REPORT TO THE NUCLEAR SCIENCE ADVISORY COMMITTEE

Neutrinoless Double Beta Decay

APRIL 24, 2014

EXECUTIVE SUMMARY

In December 2013, DOE and NSF charged NSAC to form a Subcommittee to provide guidance on an effective strategy for implementation of a possible second generation US experiment to search for the neutrinoless double beta decay (NLDBD) process. A 15 member Subcommittee was formed by NSAC to carry out the charge. This is a standing committee for two years, but we were requested to provide a preliminary report in April 2014. The Subcommittee solicited written input from the present worldwide collaborative efforts on double beta decay projects. An open meeting was held where these collaborations were invited to present material related to their current projects and proposed future extensions. We also heard presentations related to nuclear theory and particle theory aspects of the subject. The Subcommittee held an additional closed meeting where we discussed our detailed responses to the charge and this preliminary written report. The Subcommittee presented its principal findings and recommendations at the NSAC meeting in April 2014.

The subject of neutrinoless double beta decay involves the very rare decay of certain atomic nuclei that would violate a fundamental principle of the Standard Model, that of Lepton Number Conservation. The search for NLDBD has already taught us much, with dramatic improvements in experimental sensitivity and in theoretical understanding over the years. The recent discovery of neutrino oscillations and the establishment of a very light scale for neutrino masses provides new and compelling motivation to vigorously pursue the search for neutrinoless double beta decay. In particular, there is significant potential sensitivity to establish that the neutrinos and their antiparticles are identical (so called Majorana type) as opposed to distinct (Dirac type) fermions. In fact, observation of NLDBD would have far reaching implications, pointing to the existence of a new mechanism for mass generation beyond the Standard Model, and to possible scenarios to generate the matter-antimatter asymmetry of the universe.

The worldwide set of double beta decay projects presently running, under construction, and planned for the near future represent “current generation experiments”. This current generation of projects will achieve varying levels of improved sensitivity over the current best limits (1-2x10^{25} years) , approaching NLDBD half-lives of about 10^{26} years. It is then anticipated that these will lead to one or more “second generation” (≡ “next generation”) future experiments which should have sufficient sensitivity to, with high confidence, resolve the issue of Majorana vs. Dirac nature of neutrinos for the so-called “inverted hierarchy” of neutrino mass values. (The “inverted hierarchy” corresponds to the case where the lightest neutrino is dominated by muon and tau neutrino flavors, rather than the alternative where the lightest neutrino has a major electron neutrino component.) Such a second generation experiment will require half-life sensitivity significantly exceeding 10^{27} years. This increase of more than 2 orders of magnitude from the presently achieved limits is a very challenging experimental goal that will require much larger experiments and, in most cases, substantial improvements in the experimental techniques.

The first element of the Subcommittee charge is to assess the scientific importance of pursuing a second generation neutrinoless double beta decay search.

It is the assessment of this Subcommittee that the pursuit of neutrinoless double beta decay addresses urgent scientific questions of the highest importance, and that sufficiently sensitive second generation experiments would have excellent prospects for a major discovery. Furthermore, we recommend that DOE and NSF support this subject at a level appropriate to ensure a leadership position for the US in this next phase of discovery-caliber research.

The second charge element is to assess the status of the ongoing and planned current generation experiments. The report discusses each of these experiments individually, with comments on their status and prospects. The subcommittee findings can be summarized as follows:

1. There is a strong international effort to develop a variety of techniques that offer potential to demonstrate the viability of these techniques as candidates for the next generation experiment.
2. There are two projects sited within the US: EXO-200 and Majorana Demonstrator, as well as significant US contributions to several international projects: CUORE, SNO+, KamLAND-Zen, NEXT, and SuperNEMO. These experiments utilize a variety of isotopes and detection techniques suitable for observing neutrinoless double beta decay and are all sited in underground locations to reduce cosmic-ray induced backgrounds.
3. In general, the primary goal of these projects is to demonstrate sensitivity to the neutrinoless double beta decay signal by establishing an appropriate level of performance. A major issue is reduction of background processes in the region of interest of the detected energy spectrum, as these backgrounds ultimately limit the sensitivity of the experiment.
4. Each of the current approaches has technical advantages and each has significant remaining challenges to demonstrate sensitivity at a level suitable for covering the inverted neutrino mass hierarchy region. Based on the information provided to us, we judge that in a period of 2-3 years there will be much more information available from the results of these experiments. At that point one could assess the future prospects with much higher reliability than today.

The Subcommittee recommends that the "current generation" experiments continue to be supported and that the collaborations continue to work to resolve remaining R&D issues in preparation for consideration of a future "second generation" experiment. New techniques that offer promise for dramatic reductions in background levels should also be supported.

The third charge element is to consider science-driven criteria for the development of an optimal strategy for next generation experiments. The Subcommittee was aided in its consideration of this charge element by the input material from the collaborations, particularly regarding their aspirations for next generation experiments. There is also a substantial body of recent published literature, including excellent review articles, on this subject.

The Subcommittee recommends the following guidelines be used in the development and consideration of future proposals for the next generation experiments:

1.) **<u>Discovery potential</u>: Favor approaches that have a credible path toward reaching 3σ sensitivity to the effective Majorana neutrino mass parameter $m_{\beta\beta}$=15 meV within 10 years of counting, assuming the lower matrix element values among viable nuclear structure model calculations.**
2.) **<u>Staging</u>: Given the risks and level of resources required, support for one or more intermediate stages along the maximum discovery potential path may be the optimal approach.**
3.) **<u>Standard of proof</u>: Each next-generation experiment worldwide must be capable of providing, on its own, compelling evidence of the validity of a possible non-null signal.**
4.) **<u>Continuing R&D</u>: The demands on background reduction are so stringent that modest scope demonstration projects for promising new approaches to background suppression or sensitivity enhancement should be pursued with high priority, in parallel with or in combination with ongoing NLDBD searches.**
5.) **<u>International Collaboration</u>: Given the desirability of establishing a signal in multiple isotopes and the likely cost of these experiments, it is important to coordinate with other countries and funding agencies to develop an international approach.**
6.) **<u>Timeliness:</u> It is desirable to push for results from at least the first stage of a next-generation effort on time scales competitive with other international double beta decay efforts and with independent experiments aiming to pin down the neutrino mass hierarchy.**

The above guidelines are intentionally not prescriptive in recommending which of various relevant experimental features to optimize in order to attain the desired sensitivity. It is unlikely that any one approach will achieve all of the desirable features. It is best to support an approach that provides the combination of features most likely to reach the desired sensitivity at a cost that can be funded on a competitive time schedule.

The final charge element is to provide an assessment of the status and expected progress in theoretical calculations that are needed to determine the sensitivity limits that can ultimately be reached in NLDBD experiments. There is generally significant variation among different calculations of the nuclear matrix elements for a given isotope. For consideration of future experiments and their projected sensitivity it would be very desirable to reduce the uncertainty in these nuclear matrix elements.

The subcommittee recommends establishing a theory task force that aims at:

1.) **developing criteria to establish and rank the quality of existing and future calculations,**
2.) **identifying methods to constrain the less tested assumptions in existing approaches.**

This could be accomplished with the assistance of existing international infrastructure such as the Institute for Nuclear Theory or the Extreme Matter Institute, and /or through the establishment of a topical center devoted to this topic.

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1.0 NEUTRINO SCIENCE AND DOUBLE BETA DECAY

Overview

The discovery of the Higgs boson at the Large Hadron Collider has produced the final ingredient in the highly successful Standard Model of particle physics. This discovery is fundamentally important in that the coupling of the charged fermions (quarks and charged leptons) to the Higgs field is understood to be the origin of the masses of these particles. While this is a beautiful picture that explains much of our knowledge of the properties of these particles and their interactions, it fails to provide a basis for understanding the light neutral fermions, neutrinos.

In the early days, nuclear beta decay provided crucial data that established the foundation for the subsequent development of the Standard Model. More recently, nuclear beta decay has continued to provide precision tests of its validity. Moreover, the most stringent experimental limits on the masses of neutrinos come from high precision studies of nuclear beta decay. Such measurements have demonstrated that the lightest electron-type neutrino is lighter than about 2 eV, very much lighter than the charged leptons (m > 0.5 MeV) and quarks (m > few MeV). Since 1998, we have studied the phenomenon of neutrino oscillations which indicates that the mass splittings between the different neutrino states is tiny: of order 0.03 eV or less. It is astonishing that for neutrinos these fundamental particle mass differences are of the order of molecular excitation energies. It now appears highly likely that the mechanism responsible for the very light neutrino masses is completely different from the Higgs mechanism that generates the charged fermion masses in the Standard Model.

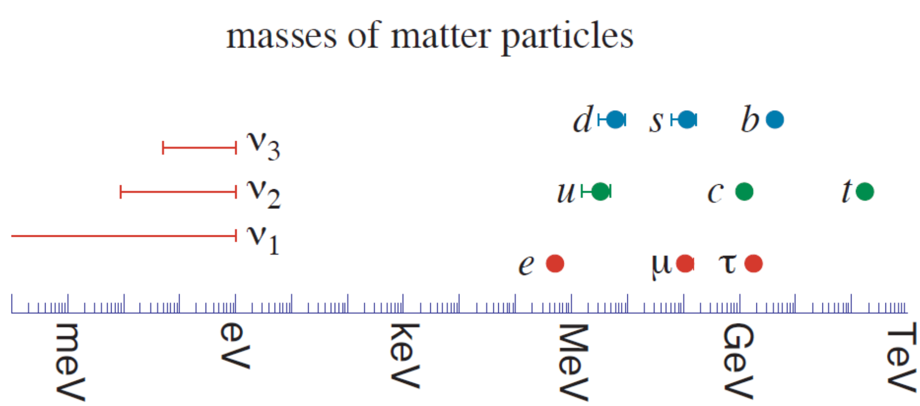

Figure 1.1. Pattern of fermion masses where the charged fermions occupy a hierarchical structure at m > 0.5 MeV and the neutral neutrinos are in the much lower m<1 eV region. (From the 2013 Snowmass report [1].)

Another property of the neutrino that sets it apart from the other fermions is its charge neutrality. For some time now it has been realized that the neutrino may not be a Dirac fermion with two spin states each for neutrino and antineutrino. Another possibility is that there are only two states available: the left-handed neutrino and the right-handed antineutrino. In this scenario the neutrino is called a Majorana fermion. In fact, the existence of a Majorana neutrino will necessarily imply that lepton number is not a conserved quantity.

Lepton number is a quantity that is predicted to be absolutely conserved in the Standard Model. The charged leptons are designated to have a quantum number called lepton number L. Particles such as electrons have L=+1 and antiparticles such as positrons have L=-1. Neutrinos and antineutrinos also have L=+1 and L=-1, respectively. All experiments performed to date confirm lepton number conservation to very high precision. If indeed lepton number conservation is violated in processes that involve neutrinos, that would be a tremendous discovery, comparable to the demonstration that parity was not conserved by weak interactions in the 1950's.

It turns out that atomic nuclei are a critical key to investigating this important issue. The experimental exploration of the Majorana vs. Dirac nature of neutrinos involves the exotic process of nuclear double beta decay. The second order weak process where 2 antineutrinos are emitted along with 2 electrons has been observed in several experiments. However, the neutrinoless double beta decay process, where a nucleus changes charge by 2 units of *e* and emits 2 electrons without any neutrinos, has never been observed. The observation of this process would simultaneously demonstrate that lepton number is violated (through the creation of 2 electrons with no antileptons) and also that the neutrino is a Majorana type fermion.

