \pm 0.71) \times 10^{-5}$ eV^2, and $|\Delta m^2_{31}| = 2.4^{+0.5}_{-0.6} \times 10^{-3}$eV^2. (The indicated values were obtained by a global fit to all oscillation data, and the error bars correspond to the 95% CL.) If the quantity Δm^2_{31} is positive ($m_3 > m_1$) we call the mass pattern a "normal hierarchy," and when it is negative ($m_3 < m_1$) we call it an "inverted hierarchy." At the present time we do not know which of these patterns corresponds to reality. There is no compelling reason to prefer one to the other. The elements of the mixing matrix are expressed through the mixing angles as follows: $U_{e1} = \cos\theta_{13}\cos\theta_{12}, U_{e2} = \cos\theta_{13}\sin\theta_{12}$ and $U_{e3} = \sin\theta_{13}e^{-i\delta}$.

As one can see in Figures 2 and 3, the two hierarchies occupy different parts of the plot. In particular, for the inverted hierarchy the effective mass $\langle m_{\beta\beta} \rangle$ is always non-zero and larger than $\sim$10-15 milli-electron Volts (meV).

A special situation could be present if all masses m_i are much larger than the mass differences.

In that case

$$\langle m_{\beta\beta}\rangle_{degenerate} = \bar{m}\Sigma_i U_{ei}^2 \, , \tag{6}$$

where $\bar{m}$ is the average absolute mass. The effective mass in this case is essentially independent of the Δm^2_{ji} values and, because $\sin^2\theta_{13}$ is small, also almost independent of that angle and the corresponding phase.

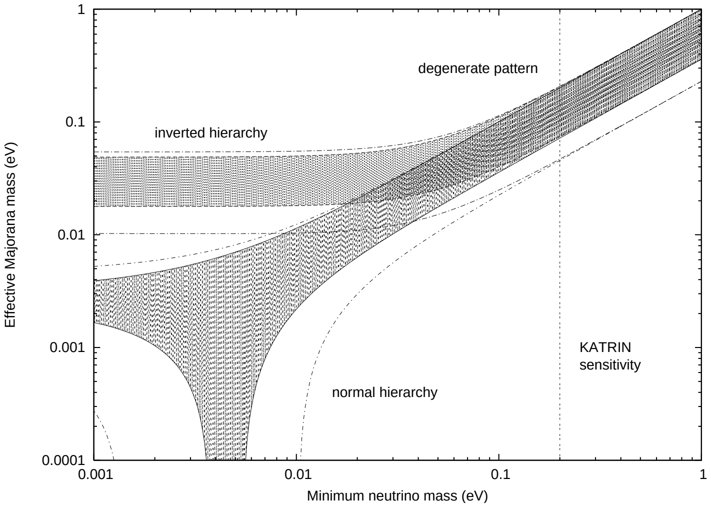

Figure 2: The relation between $\langle m_{\beta\beta}\rangle$ and the minimum neutrino mass, m_{min}, the mass of the lightest mass eigenstate. The shaded area indicates the region of possible $\langle m_{\beta\beta}\rangle$ values when only the best fit oscillation parameters are used. Its width corresponds to the uncertainty associated with the unknown Majorana phases. The dot-dashed lines indicate how the limits on $\langle m_{\beta\beta}\rangle$ are enlarged when the uncertainties in the oscillation parameters (95% CL) are taken into account. The sensitivity of the planned KATRIN tritium β decay experiment is indicated.

Several features of Figure 2 are easily understood. The horizontal band in the middle corresponds to the inverted hierarchy, i.e., $m_3 < m_1$. Neglecting the small terms and experimental uncertainties, its upper edge is simply $\langle m_{\beta\beta}\rangle \sim \sqrt{\Delta m^2_{atm}} \sim$ 50 meV, while the lower edge is $\langle m_{\beta\beta}\rangle \sim \sqrt{\Delta m^2_{atm}}\cos(2\theta_{12}) \sim$ 18 meV for the best fit parameters, which is lowered to ~10 meV when the experimental uncertainties are included. With future improved determination of the oscillation parameters, the width of this band should be reduced.

The diagonal band corresponds to the degenerate pattern of neutrino masses. Its upper edge is simply $\langle m_{\beta\beta}\rangle \sim \bar{m}$ while the lower edge is $\langle m_{\beta\beta}\rangle \sim \bar{m}\cos(2\theta_{12})$. Clearly, if one can show that $\langle m_{\beta\beta}\rangle \geq$ 0.1 eV, then the degenerate mass pattern is the right one. However, the observation of the $0\nu\beta\beta$ decay does not determine the sign of Δm^2_{atm} in that case.

Finally, the region below about 10 meV in Figure 2 corresponds to the normal hierarchy. Two characteristic features are the value for very small m_{min} where the upper and lower edges of the "nose" are approximately determined by $\langle m_{\beta\beta}\rangle \sim \sqrt{\Delta m^2_{sol}}\sin^2\theta_{12} \pm \sqrt{\Delta m^2_{atm}}\sin^2\theta_{13}$. The other characteristic feature is the "dip" where $\langle m_{\beta\beta}\rangle$ is arbitrarily small. This occurs at $m_{min} \sim \sqrt{\Delta m^2_{sol}}\sin^2\theta_{12}/\cos(2\theta_{12})$. The presence of such a dip means that one can encounter a situation, albeit a rather special one, where $\langle m_{\beta\beta} \rangle$ is extremely small, or actually vanishes, even though the neutrinos are Majorana particles.

It is important to note that the absolute neutrino mass scale can be explored, whether neutrinos are Majorana or Dirac particles, in nuclear beta decay. In that case the characteristic parameter is

$$m_{\nu_e}^2 = \Sigma_i |U_{ei}|^2 m_i^2 \tag{7}$$

independent of the Majorana phases. Thus, $m_{\nu_e}^2$ depends only on the known (with some uncertainty) oscillation parameters, and on the absolute mass scale, characterized by the minimum mass m_{min} in Figure 2. At present m_{ν_e} is constrained to be less than 2.3 eV by the existing tritium beta decay experiments [2]. The planned experiment KATRIN [3], scheduled to be operational in 2008, expects after three years of running to reach a sensitivity to neutrino mass of 0.2 eV at 90% CL. It will thus cover most, but not all, of the "degenerate" region in Figure 2 and could serve as a cross check of a $0\nu\beta\beta$ result in this region.