If the neutrino is a Majorana fermion, then we also have a natural way to understand its very light mass. The existence of heavy right-handed Majorana neutrinos would provide a mechanism, known as the "see-saw" mechanism, to generate the very light neutrino masses implied by the neutrino oscillation experiments. Such a mechanism means that the light Majorana neutrino mass is deeply related to the properties of new heavy particles at a mass scale of up to 10^{15} GeV, far beyond the energies we can hope to directly study with particle accelerator experiments. In addition, CP violation in the decays of these very heavy neutrinos could explain the observed matter-antimatter asymmetry in the universe through the "leptogenesis" scenario.

Thus we see that, in addition to violating the principle of lepton number conservation, the possibility of Majorana neutrinos offers a rather compelling explanation of the light neutrino masses, with connections to remarkable new phenomena beyond what we have observed in nature so far. **The observation of neutrinoless double beta decay would indeed generate a fundamental shift in our understanding of elementary particles.**

The rate of neutrinoless double beta decay depends on $m_{\beta\beta,}$ a combination of the three neutrino masses that depends on the neutrino mixing parameters determined in neutrino oscillation experiments and two unknown phase angles. However those experiments do not fully determine the ordering of the three masses. Two possibilities remain, which are known as the normal and inverted hierarchies. (The name "normal" indicates its likeness to the known mass pattern of the charged lepton sector; it does not indicate a preference by theoretical models.) **Our present knowledge of the neutrino mixing parameters provides a firm prediction for the range of values of the parameter $m_{\beta\beta}$ in the inverted hierarchy scenario** (see Figure 1.2 below)**.** This very recent development offers us a new opportunity for experimental study of the Majorana vs. Dirac nature of the neutrino. For the inverted hierarchy, the range of allowed values of $\langle m_{\beta\beta} \rangle$ can be studied by large neutrinoless double beta decay experiments with total isotope mass of 1 ton or more. Over the last few decades, physicists have developed low-background experiments for neutrino detection with masses up to 1000 tons (although not of the selective isotopes relevant for double beta decay). These new technologies, coupled with further developments from dedicated R&D efforts, enables the construction of powerful new double beta decay experiments in the multi-ton range. **Therefore, it is timely and compelling to embark on a discovery quest to observe neutrinoless double beta decay.**

Neutrino Oscillations

In 1998 the landscape for NLDBD changed. The Super-Kamiokande experiment reported conclusive evidence that a significant fraction of muon-type atmospheric neutrinos disappeared when traveling from the other side of the Earth to their detector. These and subsequent data have led to the conclusion that the cause for the disappearance is the mixing of the neutrino flavors, producing the oscillation of one flavor of neutrino into others. Neutrino oscillations occur when small differences between the masses of different neutrinos lead to large phase differences. Therefore, in order for neutrino oscillations to occur, at least one of the mass states must have non-zero mass. Neutrino oscillation experiments done with atmospheric neutrinos, solar neutrinos, reactors and accelerator-produced neutrino beams have confirmed this hypothesis and have now begun to accurately measure the components of the three-neutrino mixing matrix.

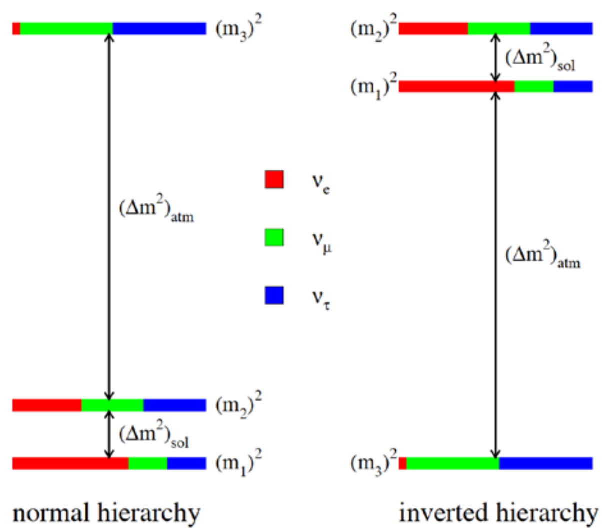

Figure 1.2. The two possible mass hierarchies, where the color-coding shows the fraction of each flavor state contained in each mass state. Note the definitions $\Delta m^2_{sol} = \Delta m_{21}^2$ and $\Delta m^2_{atm} = \Delta m_{32}^2$. (From the 2013 Snowmass Report [1].)

However, oscillation experiments do not tell us everything about the neutrino mass. These experiments are only sensitive to the relative phases of the interfering quantum mechanical amplitudes and thus can only determine the difference in the square of the masses of each mass state. Solar and reactor neutrino experiments are sensitive to $m_2^2-m_1^2 = \Delta m_{21}^2$ while atmospheric neutrinos predominantly reveal Δm_{32}^2. Measurements of matter effects in solar neutrino oscillations have determined that the sign of Δm_{21}^2 is positive while the sign of Δm_{32}^2 is still unknown. The magnitude of Δm_{21}^2 is measured to be $7.54^{+0.26}_{-0.22}$ x10^{-5} eV^2 and the magnitude of Δm_{32}^2 is measured to be $2.43^{+0.1}_{-0.06}$ x10^{-3} eV^2. This situation leaves us with two possibilities for the three-neutrino mass spectrum. These are called the normal and inverted hierarchies as shown in Figure 1.2.

In $0\nu\beta\beta$, the decay half-life can be related to an effective Majorana mass, $m_{\beta\beta}$, that depends on the known neutrino mixing matrix parameters and the unknown Majorana phases. The parameters of the neutrino mixing matrix are determined by fitting to experimental results of neutrino oscillation experiments, and are shown in Table 1.1

Parameter	**Best Fit Value**
$\sin^2\theta_{12}$	$0.307^{+0.024}_{-0.021}$
$\sin^2\theta_{23}$	$0.386^{+0.024}_{-0.021}$
$\sin^2\theta_{13}$	0.0241 ± 0.0025

Table 1.1 Best fit values of neutrino oscillation mixing angles (From the Particle Data Group [2].)

In the case of the inverted hierarchy where $m_1 \approx m_2 \gg m_3$, if we take m_3 to be zero, then, given the measurement of Δm_{32}^2 $m_{\beta\beta}$ should lie between 14 and 50 meV depending on the value of the Majorana phases (Figure 1.3).

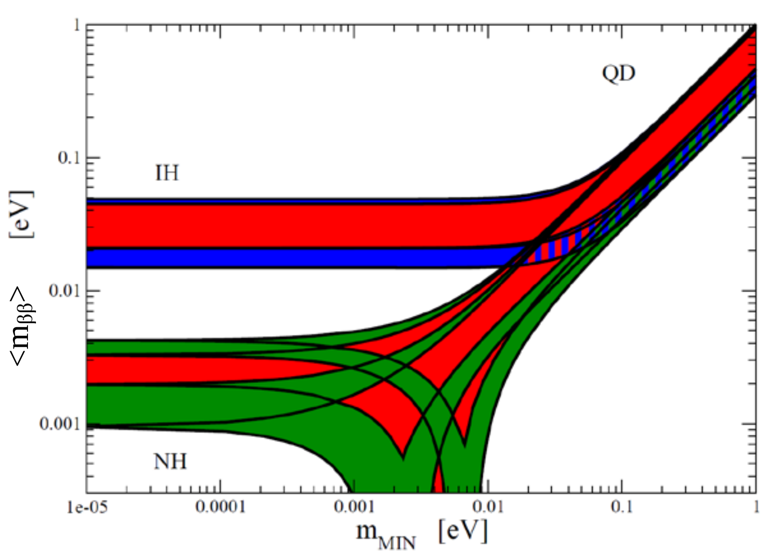

Figure 1.3 Allowed values of $<m_{\beta\beta}>$ as a function of the lightest neutrino mass for the

inverted (IH) and normal (NH) hierarchies (QD stands for "quasidegenerate"). The red, blue and green bands correspond to different allowed regions for the unknown CP violating phases in the expression for $\langle m_{\beta\beta} \rangle$ and allowed 1σ variation in the other known neutrino parameters. (From the Particle Data Group [2].)

Relation to rest of neutrino physics and cosmology

Working within the light Majorana neutrino exchange mechanism, one can identify several connections and synergies between $0\nu\beta\beta$ and other neutrino efforts, probing different properties of the light Majorana mass matrix:

(i) Better measurement of θ_{13}, mass-squared differences and, especially θ_{12} would help sharpen the target for the next generation experiments (today this is a lesser concern compared to nuclear matrix elements);

(ii) Determination of the **hierarchy** (NH vs IH) and **absolute mass scale** would sharpen the interpretation of both positive and null results in the next generation of $0\nu\beta\beta$ experiments.

Absolute Mass Scale Experiments

Experimental information on the absolute mass scale of the neutrino spectrum is provided by measurements of the electron spectrum endpoint in ordinary beta decay. This class of experiments relies on a purely kinematic effect and extracts the combination $m_e = \sum_i |U_{ei}|^2 m_i$, independent of the Majorana or Dirac nature of the neutrino and distinct from the effective mass parameter $\langle m_{\beta\beta} \rangle$ that affects neutrinoless double beta decay. Past tritium experiments set the limit $m_e < 2$ eV, and the KATRIN experiment, which will start data taking in 2015, is projected to reach the 90% CL limit $m_\beta < 0.2$ eV. This sensitivity translates into $m_{MIN} < 0.2$ eV, within the quasi-degenerate region of Figure 1.3.

Hierarchy determination from other neutrino experiments:

The recent measurement of a large value of θ_{13} has opened the possibility of determining the mass hierarchy through a variety of experiments involving accelerator, reactor, and atmospheric neutrinos. Exploiting this physics, a combined analysis of NOvA (US) and T2K (Japan) experiments might determine the hierarchy for certain ranges of oscillation parameters. LBNE will be a more comprehensive and definitive accelerator-based experiment, with increased sensitivity to determine the mass hierarchy and improved sensitivity to CP violation in the light neutrino sector. Reactor antineutrino experiments with medium baselines (~50 km), high energy resolution, and precise energy calibration allow one to probe the hierarchy, as well. Two experiments are currently proposed to make this measurement: JUNO in China and RENO-50 in South Korea. The observation of large samples of atmospheric neutrinos and antineutrinos at Hyper-K, PINGU and ORCA, will provide yet another probe of the neutrino mass hierarchy. There is a reasonable chance that, within the next decade, a combined analysis of several new experiments may well determine the neutrino mass hierarchy (see [1] for a more detailed discussion).

Neutrino masses from cosmology:

The distribution of matter in the Universe depends sensitively on the neutrino contribution to the total matter density. Therefore, current and upcoming surveys that probe the matter distribution can indirectly constrain or measure the sum of the neutrino masses. The physical basis of these constraints relies on the fact that neutrinos, being very light compared to all other particles, at the epoch of structure formation have a non-negligible thermal velocity, which controls their free-streaming length. Neutrinos do not clump on scales smaller than their free-streaming length and this leads to smearing out of over-dense regions (structure) at small scales, thus leaving a characteristic imprint in the matter distribution.

Current analyses constrain the sum of neutrino masses to be $\Sigma\, m_i < 0.23$ eV (95% CL) [3]. In the next decade there are good prospects to reach, via multiple probes, a sensitivity at the level of $\Sigma\, m_i < 0.01$ eV [4] . The plurality of probes, ranging from the cosmic microwave background to the distribution of galaxy clusters (see [4] for a complete list), will be crucial since each probe has its own set of assumptions and systematic uncertainties. Moreover, a joint analysis of different probes covering wider ranges of redshifts and distance scales will allow one to break parameter degeneracies that exist within the standard cosmological model, thus increasing the confidence in the extraction of $\Sigma\, m_i$.