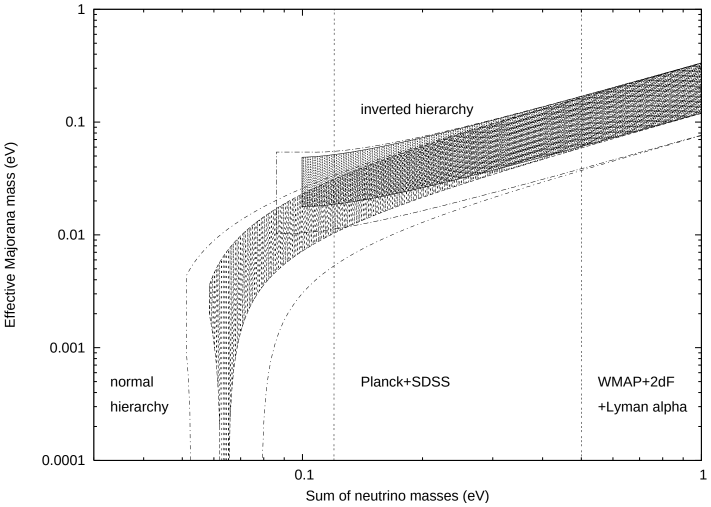

Figure 3: The relation between $\langle m_{\beta\beta} \rangle$ and the sum of neutrino masses. The shaded area indicates the region of possible $\langle m_{\beta\beta} \rangle$ values when only the best fit oscillation parameters are used. Its width corresponds to the uncertainty associated with the unknown Majorana phases. The dot-dashed lines indicate how the limits on $\langle m_{\beta\beta} \rangle$ are enlarged when the uncertainties in the oscillation parameters (95% CL) are taken into account. The limit based on the analysis of the WMAP, 2 degrees Field Galaxy Redshift Survey plus analysis of the Lyman α forest of the Sloan Digital Sky Survey (SDSS) are shown, as well as the sensitivity projected for the future Planck mission combined with SDSS.

As mentioned earlier, study of the Cosmic Microwave Background Radiation, combined with the analysis of galaxy distributions and other astrophysical data, allows one to constrain or determine the sum of neutrino masses, $M = m_1 + m_2 + m_3$ (assuming, as we do, that only three light neutrinos exist). The plot of $\langle m_{\beta\beta} \rangle$ vs. M is shown in Figure 3. Note that the sum of masses M is constrained by the existing oscillation data *from below*: $M \geq \sqrt{\Delta m_{sol}^2} + \sqrt{\Delta m_{atm}^2}$ for the normal hierarchy, and $M \geq \sqrt{\Delta m^2_{atm}} + \sqrt{(\Delta m^2_{atm} + \Delta m^2_{sol})}$ for the inverted hierarchy. This is clearly visible in Figure 3. The existing limits on M are somewhat model (or analysis) dependent, and range between about 0.5 to about 2.0 eV. Planned missions, in particular Planck, scheduled to be launched in 2007, should reach sensitivity of $M \sim$ 0.1 - 0.2 eV, covering the whole degenerate region.

From lifetime to $\langle m_{\beta\beta} \rangle$

The quantity that is determined or constrained experimentally is the half-life of the $0\nu\beta\beta$ decay. The formula for the half-life separates into a product of three terms:

$$\frac{1}{T_{1/2}} = G^{0\nu}(E_0, Z) |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2 , \tag{8}$$

where $G^{0\nu}(E_0, Z)$ is an accurately calculable phase space factor, $M^{0\nu}$ is the nuclear matrix element, and $\langle m_{\beta\beta} \rangle$ is the effective Majorana mass that we would like to determine. The phase space factor depends on the decay Q value E_0 and increases roughly as E_0^5, giving clear preference to transitions with larger E_0. Isotopes with large E_0 are also preferred experimentally since the background suppression is then easier. The nuclear charge dependence stems from the Coulomb effect on the outgoing electrons. Larger Z values are preferred.

An observation of the $0\nu\beta\beta$ decay will have qualitative importance whether an accurate value of $\langle m_{\beta\beta} \rangle$ can be determined or not. Indeed, since the observation of $0\nu\beta\beta$ decay would teach us that neutrinos are Majorana particles, the most important goal of $0\nu\beta\beta$ decay experiments is simply to observe the decay, rather than to measure $\langle m_{\beta\beta} \rangle$. On the other hand, a measured $\langle m_{\beta\beta} \rangle$ would carry information about the absolute scale of neutrino masses. To extract the $\langle m_{\beta\beta} \rangle$ from the measured half-life requires knowledge of the corresponding nuclear matrix element $M^{0\nu}$. Any uncertainty in its value will be reflected in the proportional uncertainty of $\langle m_{\beta\beta} \rangle$. Hence, an accurate evaluation of the nuclear matrix elements is a matter of great importance. Using the spread of calculated matrix elements, with no further selection, we estimate the range of the uncertainty in the nuclear matrix element to be a factor of three[4].

This is not a simple task. Since heavy nuclei are involved, the usual complications of the many-body system are involved. Two complementary approximations, the nuclear shell model (NSM) and the so-called Quasiparticle Random Phase Approximation (QRPA), are the most widely used approaches. Since the approximations involved are quite different, it is encouraging that the results, while not identical, are quite close. This gives us confidence that the calculated values are basically correct.

At present there is no consensus among the nuclear theorists about the proper way to evaluate the uncertainty in $M^{0\nu}$. Nonetheless, to be believable, the calculation must be able to describe correctly as many known related nuclear properties as possible. Prominent among them is the rate of the allowed $2\nu\beta\beta$ decay, a weak process that involves the same initial and final nuclear states and also converts two neutrons into two protons. Since this decay rate has been determined now for all but one of the $0\nu\beta\beta$ candidate nuclei, it can be used as a test of the corresponding calculations. Considering only the results of calculations that pass this test narrows the range of the calculated $M^{0\nu}$ values considerably.

With the importance associated with the $0\nu\beta\beta$ decay in the physics community, one can expect that significant progress in the calculation of the nuclear matrix elements will be forthcoming.

There are ways to test the correctness of the calculations or at least exclude from consideration the wrong ones. If the $0\nu\beta\beta$ decay is observed in more than one nucleus, the ratio of rates then depends only on the ratio of the matrix elements, not on the Majorana masses. Calculations that correctly describe, or better yet predict, this ratio are preferred.

Exploring the degenerate neutrino mass region

Present $0\nu\beta\beta$ decay experiments involve 10 kg or less of the decaying isotope and are sensitive to half-lives of $\sim 10^{25}$ years. With a single exception (to be verified), no decay has been seen, and the half-life limits translate into the effective Majorana mass $\langle m_{\beta\beta} \rangle$ limit of somewhat less than 1 eV (the exact value depends on the adopted value of $M^{0\nu}$ and could be as low as 0.3 eV). Thus, experimental exploration of the *whole degenerate mass region* is within reach. It requires a feasible enlargement of the decaying mass, to 100-200 kg, and the corresponding increases of sensitivity to half-lives of a few $\times 10^{26}$ years. Exposures of several kmole-years, with exact numbers depending on the background reduction achieved, would be needed. Several proposals to accomplish this exist, and are described later in this report.

Since, as stressed above, there is no fundamental theory of neutrino masses, the sensible approach is to explore the mass scale systematically, step by step. To study the degenerate mass region has a particular attraction. It is a region that could, and will, be explored also by other means: beta decay in the laboratory, and the study of CMB and other astrophysical observations. If $0\nu\beta\beta$ decay with a rate corresponding to that region is discovered, the same mass must be also visible in these searches that are independent of the CP properties of neutrinos, i.e., whether they are Dirac or Majorana particles. As a minor byproduct, it would also be a perfect test of our ability to calculate the nuclear matrix elements.

One can think of other possibilities as well. Suppose the direct experiments discover that neutrino mass is indeed larger than 0.1 eV. Then, if $0\nu\beta\beta$ decay experiments cover the whole of that region and see no decay, we would conclude that, theoretical prejudice notwithstanding, neutrinos are Dirac particles.

In any case, the experimental exploration of the $\langle m_{\beta\beta} \rangle$ region down to about 100 meV is feasible and very worthwhile.

Exploring the inverted hierarchy region

The following step in the $0\nu\beta\beta$ decay development should be the exploration of the “inverted” hierarchy region, extending from about 10 meV to about 100 meV. To be precise, looking at Figure 2, one can see that determining that $\langle m_{\beta\beta} \rangle$ belongs to that region would not necessarily mean that $m_3 < m_1$. The diagonal band that intersects the almost horizontal part of the shaded area corresponds to the solutions with $m_3 > m_1$ and with both mass values larger than their difference.

Again, since we have no fundamental prediction of the neutrino mass and its pattern, exploring this region is a logical next and longer timescale goal of the $0\nu\beta\beta$ decay search.

To explore this region, or a substantial part of it, would require ton-size sources that in turn require a corresponding progress in isotope enrichment. That does not seem to represent an insurmountable problem, but a relatively costly one. The corresponding background reduction is challenging, but again some of the proposals described in Section 3 project background levels that would allow them to cover most of this effective neutrino mass region. At present, reaching sensitivities to $\langle m_{\beta\beta} \rangle$ near 10-20 meV appears to be a challenging yet realistic goal.

Once the $\langle m_{\beta\beta} \rangle$ region above 10-20 meV is experimentally explored, the following conclusions will be reached: a) If $0\nu\beta\beta$ decay is observed, the Majorana nature of the neutrino is established, and an interval of the allowed sum of the neutrino masses M is determined (see Figure 3). The same M will be explored, eventually, by observational cosmology. b) If no effect is seen, there remain only two possibilities, both important. Either neutrinos are Dirac particles, or the mass pattern is the normal hierarchy, that is, m_{min} is smaller than $\sqrt{\Delta m^2_{solar}}$.

3 The Experiments

Neutrino-less double beta decay experiments have made steady progress in reaching longer half-lives in past decades. Experiments using ^{76}Ge[5, 6], ^{82}Se[7], ^{100}Mo[7], ^{116}Cd[8], ^{130}Te[9], and ^{136}Xe[10, 11] have recently reported results that can be interpreted as setting upper limits on the effective neutrino mass $\langle m_{\beta\beta} \rangle$ in the vicinity of one electron volt. One group of authors has claimed a positive signal using ^{76}Ge [6], but this result is controversial. They observe a line at the expected neutrino-less double beta decay energy, but it has not been proved that this is not due to a weak gamma-ray transition line. Furthermore, the significance of the claimed signal depends critically on the level of background assumed. This in turn depends on whether some of the other lines observed in the vicinity are due to expected decays over an approximately flat low background or whether they are due to statistical fluctuations of a larger flat background. An experiment of better sensitivity, perhaps using ^{76}Ge to avoid issues with the nuclear matrix element, will be needed to resolve this issue.

In the near-term, exploring the degenerate neutrino mass region with a neutrino-less double beta decay program necessitates measuring half-lives of order of magnitude $10^{26} - 10^{27}$ years, while exploring the inverted hierarchy region requires sensitivity to lifetimes of 10^{28} years and longer. This requires large quantities of the isotope used for the source material and a highly developed ability to suppress backgrounds. The experimentally measured half-life is:

$$\frac{\ln 2}{T_{1/2}} = \frac{N_{\beta\beta}}{\epsilon N_{source} t_{exp}} \tag{9}$$

where $N_{\beta\beta}$ is the number of candidate events, N_{source} is the number of nuclei of the isotope under investigation in the source, ϵ is the detection efficiency, and t_{exp} is the exposure time of the source nuclei.