Concerning the connection to $0\nu\beta\beta$, it is interesting to note that future cosmological surveys might provide a measurement of m_{MIN} appearing in Figure 1.3. Taking an optimistic point of view, the value of m_{MIN} inferred from cosmology may lie to the right of the funnel region at the bottom of Figure 1.3. In fact a very recent analysis [5] yielding $\Sigma\, m_i = (0.36 \pm 0.14)$ eV (68% CL) points in this direction, albeit with limited statistical significance.

Neutrinoless Double Beta Decay

A few years after Pauli first proposed the neutrino, and just three years after Fermi's 1934 paper describing the theory of nuclear β^- and β^+ decay,

$$(N,Z) \to (N-1,Z+1) + e^- + \bar{\nu}_e \;\; and \; (N,Z) \to (N+1,Z-1) + e^+ + \nu_e, \qquad (1)$$

Racah described the process of neutrinoless double beta ($\beta\beta$) decay,

$$(N,Z) \to (N-2, Z+2) + e^- + e^-, \tag{2}$$

in which a nucleus containing N neutrons and Z protons decays to a lighter nucleus, changing the nuclear charge by two units while emitting two electrons. There are about three dozen even-N even-Z nuclei that may decay only by such second-order weak interactions: the nuclear pairing force binds such even-even nuclei tightly, so that single beta decay to the odd-odd *(N−1, Z+1)* daughter is energetically forbidden. But $\beta\beta$ to the even-even *(N−2, Z+2*) daughter remains open: the nuclear physics provides a filter that isolates a very rare, second-order weak interaction (see Figure 1.4).

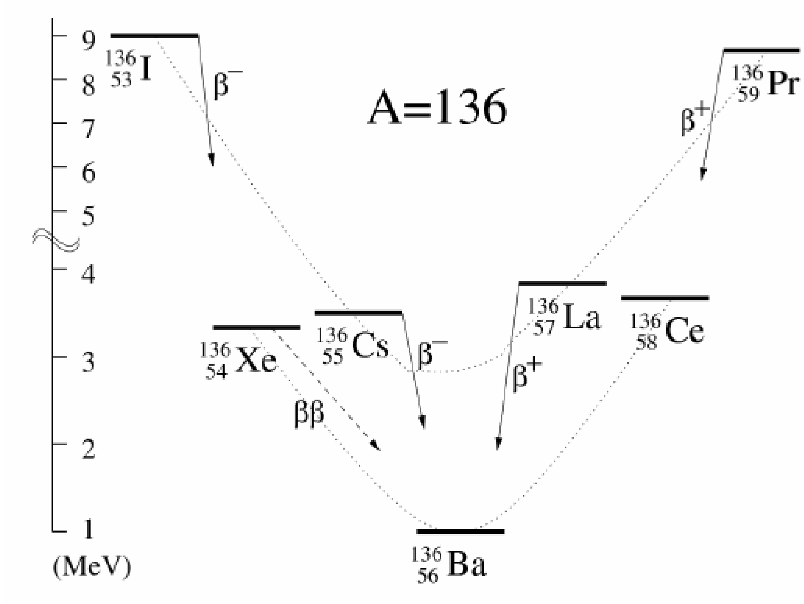

Figure 1.4. The masses of nuclei with A=136. The even-even and odd-odd nuclei are connected by two distinct dotted curves. ^{136}Xe is stable against ordinary β^- decay, but unstable against $\beta^-\beta^-$ decay. The same is true for ^{136}Ce, which can decay by $\beta^+\beta^+$ decay (the rates of which tend to be much smaller, as the Coulomb field in heavy nuclei suppresses $\beta^+\beta^+$ decay relative to $\beta^-\beta^-$ decay).

The neutrino, unlike other standard-model fermions, carries no electric charge or other quantum label that changes sign under particle-antiparticle conjugation. Consequently there is no requirement that the neutrino be distinct from its antiparticle (Dirac), rather than identical (Majorana). Yet the form of Eqs. (1), where the ν_e and $\overline{\nu}_e$ are distinguished from one another, was thought for many years to be correct, due to early efforts that failed to find any hint of Racah's process of neutrinoless $\beta\beta$ decay. Fermi's theory described, in addition to the reactions of Eqs. (1), the associated processes

$$\nu_e + (N,Z) \to (N-1, Z+1) + e^- and\ \bar{\nu}_e + (N,Z) \to (N+1, Z-1) + e^+. \tag{3}$$

Consequently, if $\nu_e \equiv \bar{\nu}_e$, then

$$(N,Z) \rightarrow (N-1, Z+1) + e^- + \bar{\nu}_e \equiv (N-1,Z+1) + e^- + \nu_e$$
$$(N-1,Z+1) + e^- + \nu_e \rightarrow (N-2,Z+2) + e^- + e^-. \tag{4}$$

That is, neutrinoless $\beta\beta$ decay could occur in a nucleus by the process illustrated in Figure 1.5, where the neutrino emitted in the beta decay of one neutron is reabsorbed on a second one, producing a final state with two outgoing electrons. The intermediate state in this process is virtual, as first-order beta decay is energetically forbidden in the cases of interest.

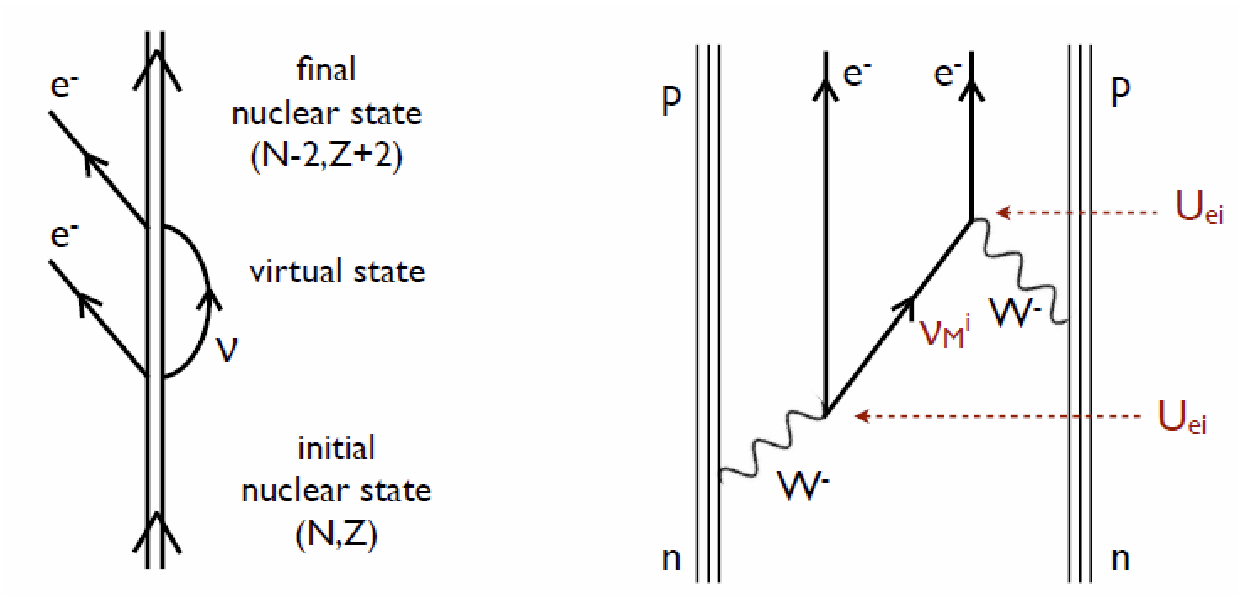

Figure 1.5. Neutrinoless $\beta\beta$ decay by emission and reabsorption of a Majorana neutrino, including the excitation of a virtual intermediate nuclear state (left), and this same process depicted at the nucleon level (right).

Two-neutrino $\beta\beta$ decay,

$$(N,Z) \rightarrow (N-2,Z+2) + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e, \tag{5}$$

is a second order weak process that is allowed in the standard model, conserves lepton number, takes place for both Dirac and Majorana neutrinos, and is the rarest decay process in nature for which half-lives have been measured. Because this $2\nu\beta\beta$ process produces a final state of four leptons, the energy release must be divided accordingly, leading to a substantial suppression of the rate due to phase space. Thus, according to the description given to this point, if the neutrino were a Majorana particle, one would have expected half lives for neutrinoless decay on the order of ~10^{12}-10^{15} y, while partial half-lives for the two-neutrino mode would be typically ~10^{20} y.

By the early 1950s a series of counter and tracking experiments had established lower bounds on neutrinoless $\beta\beta$ decay lifetimes that ranged up to 2×10^{17} y. Furthermore geochemical experiments had established a total $\beta\beta$ decay lifetime for ^{130}Te of 1.4×10^{21} y, while a radiochemical experiment for ^{238}U yielded a lower bound of 6×10^{18} y. These results were consistent with an absence of neutrinoless $\beta\beta$ decay, requiring ν_e and $\overline{\nu}_e$ to be distinct. A quantum number (lepton number L) was then introduced to distinguish the neutrino from its antiparticle: With the assignments $L(\nu_e) = L(e^-) = 1$ and $L(\overline{\nu}_e) = L(e^+) = -1$ and the assumption that lepton number is conserved additively in all weak interactions, all of the data on both single and $\beta\beta$ decay can be explained. In particular, neutrinoless $\beta\beta$ decay is then strictly forbidden, as this process changes lepton number by two units: only the lepton-number-conserving two-neutrino decay mode is allowed.

An important flaw in the argument for lepton number conservation and Dirac neutrinos became apparent in 1957, with the surprising discovery that parity is violated maximally, to the accuracy we can measure, in weak interactions. Consequently the neutrinos produced or absorbed in weak interactions have a definite handedness. Even if the neutrino is Majorana ($\nu \equiv \overline{\nu}$), neutrinos can be distinguished by their handedness

$$(N, Z) \rightarrow (N-1, Z+1) + e^- + \nu_e^{RH} \; and \; \nu_e^{LH} + (N, Z) \rightarrow (N-1, Z+1) + e^-. \qquad (6)$$

The first reaction produces only right-handed neutrinos, while only left-handed neutrinos can drive the second reaction. Consequently the neutrinoless $\beta\beta$ decay sequence for Majorana neutrinos

$$(N, Z) \rightarrow (N-1, Z+1) + e^- + \nu_e^{RH} \nrightarrow (N-2, Z+2) + e^- + e^- \qquad (7)$$

no longer works because the neutrino produced in the first step has the wrong handedness to be absorbed in the second step. Neutrinoless $\beta\beta$ decay would thus be exactly forbidden if the neutrinos were massless, as originally assumed in the standard model, regardless of the Dirac/Majorana nature of the neutrino. The historical conclusion that neutrinos are Dirac because of the absence of neutrinoless $\beta\beta$ decay is invalid. And the revelation of non-zero neutrino masses by the neutrino oscillation experiments makes the neutrinoless decay possible after all, albeit at very much longer half-lives than the initial guess above. As discussed in Sec. 2, present limits place the half-lives for neutrinoless decay above 10^{25} years.