In terms of the effective neutrino mass $m_{\beta\beta}$ measured in neutrino-less double beta decay experiments, the sensitivity of the experiment has two forms, depending on whether the background is non-zero or zero. In the case that the experiment is background limited, the sensitivity to $\langle m_{\beta\beta} \rangle$ goes as[12]:

$$\langle m_{\beta\beta} \rangle \sim \left[\frac{A}{ax\epsilon G^{0\nu} |M^{0\nu}|^2} \right]^{1/2} \left[\frac{b\Delta E}{M t_{exp}} \right]^{1/4} \tag{10}$$

where $G^{0\nu}$ and $M^{0\nu}$ are the phase space factor and nuclear matrix element defined in Section 2, A is the molecular weight of the decaying isotope, b is the background in counts/(keV·kg·year), ΔE is the energy resolution of the experiment, M is the mass of the source, t_{exp} is the exposure time of the experiment, a is the isotopic abundance of the source, x is the number of isotope nuclei per molecule in the source, and ϵ is the detector efficiency. In the case of zero background counts, the sensitivity goes as

$$\langle m_{\beta\beta}\rangle \sim \left[\frac{A}{ax\epsilon G^{0\nu}|M^{0\nu}|^2}\right]^{1/2}\frac{1}{\sqrt{Mt_{exp}}} \tag{11}$$

Improvements in experimental sensitivity typically come from increasing M and a and from decreasing b. The factor with the fourth root in Equation 10 shows the difficulty of making progress in the knowledge of $\langle m_{\beta\beta}\rangle$. To improve sensitivity to $\langle m_{\beta\beta}\rangle$ by a factor of ten for a given isotope requires a factor of 10,000 improvement in b/M, for example, by increasing M two orders of magnitude and decreasing b two orders of magnitude.

Neutrino-less double beta decay experiments use isotopes with large Q values to obtain large values of $G^{0\nu}$ and to place the signal above low energy natural radioactivity backgrounds. There are two generic approaches to neutrino-less double beta decay experiments that differ in the approach to background rejection. The first approach uses calorimetric/bolometric techniques that have excellent energy resolution to identify the mono-energetic signal and may have some segmentation to reject backgrounds through spatial and temporal correlations. The second approach is the tracking detector which trades good energy resolution for good vertex resolution to reject backgrounds. A new idea for background rejection is to trap and identify the daughter nucleus of a double beta decay event using resonance fluorescence spectroscopy[13]. The Standard Model allowed two neutrino double beta decay is an irreducible background for double beta experiments. It can be suppressed through good energy resolution.

The following paragraphs summarize the information presented to NuSAG by the proponents of the experiments under consideration. Experimental groups were asked to send recent existing documentation to NuSAG at the time NuSAG was formed. All were invited to give presentations at the first NuSAG meeting, and a common set of followup questions was sent by the panel to each experiment. NuSAG established a set of conservative nuclear matrix elements to be used by each experiment to define its sensitivity to $\langle m_{\beta\beta}\rangle$.

- CUORE:

  The proposed CUORE experiment is an extension of the existing CUORICINO experiment currently running in the Gran Sasso underground laboratory. CUORE is a cryogenic bolometer that measures the energy released in the $\beta\beta$ decays of ^{130}Te in crystals of TeO$_2$. The crystals have not been enriched as ^{130}Te has a natural isotopic abundance of 34.1%. CUORE will consist of a total of 19 towers of 52 crystals of TeO$_2$ each, for a total mass of 780 kg of TeO$_2$. The whole assembly is to be cooled by dilution refrigerators to 10 mK and the energy deposited by the decays recorded as a temperature rise of a crystal of a few tenths of a mK. This temperature rise can be measured precisely and should yield an energy resolution of roughly 0.2% FWHM. The excellent energy resolution minimizes contamination of the $0\nu\beta\beta$ signal by $2\nu\beta\beta$ events. The detector is to be located at a depth of 3800 mwe to reduce cosmic backgrounds. Careful cleaning and etching of the material surfaces should reduce other backgrounds observed in CUORICINO.

  The CUORE project is expected to begin operation in 2010 at the Gran Sasso laboratory. It should reach a 3 sigma discovery $\langle m_{\beta\beta}\rangle$ of 106-189 meV for backgrounds of $b = 0.001$ and $b = 0.01$, respectively, using the NuSAG assigned matrix element. The device could be upgraded by the use of enriched ^{130}TeO$_2$ crystals to increase the total mass of decaying nuclei. The cost of 85% enriched ^{130}Te is $9.9 per gram.

CUORE and CUORICINO are led by Italian physicists with important contributions from U.S. scientists. The total cost for the 780 kg CUORE detector is estimated to be $17.5 M of which the suggested U.S. share is $9.3 M. With adequate funding, the detector would turn on in 2010.

- EXO:

  The EXO project proposes to use a large enriched liquid ^{136}Xe time projection chamber to study $2\nu\beta\beta$ and $0\nu\beta\beta$ decay. The detector uses 85% enriched ^{136}Xe liquid as both source and detector material. The energy deposited by the double beta decay is measured by both charge and scintillation light collection, which together yield better energy resolution than ionization alone. The ionization signal is used to localize the event vertex for signal identification and background rejection. The liquid xenon can be easily purified with commercial systems and the cryogenic system used to keep the detector cold provides radioactively clean shielding. In addition, since the recoiling ^{136}Ba ion created in the double beta decay can survive a significant time in the liquid xenon, the collaboration proposes to tag each decay with the identification of the daughter nucleus using laser techniques. This would essentially remove all sources of background to the $0\nu\beta\beta$ decay other than $2\nu\beta\beta$ decay. The ultimate goal is a $\sim$ 1-10 ton experiment that would use direct detection of the decay energy and subsequent identification of the ^{136}Ba decay daughter to reduce background and reach effective neutrino mass limits $\langle m_{\beta\beta}\rangle$ in the range consistent with the inverted hierarchy neutrino mass scale.

  The EXO project is proceeding along two lines. It is building a smaller prototype experiment (EXO-200) with a Xe mass of 200 kg, 80% enriched ^{136}Xe, to be installed at WIPP. The enriched ^{136}Xe has been obtained at a cost of roughly $8.5 per gram, and construction is proceeding quickly. EXO-200 expects to measure the $2\nu\beta\beta$ process for the first time. The prototype uses no barium tagging and should reach an energy resolution of $\sigma(E)/E = 1.6$% at 2.5 MeV. If radioactive backgrounds can be kept at the projected levels, this will yield a background limited 3 sigma lifetime sensitivity of 2.9×10^{25} years in two years of running. This lifetime will probe a fair fraction of the degenerate neutrino mass regime, down to an effective neutrino mass $\langle m_{\beta\beta}\rangle$ of about 330 meV, depending on the nuclear matrix element used for the calculation.