More generally, the neutrino mass Lagrangian would in fact include terms for Dirac masses as well as terms for Majorana masses. These interactions have the form

$$\mathcal{L}_m \sim m_D \, [\, \bar{\psi}_L \psi_R + \ldots] + \; [m_L \bar{\psi}_L^c \, \psi_L + m_R \bar{\psi}_R^c \, \psi_R + h.c.] \qquad (8)$$

Here *L* and *R* represent handedness and *c* charge conjugation. The Dirac mass m_D, which represents the strength of the coupling to the Higgs field, would be the term that neutrinos would share in common with the charged fermions. Its inclusion for neutrinos already requires an extension of the minimal standard model, as this coupling involves a transition between left- and right-hand fields and thus requires introduction of a right-handed neutrino field. Two Majorana terms, coupling left-handed fields to left-handed fields and right-to-right, with strengths m_L and m_R, can also be formed. An invariance of the Lagrangian that is present for the Dirac term, under the global phase transformation $\psi \rightarrow e^{ia} \psi$ is broken when the Majorana terms are added: this is the invariance associated with a conserved lepton number. Note that m_L can be formed from left-handed neutrino fields of the standard model: one can include this term in the standard model if that model is regarded as a low-energy effective theory, with m_L representing the low-energy effects of missing higher-energy interactions. This term is the simplest dimension-full effective interaction that can be added to the standard model — and thus might be considered the most likely first correction to that model. To restore proper dimensions, a $1/m_R$ is needed — a new scale outside the standard model, representing the new physics. These various terms are represented in Figure 1.6.

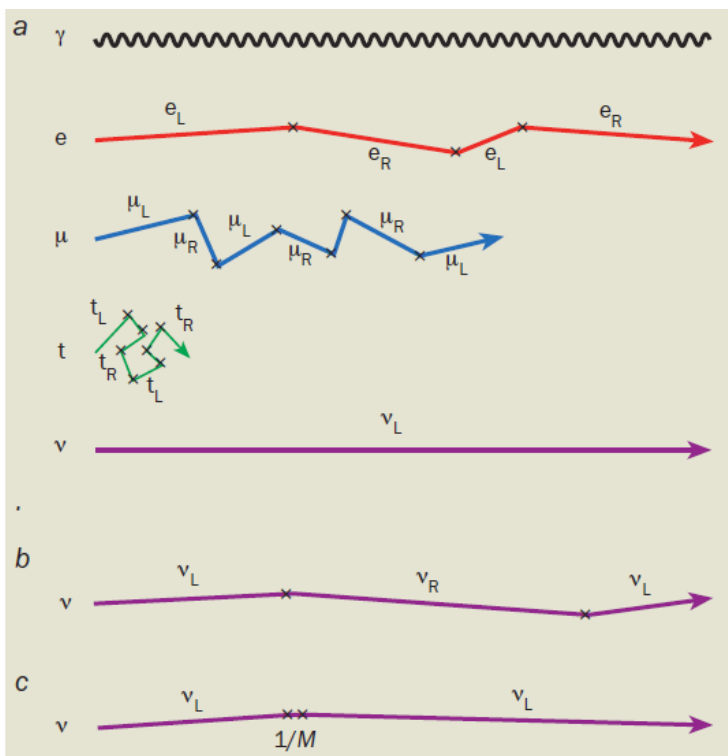

Figure 1.6. Mass generation: a) Particles acquire a mass through scattering with the Higgs field, with each interaction changing particle handedness, and with heavy particles like the tauon scattering much more frequently than light particles like the electron. The photon and neutrino are massless in the minimal standard model. b) A Dirac neutrino mass, which requires the addition of a right-handed neutrino field. c) A left-handed Majorana mass term, depicted as a second-order interaction involving some high mass scale M beyond the standard model. The

standard model's Higgs induces the Dirac neutrino masses that, in combination with the Majorana masses of the right-handed neutrinos of the seesaw mechanism, can explain the large difference between neutrino and charged-fermion masses [6].

As depicted in Figure 1.6, the new Majorana mass terms in combination with the Dirac mass provide a natural explanation for the anomalous scale of neutrino masses, providing a compelling argument for Majorana masses. The above interactions lead to a neutrino mass matrix that schematically takes the form

$$M_\nu = \begin{pmatrix} m_L \sim 0 & m_D \\ m_D & m_R \end{pmatrix} \tag{9}$$

where we have made use of the constraint $m_L << m_D$ to ignore m_L. Diagonalizing the mass matrix we find two eigenvalues, one heavy $\sim m_R$ and one light, which we associate with the light neutrino mass scale,

$$m_\nu \sim m_D \left(\frac{m_D}{m_R}\right) \tag{10}$$

This ``seesaw" mechanism predicts that light neutrino masses are not $\sim m_D$, but instead reduced from this value by the factor m_D/m_R the small parameter needed to explain why neutrinos are so much lighter than the charged fermions. There is a natural estimate for the value of m_R, made by many when Super-Kamiokande announced the discovery of atmospheric neutrino oscillations. If one associates the third-generation neutrino mass with $\sqrt{\Delta m^2_{atmos}}$ and $m_D \sim m_{top}$ one finds $m_R \sim 0.3 \times 10^{15}$ GeV. This is very close to the grand unified scale $\Lambda_{GUT} \sim 10^{16}$ GeV above which it is believed that the electromagnetic, weak, and strong forces will unify, becoming of equal strength.

Such extremely heavy right-handed Majorana neutrinos could have been produced in abundance in the early infancy of the universe, and played a critical role in establishing the matter-antimatter asymmetry we observe today. But they are beyond the reach of accelerators, and the observation of lepton number violation among the light neutrinos may be the best hope to provide indirect experimental evidence favoring their existence.

While neutrinoless $\beta\beta$ decay addresses a set of extraordinary questions, the interpretation of the results of neutrinoless double beta decay experiments will depend upon the assumed mechanism as well as theoretical calculations of the nuclear matrix elements. It is commonplace to concentrate on the mechanism of Figure 1.5, where $0\nu\beta\beta$ decay is mediated by the exchange of light Majorana neutrinos interacting through the left-handed *V-A* weak currents. The decay rate is then given by the expression

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

where $G^{0\nu}$ is the exactly calculable phase space integral, $\langle m_{\beta\beta} \rangle$ is the effective neutrino mass and $M^{0\nu}$ is the nuclear matrix element. The effective neutrino mass is

$$\langle m_{\beta\beta} \rangle^2 = |\textstyle\sum_i U^2_{ei}\ m_{\nu i}|^2$$

where the U_{ei} are elements of the neutrino mixing matrix (dependent on the known parameters θ_{12} and θ_{13} and the unknown Majorana phases $\alpha_{1,2}$) and the sum is only over light neutrinos (m_i < 10 MeV). Because of the presence of the unknown Majorana phases, cancellation of terms in the sum in $\langle m_{\beta\beta} \rangle$ is possible, and $\langle m_{\beta\beta} \rangle$ could therefore be smaller than any of the $m_{\nu i}$.

Obviously, any uncertainty in the nuclear matrix elements is reflected as a corresponding uncertainty in the $\langle m_{\beta\beta} \rangle$. There is, at present, no model-independent way to estimate the uncertainty in the nuclear theory. Good agreement with the known $2\nu\beta\beta$ transition is a necessary but insufficient condition. Clearly, more reliable evaluation of the nuclear matrix elements is a matter of considerable importance and this subject is discussed in detail in Chapter 4.

The $0\nu\beta\beta$ decay is not the only possible observable manifestation of lepton number violation. Muon-positron conversion,

$$\mu^- + (A,Z) \rightarrow e^+ + (A,Z-2)\ ,$$

or rare kaon decays,

$$K^+ \rightarrow \mu^+\mu^+\pi^-,\ K^+ \rightarrow e^+e^+\pi^-\ ,\ K^+ \rightarrow \mu^+e^+\pi^-,$$

are examples of processes that violate total lepton number conservation and where good limits on the corresponding branching ratios exist. However, it appears that at present, $0\nu\beta\beta$ is the most sensitive tool for the study of the Majorana nature of neutrinos.

2.0 CURRENT AND FUTURE PROJECTS

Experimental Approaches and Sensitivity

In the absence of background, a non-null $0\nu\beta\beta$ experiment would measure a decay rate, $\Gamma_{\beta\beta} = ln2\, T_{½}^{-1}$, where $T_{½}$ is the half-life. The statistical uncertainty scales as $\sqrt{N_{\beta\beta}}$, where $N_{\beta\beta}$ is the number of counted $0\nu\beta\beta$ events. However, the most sensitive published results report *exclusion limits* quoted in terms of the half-life. The KamLAND-Zen [7] and EXO-200 [8] Collaborations find 90% C.L. exclusions for the ^{136}Xe 0νββ half-life below 1.9 x 10^{25} and 1.1 x 10^{25} yr, respectively. The GERDA (^{76}Ge) [9] collaboration has published a 90% C.L. limit of >2.1 x 10^{25} years. (A previously reported [10] positive observation of 0νββ in ^{76}Ge, $T_{1/2} = (1.19^{+0.37}_{-0.23}) \times 10^{25}$ yr., is now effectively ruled out based on these recent results.)

The $2\nu\beta\beta$ decay channel has been observed in many isotopes with high statistics. Half-lives for that process can be reliably determined and are in the range of ~10^{19} to ~10^{21} years.

The much sought $0\nu\beta\beta$ mode has, in principle, a unique and characteristic signature: two electrons are emitted against a recoiling nucleus. The electrons carry a total kinetic energy essentially equal to the *Q* value of the decay. For isotopes employed in large-scale experimental campaigns, *Q* ranges from a low of 2039 keV for ^{76}Ge to a high of 2527 keV for ^{130}Te. Higher *Q* values exist for double-beta-decay candidate nuclei such as ^{150}Nd (3371 keV), ^{100}Mo (3034 keV), ^{82}Se(2995 keV) and ^{96}Zr (3350 keV). The incorporation of these isotopes in detector-ready materials is being explored for future efforts. The *Q* value is not only important because higher Q-values increase the decay rate, but also as it relates to potential backgrounds that might lie under a $0\nu\beta\beta$ peak. A Q-value greater than ~3 MeV would place the $0\nu\beta\beta$ energy Region of Interest (ROI) above the energy of gamma rays from nearly all naturally occurring radioactive isotopes.

The dominant experimental technique used to date in $0\nu\beta\beta$ search experiments is pure calorimetry, where the total electron energy of the two decay electrons is measured by scintillation light, ionization, or heat deposition (bolometers). A peak above background in the energy spectrum at the *Q* value would then indicate observation of the $0\nu\beta\beta$ decays. Figure 2.1 illustrates a background-free energy spectrum for both 0ν and 2ν double beta decay processes. Excellent resolution is desired to reduce the background from the tail of the $2\nu\beta\beta$ continuous distribution and to minimize the width of the ROI around the Q value, where contaminant gamma-ray conversions or other backgrounds could produce a structured or smoothly varying background. To approach this ideal situation, calorimetry is usually augmented by some form of particle identification and event isolation that minimizes background (fiducialization). In larger detectors, interior events can be selected by timing signals or pulse-shape signals; this selection effectively reduces backgrounds from surface contaminants and external penetrating gamma rays owing to the self-shielding of the outer part of the volume compared to the inner region. For smaller individual crystal detectors, a signal-shape analysis can effectively distinguish gammas from betas and, even in some situations, alphas. Hybrid detectors such as time projection chambers (TPCs) combine scintillation light and ionization measurements to distinguish alphas from betas. Similarly, a new idea for light-emitting bolometric crystals with dual readout would permit discrimination by the ratio of the heat to light signals, with the primary goal to veto alphas.

In all cases, detector installations must be located deep underground to suppress cosmogenic backgrounds and their components that are close to the sensitive fiducial volume must be built from highly radio-pure materials. The detectors also must include cosmic-ray veto capability, usually from an active shield. These steps are designed to eliminate background because the sensitivity, and ultimately the scalability of the experiment, depend on the background level.