  In parallel, the EXO team is investigating different approaches for barium tagging that could be incorporated in the final full-scale experiment. The most promising approach would use extraction of the ions from the liquid xenon and transfer to an ion trap where laser tagging would identify the barium ion. The tagging is a challenging R&D project, but a number of the steps required have been independently demonstrated.

  Although the two efforts (200 kg prototype and Ba tagging) have a common final goal, they are essentially independent. The 200 kg prototype is fully funded and should be operational at WIPP in 2008-2009. The barium tagging, on the other hand, is at an R&D stage and needs to be demonstrated before a larger liquid xenon detector capable of exploring the inverted hierarchy neutrino mass regime for $\langle m_{\beta\beta}\rangle$ would be considered.

EXO is a U.S. led effort with important contributions from Canada, Russia, and Switzerland. The EXO-200 experiment expects to operate in 2008-2009. The estimated budget to complete the barium tagging R&D is about \$2.4 M. An estimate of the cost of the full EXO experiment with barium tagging is \$28.5 M for a one ton experiment and \$105 M for a ten ton experiment where the latter cost is dominated by the cost of the enriched isotope.

- Majorana:

  The Majorana experiment proposes to use the well established technology of germanium detectors to study $0\nu\beta\beta$ decay. Large germanium crystals, enriched to 86% in ^{76}Ge, would be used as both source and detector. The proposed initial configuration of the Majorana experiment, Majorana-180, would consist of 180 kg of germanium in 171 segmented n-type crystals, distributed in 3 independent ultra-clean electro-formed cryostats containing 57 crystals each. The whole assembly would be enclosed in a low-background passive shield and active veto and be located deep underground.

  The performance of germanium detectors is well understood and an excellent resolution of 0.16% FWHM should be achievable, essentially eliminating any contamination of the $0\nu\beta\beta$ decay signal by $2\nu\beta\beta$ decay. Other backgrounds are reduced by using ultra-clean materials and techniques together with close packing of the crystals in large modules such that neighboring crystals can be used as vetoes. The use of germanium crystals also allows further background suppression via pulse-shape discrimination and segmentation, both having been successfully demonstrated at existing low-energy nuclear physics facilities. The modular approach allows for easy scaling of this experiment to larger size, limited mainly by the cost of \$56 per gram of the enriched isotopes (going to \$46 per gram for 200 kg/yr throughput with a \$5M investment). The proposed 180 kg experiment is expected to reach a 3 sigma lifetime limit of 5.1×10^{26} years corresponding to a 3 sigma effective neutrino mass $\langle m_{\beta\beta} \rangle$ sensitivity of around 130 meV. The proposed total cost of the 180 kg experiment is about \$57M.

  A competing European experiment, GERDA, also proposes to use enriched ^{76}Ge detectors to study $0\nu\beta\beta$ decay. This smaller scale experiment will use a different background suppression approach with the crystals enclosed in a bath of liquid nitrogen or liquid argon that will be used as a scintillation veto to remove external backgrounds and many internal backgrounds. Most other materials will be removed from the vicinity of the crystal, lowering radioactive backgrounds. This approach has a number of advantages but might affect the quality of the electronic signals extracted from the system. Which of the two approaches is best remains to be determined, and the Majorana and GERDA collaborations are in contact with each other. They might join forces if a future larger scale ^{76}Ge based detector is required. A hypothetical Majorana-GERDA collaboration on a 1000 kg detector with a factor of ten background improvement over Majorana-180 would have a 3 sigma lifetime of 3.2×10^{27} years and corresponding $\langle m_{\beta\beta} \rangle$ sensitivity of 51 meV.

  Majorana is a U.S. led experiment with important Canadian, Japanese, and Russian contributions to the collaboration. The cost of Majorana-180 is estimated to be \$57 M, most of which would be provided by the U.S. A larger 480 kg detector has an estimated cost of \$125 M dollars. The Majorana-180 experiment expects to start collecting data from the first 60 kg module five years following CD-0 approval. They expect the second 60 kg module to operate 11 months later, and after an additional 11 months the full experiment would be operational.

- MOON:

  The proposed MOON experiment is a scintillator-based double beta decay tracking calorimeter with thin ^{100}Mo isotope source foils. Backgrounds from non double-beta sources are substantially reduced by the ability to reconstruct the two β's in an event at a common vertex.

  ^{100}Mo is also sensitive to low energy solar neutrinos with a sensitivity to pp and ^{7}Be an order of magnitude higher than ^{71}Ga. The signature for solar neutrino interactions is a transition to ^{100}Tc, followed by a second decay with a half life of 16 seconds.

  Clean detection of single decay events with two electrons in the presence of backgrounds imposes a requirement that the spatial segmentation of the detector have very high granularity. For a 1 ton detector, the ability to localize the decays to a volume 10^{-9} of the total size is needed. This can be achieved by using scintillator elements with a cross sectional area of 4 mm^2. A prototype experiment with scintillator plates is now running at the Oto Cosmo observatory in Japan. The prototype is expected to have 0.8 kg of ^{100}Mo in 2006.

  The major background for the $0\nu\beta\beta$ measurement will be the $2\nu\beta\beta$ decays for which the rate is relatively high. The scintillator detection technique can support other isotopes and, if ^{82}Se is used instead of ^{100}Mo, the $2\nu\beta\beta$ backgrounds would be substantially reduced at the expense of losing solar neutrino detection capability.

  Future plans call for a 200 kg stage, with either ^{100}Mo or ^{82}Se, followed by a 1 ton phase. The 3 σ lifetime sensitivity for a 3 year run with 200 kg is 0.71×10^{26} years for ^{100}Mo and 1.1×10^{26} years for ^{82} Se. The interpretation of these lifetimes in terms of neutrino masses depends on the matrix elements assumed but is around 403 meV for ^{100}Mo and 97 meV for ^{82}Se using the NuSAG matrix elements. For a one ton experiment running for five years, these numbers become 141 meV and 34 meV, respectively. The cost for isotopic enrichment of either ^{100}Mo or ^{82}Se is expected to be similar to the cost for isotopic enrichment of ^{76}Ge, which is presently of order \$50/gram.

  MOON is a Japanese led experiment with international collaborators from the U.S., the Czech Republic, and Russia. The present focus of R&D is on obtaining good energy resolution in order to improve rejection of the $2\nu\beta\beta$ background. A full proposal for the 200 kg detector is anticipated in 2007. A 200 kg detector might cost \$10 M and a one ton experiment could cost approximately \$50 M.

- Super-NEMO:

  The proposed Super-NEMO experiment is an extension of the NEMO-3 experiment currently running in the Modane underground laboratory in the Frejus Tunnel. The NEMO-3 detector module consists of cylindrical isotopic foils surrounded radially by Geiger cells, which are in turn surrounded by plastic scintillator calorimetry. The complete detector is 3 meters in radius and 3 meters tall and is immersed in a weak magnetic field. It is divided azimuthally into 20 sections, each of which can support a different foil, for a total of approximately 10 kg of enriched isotope, currently dominated by 6.9 kg of ^{100}Mo and 0.9 kg of ^{82}Se. The combination of time of flight measurements, magnetic tracking and calorimetry allow precision characterization of double beta decays and rejection of backgrounds due to random coincidences. The $2\nu\beta\beta$ decay background shares the same signature as $0\nu\beta\beta$ and can only be rejected via good energy resolution and a tight energy window at the end point. The NEMO-3 experiment has already measured the lifetimes for $2\nu\beta\beta$ decays of ^{100}Mo and ^{82}Se with high statistics. Lifetime limits for $0\nu\beta\beta$ of 4.6×10^{23} and 1.0×10^{23} years have been set at 90% CL for ^{100}Mo and ^{82}Se respectively. The experiment is continuing to run with reduced Radon backgrounds and is expected to achieve limits of 2×10^{24} years (^{100}Mo) and 8×10^{23} years (^{82}Se) after 5 years of running.

The Super-NEMO experiment will scale the NEMO-3 technology to accommodate 100 kg of ^{82}Se foils spread among 20 detector modules. The estimated cost of enriched ^{82}Se is about $60 per gram. The energy resolution will be improved from 12% FWHM to 7% FWHM, allowing more of the signal to be included in the signal selection window and resulting in an improvement of the signal detection efficiency from 8% to 40%. The detector modules will have an active water shield to further reduce any cosmic ray backgrounds.

Since the existing NEMO-3 module is already very large, an increase in foil area by an order of magnitude and inclusion of shielding will require a larger hall than is currently available at Frejus. An expansion of the facility is possible and other locations are being investigated. Super-Nemo is expected to reach a 3σ lifetime sensitivity for ^{82}Se of 1.1×10^{26} after 5 years. This corresponds to a 3 σ discovery sensitivity for $\langle m_{\beta\beta} \rangle$ of 150 meV. Super-NEMO is projected to start operations in 2011 if funding is available.

The detector design itself is scalable to 1000 kg due to its modularity, but such a detector system has a very large footprint due to the low volume fraction occupied by the foils. The proponents have noted that, at the 1000 kg scale, considerable attention would need to be paid to radio-purity of the detector systems. Experience with the 100 kg system will be needed to determine if scaling to larger sizes is feasible.

Super-NEMO is an international collaboration led by French physicists. A crudely estimated total cost is $20-30 M with a suggested U.S. contribution of $5-10 M. The experiment would start operation in 2011.

A summary of the “3 sigma” discovery mass sensitivity in these experiments is given in Table I. The numbers are those reported by the experiments, and there are some differences in the statistical procedure used to obtain the numbers. In all cases the NuSAG assigned matrix elements were used. For comparison, the central value of the claimed signal from Reference [6] is given, but scaled by the ratio of matrix element used in that paper and the NuSAG matrix element.

All of the experiments under consideration have merit. The different isotopes employed are directly associated with a specific detector technology. In considering the United States and international programs in neutrino-less double beta decay, it is important to consider the number of different isotopes that must be measured if a positive signal is found in neutrino-less double beta decay.

- The observation of a statistically significant signal in a single experiment might not be considered a discovery without clear confirmation from other independent experiments utilizing different isotopes. For example, a very weak line from a gamma-ray transition might produce a false signal.

Table 1: **Table of effective mass sensitivities**

For each experiment, the $3\ \sigma$ "discovery sensitivity" is given as reported by the experimenters using conservative nuclear matrix elements presented by NuSAG. The constants in the comments section refer to the parameters in Equation 10 in the text. ROI refers to the "Region of Interest" for the signal width as defined by the experiments and Γ is the energy resolution FWHM. The Heidelberg-Moscow result is shown for relative comparison.

Experiment	Isotope	$3\ \sigma$ sensitivity to $\langle m_{\beta\beta} \rangle$ meV		Comment
		Near term	Mid term	
CUORE[a]	^{130}Te	189		$M_{tot} = 750$ kg, $b = 0.01$, $t_{exp} = 5$ yrs, $\Gamma = 5$ keV
			63	$M_{tot} = 750$ kg at 95% enrichment, $b = 0.001$, $t_{exp} = 5$ yrs, $\Gamma = 5$ keV
EXO[b]	^{136}Xe	330		EXO-200 (200 kg, 80% enriched), bkgd=20 counts/yr in ROI, 2 years
			59	1 ton 85% enriched, bkgd=0.2 cts/yr in ROI, $t_{exp} = 5$ yrs, $\sigma/E = 1.6\%$
Majorana M180[c]	^{76}Ge	130		$b\Delta E = 0.001$, $t_{exp} = 5$ yrs, $\Gamma = 3.3$ keV
MG1000			51	Hypothetical 1000 kg, $b\Delta E = 0.0001$, $t_{exp} = 5$ yrs
MOON[d]	^{100}Mo ^{82}Se	403 97		$Mt_{exp} = 200$ kg $\times$ 3 yrs; $\sigma_E = 3\%$
	^{100}Mo ^{82}Se		141 34	$Mt_{exp} = 1000$ kg $\times$ 5 yrs; $\sigma_E = 2.1\%$
Super-NEMO	^{82}Se	153		$Mt_{exp} = 100$ kg $\times$ 5 yrs, $\Gamma = 7.0\%$
				No plan beyond 100 kg.
Heidelberg - Moscow	^{76}Ge	924		Scaled H-M published 440 meV result [6] by H-M/NuSAG matrix element ratio from [4]. Comparison to ^{76}Ge experiments is independent of matrix element choice. H-M claims $\langle m_{\beta\beta} \rangle$ is within the range 100-900 meV at 99.73% C.L. including $\pm 50\%$ matrix element uncertainty