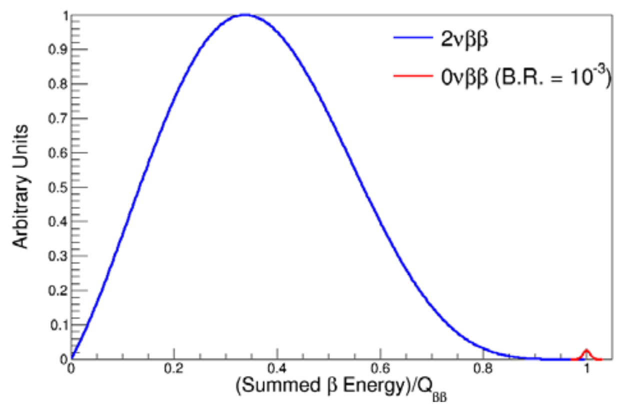

Figure 2.1. Illustration of a hypothetical two-neutrino (blue) and zero-neutrino (red) double beta decay energy spectrum. The resolution and ratio of decay rates affects the potential overlap of the blue and red curves in the ROI surrounding *Q* = 1.

The sensitivity of a double beta decay experiment can be expressed in numerous formats. A generic one gives the half-life sensitivity as

$$T_{1/2} > \frac{\ln 2 \ \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

where ε is the efficiency of detecting a $0\nu\beta\beta$ event, N_{source} is the number of isotope nuclei in the fiducial volume, and T is the observation time. The product $N_{source} \cdot T$ is sometimes called the *exposure*. The function $UL(B(T) \cdot \Delta E)$ represents the upper limit (UL) for a process that has the expectation of *B* background events in a ROI of width ΔE for an exposure of duration *T.* With *UL* representing the expected background counts in the ROI the half-life sensitivity tends to improve only as the square root of an increase in the exposure or from a decrease in the background rate. This rule of thumb is quite important in experimental design.

In an ideal experiment having no background in the ROI, the expression for the half-life sensitivity is simply

$$T_{1/2} > \ln 2 \;\; \varepsilon \cdot N_{source} \cdot T.$$

Under a background-free condition, the sensitivity improves with *linear proportionality* to an increase in the exposure. To date, no experiment has demonstrated a background-free level at the sensitivity required to cover the inverted hierarchy region, although several interesting R&D efforts and prototype detectors underway do aim for near background-free operation.

From a design perspective, a $0\nu\beta\beta$ event can—in principle—be uniquely imaged and discriminated against backgrounds, such as gammas and alphas. In one type of installation, a gaseous time-projection chamber in which the isotope source is also the active detector material can image the event track topology and also measure the total kinetic energy. In a different type of experiment, a high-resolution tracking spectrometer is positioned to view thin foils containing candidate double beta decay isotopes. In an entirely different approach, the capture of the unique daughter ion following a candidate $0\nu\beta\beta$ decay event would serve as a clear signature of double beta decay. With good energy resolution, a true $0\nu\beta\beta$ event can then be unambiguously isolated from the competing 2ν mode. The concept of "Ba tagging" in experiments involving the ^{136}Xe isotope is being vigorously explored, but has yet to be realized. The extent to which classic calorimetry techniques—augmented by combinations of creative background reduction methods, particle identification, shielded fiducial volumes, and rigorous material preparation—can demonstrate near-zero background is central to the current campaign of many mid-scale installations. If background remains, the precision and accuracy with which it can be subtracted are better if the background is smooth, rather than structured, in the $0\nu\beta\beta$ ROI. The lessons learned will guide future plans and better predict the eventual neutrinoless double beta decay sensitivities of the techniques described in the next section.

Current Projects and Next-Generation Concepts

The Charge to the Subcommittee requests *an assessment of the status of ongoing and planned first phase NLDBD experiments toward achieving their goals, including major remaining challenges.* To that end, we solicited information from the various projects following a provided template. Additionally, each project presented an oral report to the Subcommittee, with accompanying sets of projections. This Chapter summarizes that information, often using the descriptions provided by the projects themselves. For current efforts, we remark on *strengths* and *challenges* in the bullets that follow each short narrative description. For future conceptual efforts, we provide our *observations.* We assert that the numerical estimates reported in this summary are provided by the Collaborations; they have not been filtered by the Subcommittee, nor should their accuracy be interpreted to be certified by the Subcommittee. (Written material was received from COBRA, but this effort is in a very early R&D phase and so we did not receive a presentation and we do not include it here. In addition, an estimate of the capability of the LZ dark matter experiment was submitted to the subcommittee. While that experiment could have some capability to observe $0\nu\beta\beta$ it is not currently seen as a competitive path to a next generation experiment so we do not discuss it here.)

The order of the projects in the following is chosen according to the agenda of the presentation meeting (Appendix 3). There is no significance intended or implied to this order.

CUORE

CUORE, the Cryogenic Underground Observatory for Rare Events, is a bolometric detector being constructed by an international collaboration of Italy, the US, and others. The detector will consist of a close packed array of 988, 5×5×5 cm^3, natural TeO_2 crystals operated as cryogenic calorimeters (bolometers) at a temperature of about 10 mK. This corresponds to a total active mass of 741 kg, or 206 kg fiducial mass of the ^{130}Te isotope. The signature of the $0\nu\beta\beta$ decay is a narrow peak in the summed-energy spectrum of the final-state electrons centered at the Q-value of 2527 keV. The energy is measured by neutron transmutation- doped thermistors attached to each crystal. The apparatus is currently under construction at Laboratori Nazionali del Gran Sasso (LNGS) in Assergi, Italy, with an overburden depth of 3650 meters water equivalent (m.w.e.). Operations are expected to start in 2015 with a 5 year projected sensitivity of $T_{1/2} > 10^{26}$ years at 90% C.L.

The CUORE approach has a number of strengths:

- The bolometric crystals are both source and detector. They exhibit demonstrated excellent energy resolution of ~0.2% FWHM (5 keV) in the Region of Interest (ROI).

- The use of natural Te exploits the sizable natural abundance (34.1%) of ^{130}Te.
- The collaboration has significant experience through staged efforts. The CUORICINO array of 62 crystals is complete and data has been published establishing a half-life limit of $T_{1/2} > 2.8 \times 10^{24}$ years at 90% C.L. A full tower of 52 CUORE modules is being tested in realistic conditions in the CUORICINO cryostat, a stage dubbed CUORE-0. This experience will test backgrounds and the detector and electronics in a realistic installation.
- Multi-site events can be vetoed by coincidence between detectors.
- The experiment is in a fairly advanced stage with many key components being commissioned.

The CUORE approach faces the following challenges

- The required pulse tube refrigerator and cryostat will be among the most powerful dilution fridges in the world. Final commissioning and sustained operation of the fully loaded fridge over long data collection periods, together with minimization of vibrations affecting bolometer resolution will be ongoing challenges.
- The intrinsic time response of the thermal signal is slow, which increases the importance of low background rates.
- The primary background concerns are from α-decays (U and Th chains) on the passive surfaces surrounding the crystals and on the crystal surfaces. Additional γ-ray backgrounds are from the multiple Compton scattering of the ^{208}Tl line. To reach their sensitivity goal, CUORE must reduce backgrounds by a factor of 7 from the level achieved to date with CUORE-0.
- Like many other experiments, the assembly requires extremely clean conditions and will employ robotics. Some mechanical assembly must be done in a radon-free cleanroom and in dedicated glove boxes
- The installation must have a high degree of vibrational isolation to maintain resolution.
- Low-noise electronics are required.

Beyond CUORE

The next stage of the bolometric approach will use a dual readout (heat + light) of either TeO_2 crystals, or alternatives such as ZnSe, $CdWO_4$, or $ZnMoO_4$. While TeO_2 produces only a modest amount of Cherenkov light, the other crystals scintillate. The dual readout is designed to discriminate between α and β events. Demonstrated discriminating power obtained to date ranges from a low of 1.5σ α–β separation for TeO_2 to a high of nearly 20σ for $ZnMoO_4$. The aim is a background free experiment with a mass that can be inserted into the existing CUORE cryostat. Assuming significant improvements in the light-response and isotopically enriched rather than natural crystals, the proponents target a $0\nu\beta\beta$ half-life sensitivity exceeding 10^{27} years for any of the selected crystals. Important background rates—presently derived from upper limits of assayed components—exceed the allowed budget, but they should be measured directly using CUORE itself. The intermediate project, LUCIFER, is a focused effort to build and operate a small system using dual light and heat readout on a shorter time scale.

Committee Observations

- Development of the dual-readout bolometers is an important R&D effort that could open up opportunities with several isotopes having high energy resolution, high Q value, and excellent background rejection.

Majorana Demonstrator

The MAJORANA DEMONSTRATOR (MD) is an array of enriched and natural germanium detectors that will search for the $0\nu\beta\beta$ decay of the isotope ^{76}Ge; Q-value equals 2039-keV. The experiment is located in the Sanford Underground Research Facility (SURF) in South Dakota. It is a staged plan on a path toward a full-scale 1-tonne detector that will aim to probe the inverted hierarchy. The specific goals of MD are to demonstrate a background rate of 3 counts/tonne-yr in the 4-keV wide ROI, which scales to the required 1 count/(tonne-year) in the same ROI for the Large-Scale Ge (LSGe) Detector, owing to self shielding within the array. Additionally the collaboration aims to establish technical and engineering scalability toward a tonne-scale instrument. Besides $0\nu\beta\beta$ physics, MD will perform searches for physics beyond the standard model, such as the search for dark matter and axions. The Demonstrator is a modular instrument composed of two cryostats built from ultra-pure electroformed copper, with each cryostat capable of housing over 20 kg of p-type point-contact (PPC) detectors. PPC detectors were chosen after extensive R&D by the collaboration and each has a mass of about 0.5-1.1 kg. The baseline plan calls for 30 kg of the detectors to be built from Ge material enriched to 87% in isotope 76 (11.44 moles ^{76}Ge/kg) and 10 kg fabricated from natural-Ge (7.8% ^{76}Ge). The modular approach allows assembly and optimization of each cryostat independently, providing a fast deployment with minimum interference to already-operational detectors.

The MD approach based on p-type point contact high-purity germanium (HPGe) detectors has a number of strengths:

- Low background in the bulk germanium source material has been demonstrated.
- The enrichment chemistry is well developed.
- The energy resolution is excellent, with ~3 keV FWHM at $Q_{\beta\beta}$
- There are sophisticated event reconstruction signatures based on pulse-shape analysis, detector hit granularity, single-site time correlations, and cosmic-ray veto tags.
- The background in the ROI is flat.

The main technical challenges include:

- Reduction of environmental ionizing radiation backgrounds by a factor of more than 10 compared to previously achieved results. Specific issues that remain under investigation are:
  - Radioactivity in the lead shielding. Based on recent radioassays, it appears that this may be manageable, but remains as a concern.
  - U and Th in the cables and connectors.
  - Radioactivity in the front-end electronics near the detector.

GERDA Phase I and II

GERDA Phase I, located in the Gran Sasso underground laboratory in Italy, started in Nov. 2011 with a 17.67 kg array of recycled Ge detectors enriched to 86% ^{76}Ge. In July 2012, 3.63 kg of enriched p-type Broad Energy Ge (BEGe) detectors were added. The detectors were mounted on low-mass copper supports and immersed in a 64 m^3 cryostat filled with liquid argon (LAr), which served as a cooling medium and as a shield against external backgrounds. The LAr shield is surrounded by 3 m of water instrumented with photomultipliers to detect Cherenkov light generated by muons. An exposure of 21.6 kg-yr of enriched Ge, or 215 mol-yr of ^{76}Ge within the fiducial volume was analyzed for $0\nu\beta\beta$ physics. Background was observed from ^{42}K, the daughter of ^{42}Ar in the argon, with additional gamma background from ^{40}K, ^{214}Bi, ^{214}Pb, and ^{208}Tl. Besides gamma rays, there is also alpha background from ^{226}Ra decay chain, and beta background from ^{39}Ar. Before pulse-shape discrimination was applied, a total of 7 events were detected in the blinded energy window $Q_{\beta\beta} \pm 5$ keV. The number of events after pulse shape discrimination is 3. The background model predicts a flat background with no lines near the Q-value. A fit to the data assuming a flat background in a "background interpolation region" (1930 keV – 2190 keV) and a Gaussian peak at $Q_{\beta\beta}$ with standard deviation σ_E according to the expected value, yields a best fit with no excess events above background, implying a half-life for neutrinoless double beta decay of > 2.1 x 10^{25} yr (90% C.L.).

GERDA Phase II is an on-going upgrade to reduce backgrounds and improve the sensitivity. The strategy includes new BEGe detectors, which have superior background rejection power; improved energy resolution; instrumenting the LAr shield with photo-detectors to detect LAr scintillation photons to veto background; and, reduction of radioactive materials near or on the detector array.

GERDA shares the strengths of the Majorana Demonstrator:

- Low background in the bulk germanium source material has been demonstrated.
- The enrichment chemistry is well developed.
- The energy resolution is excellent, with ~3 keV FWHM at $Q_{\beta\beta}$
- There are sophisticated event reconstruction signatures based on pulse-shape analysis, detector hit granularity, single-site time correlations, and cosmic-ray veto tags.
- The background in the ROI is flat.

Comments and Technical Challenges:

- GERDA Phase II is an essential step for evaluating the feasibility of employing cryogenic shielding for reaching the goal of a tonne-scale detector needed for probing neutrinoless double beta decay in ^{76}Ge in the inverted hierarchy.

- Reducing the background from ^{42}K decay in the liquid argon may be a technical challenge. A possible mitigation strategy is to use argon with lower levels of ^{42}Ar extracted from certain underground sources.

Future Large Scale Ge (LSGe) Detector: Majorana+Gerda

MAJORANA and GERDA are working towards the establishment of a single international ^{76}Ge $0\nu\beta\beta$ collaboration. They envision a phased, stepwise implementation of detectors up to a total mass of 1000 kg, e.g. 250 → 500 → 1000 kg. They are moving forward predicated on demonstration of projected backgrounds by MD and/or GERDA. They anticipate down-select of best technologies, based on results of the two experiments. During 2014/2015 both GERDA Phase II and MD Cryo1 should be collecting data. The tentative schedule for technology down-select is in 2017.

Three possible configurations for the LSGe experiment are being considered. Two are based on the current designs of the Majorana Demonstrator "Compact" and the Gerda "Cryogenic" shield, whereas a third possibility is a hybrid that encompasses features of both, possibly deploying the LSGe detector array in a liquid scintillator surrounded by a water shielding tank. The required radio-purity of the scintillator or water has already been achieved in other experiments. The Cryogenic design requires more underground space, whereas the "Compact" design may require a deeper site. Both designs have similar backgrounds from internal sources. The proposed detector is expected to probe the inverted hierarchy with a background of < 1 count/(tonne-yr) and an exposure of 10 tonne-yrs.

Committee Observations

- When complete, the Majorana Demonstrator and Gerda Phase 2 detectors will provide thoroughly researched options for a tonne-scale detector with detailed studies of background and technologies by two large experienced groups.
- Although the projected background under and near the ROI is not completely negligible at present, it appears to be flat and thus can be more easily modelled.
- To convincingly cover the inverted mass hierarchy region, the experiment may require a larger exposure than other cases due to the lower Q-value and phase space factor for ^{76}Ge. Either a multi-tonne scale installation or a longer observation time may be needed, depending on the observed background level.

EXO-200

- EXO-200 searches for the neutrinoless double beta decay of ^{136}Xe at the Waste Isolation Pilot Plant (WIPP) near Carlsbad NM with ~1600 m.w.e. overburden. The experiment began data taking in May 2011 and is conducted by an international collaboration consisting of 20 institutions from 7 countries. A total of 200 kg of isotopically enriched Xe (80.7% enrichment) are available of which 110 kg (79 kg fiducial isotope mass) are active in the detector. A liquid filled TPC with simultaneous read-out of ionization and scintillation forms the heart of the experiment. The Xe is contained in a thin-walled copper vessel, surrounded by a ~50 cm thick layer of cold ultra-clean fluid which forms the thermal bath and innermost radiation shield. 25 cm of low activity lead form the outermost radiation shield. The experiment, together with all services, is contained in a clean room that is surrounded on four sides by large plastic scintillation detectors, forming an active cosmic ray veto shield with 96.2% efficiency.

The EXO approach has several clear strengths:

- EXO-200 is currently operational and taking data.
- EXO-200 has published a limit on the half-life for the $0\nu\beta\beta$ decay of ^{136}Xe of $T_{1/2} > 1.1 \times 10^{25}$ yr (90% CL).
- The 3D spatial resolution of ±2.6 mm in x-y (in the wire planes) and ±0.46 mm in z (time dimension) allows discrimination of multi-scattering gamma-ray background events from single-site electron events such as those produced by double beta decay.
- As an inert, cryogenic fluid, xenon is capable of excellent chemical purification.
- Ability to remove or replace the enriched isotope without affecting detector performance, in order to verify the reality of a possible non-null signal.

The EXO approach faces the following challenges

- Even with an energy resolution of 3.6% FWHM in the ROI near the Q value of 2457.83 keV, two common gamma ray backgrounds are nearby, one at 2447.8 keV from ^{214}Bi decay to ^{214}Po in the ^{238}U chain and the other nearby at 2614.53 keV from ^{208}Tl decay to ^{208}Pb in the ^{232}Th chain. These backgrounds must be extremely well understood and calibrated, and experimental limits will depend on detailed background models and fits to attain the requisite sensitivity.

- Achievement of a 3 year running goal for the half-life at approximately 10^{26} years will require a substantial (factor ~ 2) reduction in background rate, reduced fiducial volume uncertainty, and improved energy resolution (to 2.3% in the ROI).

nEXO Next-Generation Approach

The nEXO approach is envisaged to use 5 tonnes of enriched Xe with a design that is derived from the EXO-200 experiment but also includes important design modifications. Because of the monolithic nature of the detector, the increase in size by a factor of ~3 in linear dimensions provides improved self-shielding and hence superior rejection of gamma-rays. In addition, the better self-shielding should provide more background-discriminating power in the fit variable representing the distance of events from the boundaries of the fiducial volume. The nEXO goal is to retain the energy resolution achieved in the final version of EXO-200, estimated to be FWHM $\beta\beta/Q_{\beta\beta}$ = 2.3%, with the larger detector. While nEXO appears to be appropriate for installation at SURF, it would benefit from the greater depth available at SNOlab. It is noteworthy that a large quantity of enriched xenon could be conveniently converted from liquid to gaseous form if a gaseous detector technology alternative turns out to offer comparable or better $0\nu\beta\beta$ sensitivity.

Committee Observations

- As mentioned above for EXO-200, the ^{214}Bi gamma ray at 2448 keV will not be resolved from a possible $0\nu\beta\beta$ peak. This structured background feature will present a significant analysis challenge and increase the burden of proof for any potential discovery claim.
- R&D on detector performance and additional background studies should be carried out to provide a convincing demonstration that the proposed half-life sensitivity of 6 x 10^{27} years can be achieved. Specifically, efforts should be made to reduce the levels of ^{214}Bi even beyond the Collaboration's present projection.

NEXT and NEXT-100

The NEXT experiment – the Neutrino Experiment with a Xenon TPC – searches for the 0νββ decay of ^{136}Xe. It proposes to use a high pressure (15 bar) gaseous TPC. NEXT will be installed at the Canfranc Underground Laboratory in Spain. The detector design will employ different sensors for tracking and calorimetry. For tracking, silicon photomultipliers (SiPMs) coated with a suitable wavelength shifter are envisioned, while radio-pure PMTs will be used for the energy measurement and to estimate the event decay time. The first phase of the experiment is currently under construction. It will use 10 kg of ^{136}Xe and is planned for operation in 2015. The second phase, NEXT-100, which will use the full existing inventory of 100 kg, is scheduled for operation in 2016.

The strengths of the NEXT approach include:

- The simultaneous detection of both energy and tracking information is laudable. The unique feature of detecting the topological evidence for a double beta decay event, coupled with the resolution to resolve the 2ν mode, should lead to a low-background experiment.
- The use of a gaseous sample allows high purity as well as continuous sample purification.
- Ability to remove or replace the enriched isotope without affecting detector performance, in order to verify the reality of a possible non-null signal.

The challenges of the NEXT approach include:

- The large pressure vessel must be fabricated from very low background material. However, recent radioassay measurements are very promising.
- The “unique” topological signature fidelity must be well understood against known backgrounds from single electrons, accompanied by in-time X-rays from xenon de-excitation. The efficiency of reconstruction is relatively low.

MAGIX

MAGIX is a proposed second generation experiment that will employ the high pressure TPC energy and tracking technique under development for NEXT. The experiment proposes a fiducial mass of ~1 tonne. Phototubes will be placed outside the detector volume and the entire ultra-pure copper detector chamber will be placed within a water volume that is contained in the stainless steel pressure vessel to improve shielding and reduce backgrounds.

Committee Observations

- One of the few approaches that can measure and image the full final state kinematics of a 0νββ event.
- Promising results for tracking and resolution have been reported for a small-scale installation. The final design and performance of MAGIX will await the lessons learned and results obtained from the NEXT-100 experiment.
- The envisioned fully tagged reconstruction efficiency at ~30% is lower than for most other experiments.

KamLAND-Zen

The KamLAND-Zen Collaboration has adapted the running KamLAND liquid scintillator detector and infrastructure to a 0νββ search by inserting into the center of its 6.5 m radius main balloon a 1.5 m radius mini-balloon filled with liquid scintillator loaded with xenon enriched to 90% ^{136}Xe. The experiment is housed in the Kamioka mine in Japan, with funding and effort primarily from Japan. An unanticipated dominant background in the early spectra from ^{110m}Ag, of undetermined origin, is still present in subsequent data-taking after Xe gas was removed from the scintillator in the mini-balloon. In the next phase, anticipated to begin in 2014, a new clean mini-balloon of 1.8 m radius will be filled with re-purified liquid scintillator loaded with ~600 kg of enriched Xe, already in hand. The Collaboration hopes that these steps will reduce the ^{110m}Ag background rate by two orders of magnitude. They project the remaining backgrounds to be dominated by ^{136}Xe 2νββ and ^{214}Bi decays, contributing to an overall background rate of about 24 events/year. The collaboration plans to operate the detector with 434 kg of isotope fiducial mass for 5 years to improve their sensitivity to neutrinoless double beta decay.

The strengths of the KamLAND-Zen approach include:

- The cost-effectiveness of reusing an existing large-volume detector and infrastructure, which can simultaneously pursue other topics in neutrino physics (e.g., studies of geo-neutrinos);
- The early start on 0νββ studies and the large amount of enriched isotope already in hand, leading to perhaps the best half-life limit attainable before the end of the current decade;
- Suppression of gamma backgrounds from external sources in the large volume of scintillator surrounding the mini-balloon;
- The possibility to reduce internal backgrounds at moderate cost by re-purifying the Xe-loaded liquid scintillator and replacing the mini-balloon;

- The use of triple μ-n-γ coincidences to suppress background from ^{12}C spallation products (with the neutron subsequently undergoing radiative capture on a proton in the liquid and the gamma from annihilation of the daughter positron from ^{10}C decay);
- The technique's scalability to even larger isotope masses in next-generation experiments and adaptability to loading the liquid scintillator with other isotopes of interest in $0\nu\beta\beta$ research.
- Ability to remove or replace the enriched isotope in order to verify the reality of a possible non-null signal.