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[a] CUORE gave $1\ \sigma$ limits, NuSAG converted to $3\ \sigma$

[b] Near term is EXO-200, Mid-term is EXO with barium tagging

[c] Majorana "naive" $3\ \sigma$ reply chosen to compare to other experiments

[d] ^{100}Mo also measures solar neutrinos; ^{82}Se has lower $2\nu\beta\beta$ bkgd by factor of ~ 10

- A nuclear matrix element $M^{0\nu}$ is necessary to deduce $\langle m_{\beta\beta} \rangle$ from a measured neutrino-less double beta decay rate. Since theoretical calculations of $M^{0\nu}$ may include a substantial uncertainty, one needs experiments on different isotopes to extract a reliable value for the effective mass. The ratio of two observed decay rates is independent of the unknown $\langle m_{\beta\beta} \rangle$ and depends only on the squares of the nuclear matrix elements and calculated phase space factors. The neutrino physics parameter $\langle m_{\beta\beta} \rangle$ is well determined only when the ratio of rates of multiple isotopes is accurately calculated by nuclear theory.

- Although light-neutrino exchange is the most natural explanation for neutrino-less double beta decay if it exists, there are other possibilities. The relative matrix element values for different nuclei depend on the mechanism. Furthermore, the matrix element situation is encouraging and one can anticipate an improvement in the calculation precision. Therefore, measurements in several nuclei might be the most straight forward way to provide insight into the mechanism of neutrino-less double beta decay.

The international program in neutrino-less double beta decay must measure multiple isotopes. At the present time there are several promising isotopes and technologies.

4 A Future Program in Neutrino-less Double Beta Decay

4.1 Criteria for Establishing a Neutrino-less Double Beta Decay Program

Neutrino-less double beta decay experiments have made steady progress in reaching longer half-lives in past decades. The plan presented here will continue the advance in this important work.

The near-term and mid-term goals of the international program in neutrino-less double beta decay are to explore $\langle m_{\beta\beta} \rangle$ through the region of degenerate neutrino masses and to continue the exploration of $\langle m_{\beta\beta} \rangle$, if necessary, through the region of the inverted neutrino mass hierarchy. The latter phase will require sources of the order of one metric ton of enriched isotope.

The first phase of the neutrino-less double beta decay program will address effective neutrino masses of a few hundred milli-electron volts using sources of the order of 100 kg of isotope. These experiments are quite challenging and require background reduction of two to three orders of magnitude over those of present experiments. A number of background reduction techniques are under development by the different experiments, but it is too early to know which experimental techniques will be scalable to the one ton source mass needed in the second phase. Nonetheless, potential for extension to a one ton source mass is an important consideration.

Observation of neutrino-less double beta decay is the only practical way to demonstrate that neutrinos are their own anti-particles, that is, they are Majorana particles and not Dirac particles. Neutrino-less double beta decay, if it occurs, also offers the best sensitivity for determining the absolute scale of neutrino mass. The panel found the following scientific criteria to be relevant for a phased United States program in neutrino-less double beta decay:

1. How thoroughly does the experiment explore the region of degenerate neutrino masses, $\langle m_{\beta\beta} \rangle \geq 100 - 200$ meV?

2. What are the future prospects for increasing the sensitivity of the technique to be able to explore the region of the inverted mass hierarchy $\langle m_{\beta\beta} \rangle \geq 10 - 20$ meV? Is an experiment with one metric ton of source isotope realistic?
3. Is there any prospect for a future experiment guided by present R&D support to be able to explore the region of the normal mass hierarchy $\langle m_{\beta\beta} \rangle \leq 10 - 20$ meV?

Beyond the scientific potential of the experiments, NuSAG was charged to look at the timeliness of the scientific output, the likely costs to the U.S. and the broad international context. The development of cost and schedule information varies greatly among the experiments. NuSAG worked with the best estimates provided by the experiments.

4.2 Recommendations for a United States Program

The Neutrino Scientific Assessment Group recommendation below provides guidance for both the near-term activities in neutrino-less double beta decay and for the mid-term goals of the discipline. The panel finds that it is important for the program in neutrino-less double beta decay to develop detector technology to explore the inverted neutrino mass hierarchy region. At the present time, the most promising isotope and technology for a detector at the one ton scale cannot be identified.

Recommendation: The Neutrino Scientific Assessment Group recommends that the highest priority for the first phase of a neutrino-less double beta decay program is to support research in two or more neutrino-less double beta decay experiments to explore the region of degenerate neutrino masses ($\langle m_{\beta\beta} \rangle > 100$ meV). The knowledge gained and the technology developed in the first phase should then be used in a second phase to extend the exploration into the inverted hierarchy region of neutrino masses ($\langle m_{\beta\beta} \rangle > 10 - 20$ meV) with a single experiment.

For the region of degenerate neutrino masses, NuSAG recommends the following implementation strategy for the specific experiments. The following three experiments, listed in alphabetical order, have the highest priority for funding.