The approach also faces several challenges, including:

- Limited energy resolution (~250 keV, 9.5% FWHM), leading to significant $2\nu\beta\beta$ background within the peak region for a $0\nu\beta\beta$ signal;
- The need to identify and eliminate the source of the currently dominant ^{110m}Ag background peak in the immediate vicinity of the ROI;
- Radioactive impurities on the surface and in the bulk material of the mini-balloon;
- The need to demonstrate accurate modeling of the detector and the background sources in order to extract a potential signal with modest energy resolution in the midst of a background of non-trivial shape.

KamLAND2-Zen Next-Generation Approach

In order to extend sensitivity to $0\nu\beta\beta$ half-life values in the 10^{27} year range, the Collaboration proposes a major upgrade of the detector for a next-generation experiment. The phototubes would be replaced with ones of higher quantum efficiency, and light concentrators would be added to improve PMT coverage. In addition, the liquid scintillator light yield would be increased. The net effect of these changes would be an improvement in energy resolution from 250 keV to better than 150 keV. The enriched Xe mass would be increased to 1000 kg. Other possible upgrades aimed at further improving the signal-to-background ratio are the subject of ongoing R&D: the use of pressurized Xe, of scintillating film for the mini-balloon material, and of improved optics design to provide β/γ discrimination. A goal of a factor of 10 reduction in background is also part of the upgrade toward higher sensitivity.

Committee Observations

- The energy resolution of this approach tends to limit its potential. However, the approach does represent a method to study a very large mass of isotope in a timely way. If the background is very low, the technique can achieve a sensitive $0\nu\beta\beta$ bound.

- The comparatively poor resolution places a high demand on knowing the energy resolution in detail, allowing for variation in light yield in the large detector volume, among other factors.

SuperNEMO

The SuperNEMO Collaboration employs a tracking-and-calorimetry approach, in which isotope material in the form of thin source foils is interleaved with high-granularity wire-chamber trackers and segmented calorimetric elements (plastic scintillators) for measurement of β^- energy and time-of-flight. The preceding NEMO3 experiment employed a total of 10 kg of various $\beta\beta$ isotopes (^{100}Mo, ^{82}Se, ^{130}Te, ^{116}Cd, ^{150}Nd, ^{96}Zr and ^{48}Ca, with ^{100}Mo as the 7-kg dominant share) arranged in a “Camembert” structure; this experiment has successfully measured the isotope $2\nu\beta\beta$ half-lives. The SuperNEMO geometry differs from that of NEMO3, consisting of rectangular modules each comprising a central source foil sandwiched by tracker cells and scintillator counters. The “Demonstrator” module can accommodate 7 kg of enriched isotope (^{82}Se- and/or ^{150}Nd), and has the aim of demonstrating background levels low enough for a 100-kg detector. The detector location is the Fréjus laboratory at 4800 m.w.e depth. In the current schedule the Demonstrator will run from 2015-2017, and the 100-kg full SuperNemo will run from 2017-2023. The collaboration projects no background for the Demonstrator. Validation of the background level and a decision for the full-scale SuperNEMO will occur in 2016.

The SuperNEMO approach has a number of strengths:

- The main advantage of the tracking-and-calorimetry approach is that it enables precision measurements of the full kinematics of the β^- products. This not only helps with selection of signal from background, but also, in the event of a signal, will help to elucidate the underlying physical mechanism of $0\nu\beta\beta$ from the measured angular distribution of the β^- products.
- The technology is tested and the feasibility of scaling by the addition of modules has been successfully demonstrated.
- Source foils can be swapped out for evaluation of different isotopes and the selection includes promising isotopes having the largest Q values, which yield large phase space factors and ROI’s above most important backgrounds: ^{82}Se ($Q_{\beta\beta}$ = 3.0 MeV), ^{150}Nd ($Q_{\beta\beta}$ = 3.4 MeV) and ^{48}Ca ($Q_{\beta\beta}$ = 4.3 MeV).
- Copper foils can be used to evaluate the background model.

- Ability to remove or replace the enriched isotope without affecting detector performance, in order to verify the reality of a possible non-null signal.

The SuperNEMO approach also faces a number of technical challenges:

- Control of backgrounds has yet to be demonstrated. The geometry has a high surface-to-volume ratio and is vulnerable to radon and other external backgrounds.
- Source foil radio-purity must be both very good and well understood.
- Detector cost per unit isotope mass is relatively high for this experimental configuration.

SuperNEMO Next-Generation Approach

The “full” SuperNEMO experiment is envisioned as having 100-kg of isotope. Additional mass can be deployed by adding identical modules. The detector is to be located in an extension of the Modane laboratory at Fréjus. According to the indicated schedule, assuming backgrounds are demonstrated to be sufficiently low by the Demonstrator, the 100-kg full SuperNEMO would run from 2017-2023. Relative amounts of the isotope to be deployed will depend on radon levels, and availability and cost of enriched isotope.

Committee Observations

- SuperNEMO is one of the few approaches that can measure and image the full final state kinematics of a $0\nu\beta\beta$ event.
- The requirement that thin foils of isotope must be used to minimize electron scattering and energy loss effects likely limits the extension of this technique to a sensitivity below 10^{27} years.

SNO+

The SNO+ Collaboration plans to retrofit the SNO solar neutrino detector and infrastructure to operate with 780 kg of tellurium-loaded (linear alkylbenzene, or LAB) liquid scintillator. The SNO+ detector includes upgrades to the electronics and data acquisition systems. Phase I of the project will utilize 0.3% loading with natural Te to search for neutrinoless double beta decay of ^{130}Te, in parallel with several other avenues of neutrino physics research. The current schedule calls for 3 years of data-taking, following completion in late 2015 of the filling and loading of the scintillator.

The SNO+ approach has a number of clear strengths:

- It reuses a large volume existing detector housed in a large and very deep (6010 m.w.e) underground cavity.
- The use of natural Te exploits the sizable natural abundance (34.1%) of ^{130}Te to allow a cost-effective approach to quite large isotope fiducial masses, even with relatively severe fiducial cuts to reduce backgrounds. The fiducial isotope mass anticipated for Phase I is 160 kg.
- The absence of an interior isotope container keeps external background sources at significant distance from the fiducial volume, so the scintillator itself attenuates background particles.
- Internal backgrounds can be ameliorated by multiple-pass purification of the liquid scintillator.
- The fast timing facilitates rejection of Bi-Po delayed coincidences.
- The experiment offers a broad physics program beyond $0\nu\beta\beta$.
- Ability to remove or replace the $\beta\beta$ isotope in order to verify the reality of a possible non-null signal.

The SNO+ approach also faces a number of technical challenges:

- The energy resolution of the detector is limited (270 keV near the ROI assuming a light yield of 200 photoelectrons/MeV from the Te-loaded scintillator), leaving a significant background within the peak region from the $2\nu\beta\beta$ decay of ^{130}Te.
- A number of non-Te background sources, including ^{8}B solar neutrinos, contribute to a significant overall background of non-trivial shape in the ROI.
- The simulated total background rate within an optimized ROI which is asymmetric about the $0\nu\beta\beta$ peak position is 22 events/year. Extraction of a possible signal or upper limits on the signal must rely on fitting the measured energy spectrum with a very detailed and accurate model of detector performance, optical system, and background contributions.

- The light yield, and hence energy resolution, is likely to vary with Te loading, again requiring accurate detailed modeling to make use of scaling tests by varying the Te loading fraction.
- The monolithic detector design weakens rejection of multi-site backgrounds in comparison with segmented detectors.
- Aggressive fiducialization to reduce backgrounds implies significant "waste" of isotope mass.
- Production capability for the Te-loaded LAB at the mass scale, loading fraction, light yield and radio-purity required for the experiment has not been fully demonstrated.

SNO+ Next-Generation Approach

A Phase II SNO+ project would take advantage of the fact that a number of the background contribution rates are independent of the Te loading of the liquid scintillator, so that the signal to background ratio for a given half-life sensitivity increases rapidly with loading fraction. The Collaboration's stated goal for Phase II is to increase loading fraction from 0.3% to 3%, while simultaneously improving the light yield from 200 to 300 photoelectrons/MeV (improving energy resolution to 200 keV) and increasing the fiducial volume to achieve a fiducial isotope mass of 2.3 tonnes using natural Te. Attainment of the technical improvement goals requires considerable R&D on the Te-loading process and radio-purity, in combination with replacement of the SNO photomultiplier tubes either with tubes of higher quantum efficiency and size or possibly with large-area photodiodes. A possible alternative approach to reach the same sensitivity with less aggressive R&D demands, but at considerably higher cost, would involve the use of 1% loading of enriched ^{130}Te.

The basic technique of using loaded liquid scintillator could, in principle, be expanded to 100-tonne scale samples in the longer-term future, utilizing either conventional or water-based liquid scintillator. The detection of Cerenkov light, in addition to scintillation light, would help to suppress the ^{8}B background. However, the limited energy resolution achievable with liquid scintillators would still leave the tail of the $2\nu\beta\beta$ spectrum as a dominant background.

Committee Observations

- The energy resolution of this approach tends to limit its potential. However, the approach does represent a cost-effective method to study a very large mass of isotope. If the background is very low, the technique can achieve a sensitive $0\nu\beta\beta$ bound.

- The comparatively poor resolution places a high demand on knowing the energy resolution in detail, allowing for variation in light yield in the large detector volume, among other factors.
- The collaboration will need to demonstrate low background with the Te-loaded scintillator and increased Te-loading without deteriorated energy resolution.

Notional Timeline of Presented Projects

Based on the information supplied to the Subcommittee by the collaborations, we have compiled the timeline for these projects in Figure 2.2. One can see that there is at least 1 more year of construction and assembly before all the projects are in an operational phase taking data. After an additional period of 1-2 years one can expect to have valuable information based on real data for these different techniques. At that point, one would expect that an assessment of the relative merits would be much more reliable than the present time.

Figure 2.2. Approximate timelines for the presented projects. The orange bars represent nominal construction periods and green illustrates actual or intended running.

3.0 CRITERIA AND GOALS FOR FUTURE DEVELOPMENT OF NLDBD (Guidelines for the Next Generation Experiments)

As described in Sec. 1, a convincing discovery of lepton-number-violating neutrinoless double beta decay would have profound impact on our understanding of physics beyond the Standard Model. Attractive theoretical speculations, capable in principle of accounting for both the lightness of the known neutrinos and the origins of the baryon-antibaryon asymmetry of the universe, suggest that the light neutrinos may be Majorana particles with an inverted mass hierarchy. The goal of next-generation $0\nu\beta\beta$ searches should be to test this hypothesis as definitively as possible.

The current projects summarized in Sec. 2 represent a very useful suite of promising complementary approaches, each with significant advantages, but also with daunting remaining challenges to reach the sensitivity needed to test the Majorana/inverted hierarchy hypothesis definitively. Given the high cost anticipated for such definitive tests, it is inevitable that a future down-selection among the competing approaches will have to be made. It is too early now to make such a down-selection, as some approaches are just getting under way and it is difficult to predict which approach will succeed most quickly in overcoming its challenges.

The Subcommittee thus provides here a set of science- and technology-driven criteria to guide the development of a coherent funding strategy for next-generation searches. These criteria take into account the significant uncertainties regarding the half-life sensitivities needed for a definitive test. On the one hand, there is a considerable range of effective neutrino masses $m_{\beta\beta}$ within the inverted hierarchy (see Figure 1.3), influenced by Majorana phases that are likely to remain unknown at the time down-select decisions will be needed, and to a lesser extent by existing measurement uncertainties on neutrino mixing parameters, which may be reduced by ongoing and near-future neutrino oscillation experiments. On the other hand, even for a fixed $m_{\beta\beta}$ target sensitivity, there is a significant range of relevant $0\nu\beta\beta$ half-life sensitivities for any given isotope, corresponding to the nuclear matrix elements (NMEs) calculated in different nuclear structure models.