- **CUORE:** The CUORE ^{130}Te experiment has potential for good energy resolution and low background, provided the technology develops as planned. The high natural abundance of ^{130}Te results in a relatively low cost for a detector sensitive to the degenerate neutrino mass region. The cost of enriched ^{130}Te needed to extend the sensitivity is lower than for some other isotopes. The schedule presented by CUORE is timely. The panel is concerned that the requested budget share is not commensurate with the U.S. involvement in the project.
- **EXO:** The EXO-200 ^{136}Xe experiment is presently under construction and should continue to be supported. R&D for barium tagging is a priority as a step to a one ton scale $0\nu\beta\beta$ experiment. If barium tagging is successful, EXO may offer a unique and cost effective approach to a one ton or larger experiment.
- **Majorana:** The excellent background rejection achieved from superior energy resolution in past ^{76}Ge experiments must be extended using new techniques. The panel notes with interest the communication between the Majorana and GERDA ^{76}Ge experiments which are

pursuing different background suppression strategies. The panel supports an experiment of smaller scope than Majorana-180 that will allow verification of the projected performance and achieve scientifically interesting physics sensitivity, including confirmation or refutation of the claimed ^{76}Ge signal. A larger ^{76}Ge experiment is a good candidate for a larger international collaboration due to the high cost of the enriched isotope.

The following two experiments, listed in alphabetical order, have a lower priority for funding.

- **MOON:** The MOON ^{100}Mo detector is in a state of R&D and expects to have a proposal for a 200 kg detector in 2007. Support beyond the R&D phase is not a priority at this time.
- **Super-NEMO:** The Super-NEMO ^{82}Se experiment is entering an R&D phase to prepare for a 100 kg detector. Super-NEMO does not have a convincing path to explore the inverted hierarchy neutrino mass region at present. Support is not a priority.

To include some financial realism in the NuSAG recommendations, only a few approaches, those that in our opinion have the best chances of success, have been given the highest priority for the US program. It should be evident that other national programs may decide to prioritize different projects. This would be beneficial as it would broaden the range of techniques explored which, in turn, would result in a more objective selection of the optimal technique to be pursued to the next stage. We also recommend a concerted effort to improve calculation of the $0\nu\beta\beta$ decay nuclear matrix elements in relevant nuclei. This would require sustained and targeted investment in low-energy many-body theory and would lead to a better constrained experimental value of the effective mass if double-beta decay is seen in the first or later phase experiments.

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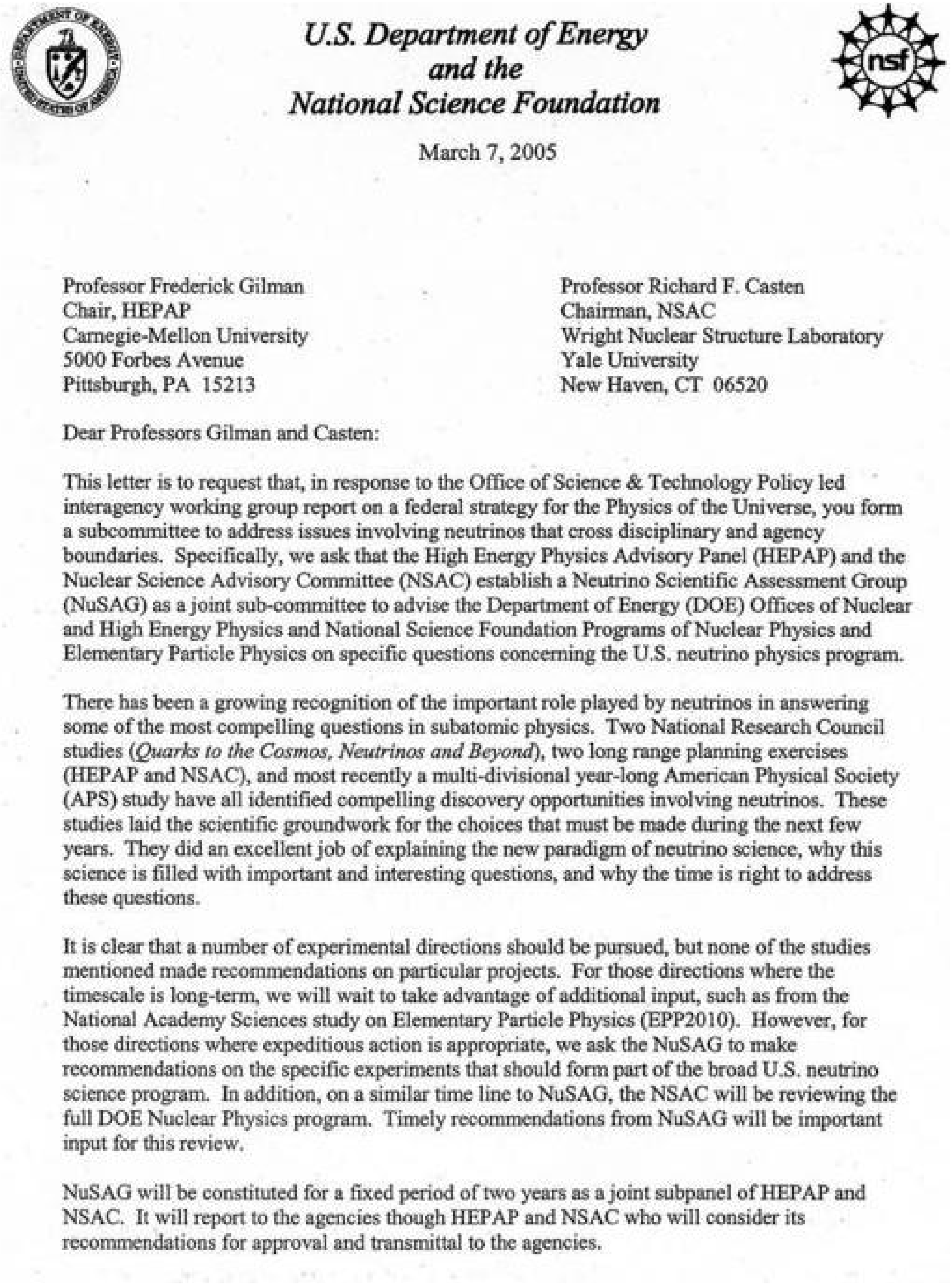
A Charge



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

March 7, 2005

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

Professor Richard F. Casten
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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
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Office of Nuclear Physics
Department of Energy

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

Michael S. Turner
Assistant Director
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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)
Rick Casten (Yale University) NSAC Chair *ex-officio*
Fred Gilman (Carnegie-Mellon University) HEPAP Chair *ex-officio*
John Hardy (Texas A&M) from Jul 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)

C May Meeting Agenda

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

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