The influence of the range of calculated NME values is illustrated in Fig. 3.1, adapted from [11]. The figure presents, for each of the isotopes under consideration, the $0\nu\beta\beta$ half-life corresponding to $m_{\beta\beta}$ = 15-19 meV and to each of the NME calculations currently considered viable. The range of $m_{\beta\beta}$ values reflected in each "error bar" in the figure corresponds to the bottom of the inverted hierarchy region for the best-fit value of the mixing parameter θ_{12}, while allowing other mixing parameters to vary within their $\pm 3\sigma$ ranges. It is clear from the figure that reasonable sensitivity within the inverted hierarchy region requires experiments capable of reaching half-life sensitivities of at least a few times 10^{27} years. The demands are somewhat more stringent for isotopes with relatively low Q-value and phase space factor, such as ^{76}Ge. But in nearly all cases, covering the full inverted hierarchy region even for the most conservative matrix elements requires eventually pushing the half-life sensitivity toward, or in some cases even beyond, 10^{28} years.

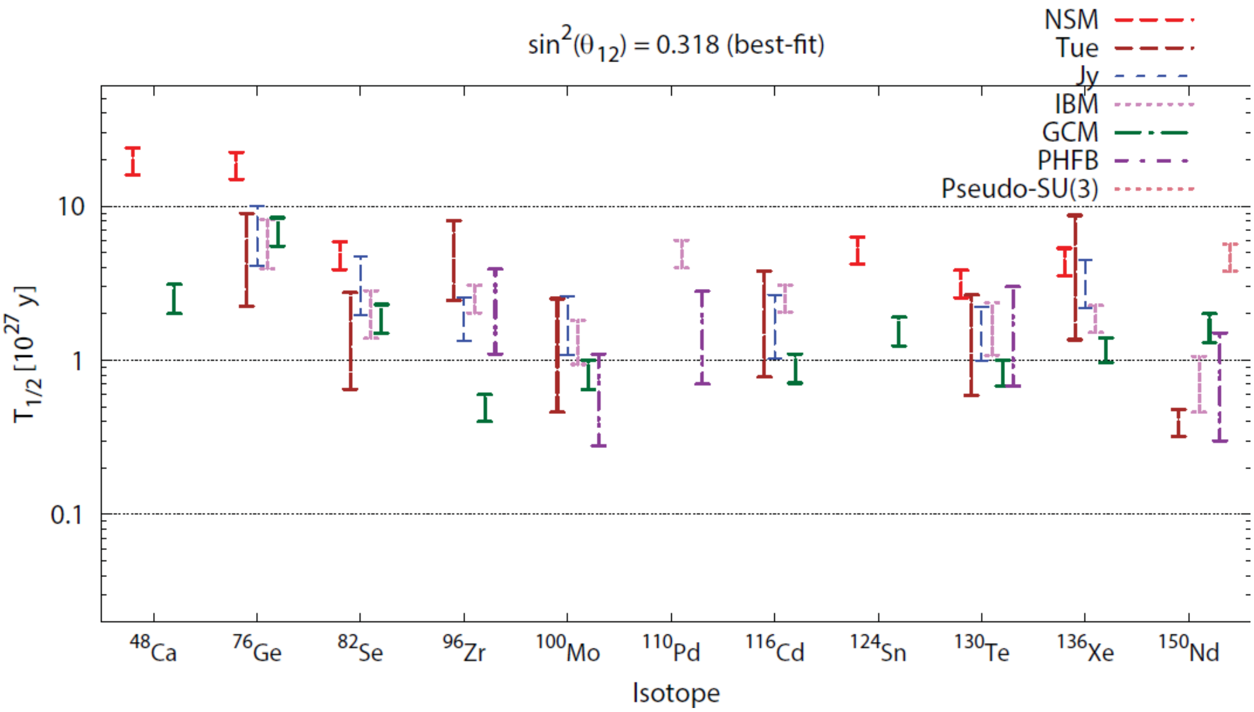

Figure 3.1. The figure, adapted from [11], plots for various relevant double beta decay isotopes and nuclear matrix element calculations (scaled to g_A=1.25) the $0\nu\beta\beta$ half-life corresponding to an effective neutrino mass at the bottom of the inverted hierarchy ($\sin^2\theta_{12}$=0.318, $\langle m_{\beta\beta}\rangle$=17.5 meV). The color-coding of the bars corresponds to the nuclear structure calculation legend in the upper right, while the height of each bar incorporates the range of values when other neutrino mixing parameters are allowed to vary within their $\pm 3\sigma$ experimental uncertainty ranges. The current best fit for θ_{12} (from the Particle Data Group) is $\sin^2\theta_{12}=0.307^{+0.024}_{-0.021}$, and this 1σ range would imply an additional ~±20% variation in $T_{1/2}$.

In the light of these uncertainties, the Subcommittee recommends an approach that combines the experimental reach to make a $0\nu\beta\beta$ discovery even under conservative assumptions of Majorana phases, neutrino mixing parameter fluctuations and NMEs, with a staged process that provides early opportunities to “get lucky” with regard to these parameters while building toward the ultimate experiment. The intermediate stage of such an approach may already be a large and costly project, accumulating sufficient isotope mass and counting time to probe and demonstrate understanding of backgrounds at sensitivity levels appropriate for the ultimate experiment. This philosophy is reflected in the following recommended guidelines:

1) **Discovery potential:** Favor approaches that have a credible path toward reaching 3σ sensitivity to $m_{\beta\beta}$=15 meV within 10 years of counting, assuming the lower NME values among viable nuclear structure model calculations. To achieve such conservative coverage of the inverted mass hierarchy region with our present knowledge of matrix elements, a half-life goal exceeding a few times 10^{27} years is necessary. Reaching such sensitivity is likely to require more than a tonne of isotopic material, with the detailed

mass requirement depending on both chosen isotope and achieved background level in the ROI.

2) **Staging:** It would be extremely challenging and expensive to reach the goal of criterion 1 in a single-shot upgrade from the current generation of experiments. There is substantial discovery potential corresponding to more favorable values of Majorana phases, neutrino mixing matrix elements and/or NMEs. Furthermore, background reductions and isotope purchases are most likely to be achieved in stages. Hence, it makes sense to support one or more intermediate stages along the maximum discovery potential path. For example, an intermediate goal of attaining 90% C.L. sensitivity to 20 meV in 5 years, with mid-range NME values, would provide both significant discovery potential and, if $0\nu\beta\beta$ decay is not convincingly discovered, an opportunity to demonstrate sufficient control of backgrounds to reach criterion 1 in a subsequent stage.

3) **Standard of proof:** Each next-generation experiment worldwide must be capable of providing, on its own, compelling evidence of the validity of a possible non-null signal. This requires clear plans to calibrate and demonstrate a detailed understanding of the detector performance, the backgrounds, and the analysis procedures. The barrier is higher in this regard for approaches where the background has structure underneath or adjacent to the $0\nu\beta\beta$ peak. Such proof may also benefit from the capability to remove or replace the isotope under study with unenriched material or different isotopes.

4) Continuing R&D: The demands on background reduction are so stringent that modest-scope demonstration projects for promising new approaches to background suppression or sensitivity enhancement should be pursued with high priority, in parallel with or in combination with ongoing $0\nu\beta\beta$ searches. Potentially high-impact R&D projects include scintillating bolometers, high-pressure gaseous TPCs (using ^{136}Xe or other relevant isotopes), techniques to tag the decay daughter nucleus, and possible methods to enrich significant quantities of isotopes with $0\nu\beta\beta$ Q-values above 3 MeV.

5) **International cooperation:** A discovery in any one isotope will beg confirmation by a different approach for a different isotope, and it would be undesirable to have to wait another generation for such confirmation. Given the likely cost of these experiments, it is then important to work with other countries and funding agencies to develop an international approach. It is desirable to ensure that next-generation approaches worldwide work on at least two different isotopes, with similar sensitivity goals.

6) **Timeliness:** It is desirable to push for results from at least the first stage of a next-generation effort on time scales competitive with other international double beta decay efforts and with independent experiments aiming to pin down the neutrino mass hierarchy.

The above guidelines are intentionally not prescriptive in recommending which of various relevant experimental features to optimize in order to attain the desired sensitivity. It is straightforward to list the highly desirable features of any next-generation double beta decay search:

- Very low, and preferably flat, background within the spectral region of interest, relative to the signal size anticipated at the half-life sensitivity goal;
- Good energy resolution with excellent energy calibration, to enhance a potential signal above backgrounds and to minimize the $2\nu\beta\beta$ tail underneath the $0\nu\beta\beta$ peak;
- Ability to scale the experimental approach to larger masses at realizable cost, as needed to maximize the discovery potential within the inverted hierarchy region;
- Tracking capability to enhance identification of $0\nu\beta\beta$ decay event topology;
- A favorable $0\nu\beta\beta$ Q-value to enhance the phase space factor and provide a region of interest above many of the gamma ray lines from U- and Th-chain contaminants;
- Ability to remove or replace the enriched isotope without affecting detector performance, in order to verify the reality of a possible non-null signal.

However, it is unlikely that any one approach will achieve all of these desirable features. It is best to support the approach that provides the combination of these features most likely to reach the desired sensitivity at a cost that can be funded on a competitive time schedule.

4.0 THEORETICAL CALCULATIONS

Theory of Neutrinoless Double Beta Decay

Double Beta Decay Mechanisms

The overall rate for $0^+ \rightarrow 0^+$ neutrinoless $\beta\beta$ decay for mechanisms in which the final state consists of the daughter nucleus and two outgoing electrons can be written

$$\omega \sim G^4_F \cos^4\theta_c \mathcal{F}(T_0) \,|\mathcal{M}|^2 \tag{11}$$

where G_F is the Fermi coupling; θ_c is the Cabibbo angle; $\mathcal{F}(T_0)$ is a phase space factor that, in the limit of large energy releases, varies as $\sim T_0^5$; T_0 is the kinetic energy carried by the outgoing electrons, in units of the electron mass; and $\mathcal{M}$ carries the nuclear/particle physics of whatever mechanism is being considered -- the nuclear transition amplitude and the parameters governing the source of lepton number violation. In most cases of interest, the nuclear and particle physics aspects of the problem can be factored into separate pieces, to good accuracy. Two examples discussed below are the cases when the neutrinos mediating the $\beta\beta$ decay are either much lighter or much heavier than typical nuclear scales.

The phase space factor $\mathcal{F}(T_0)$ is obtained by integrating over single electron energies and angles, and by summing over final-state spins. This is generally accomplished by treating the electrons as relativistic outgoing plane waves, then correcting the result to account for the effects of the nuclear Coulomb field, which enhances the electron wave functions near the nucleus. Because the weak interaction is point-like, the necessary correction factor is the probability of finding the electron at the nucleus, relative to the plane wave result. This Coulomb correction is typically taken from numerical solutions of the Dirac equation for the $1s_{1/2}$ state, solved for the specific nucleus of interest, using a finite nuclear charge distribution. It has been appreciated for many years that simple nonrelativistic Coulomb corrections are inadequate for all but the very lightest parent nuclei.

Light neutrino exchange: The simplest and most discussed mechanism mediating neutrinoless $\beta\beta$ decay involves the exchange of light active Majorana neutrinos, whose mass splittings and mixing angles are determined by oscillation experiments. We refer to this as the standard mechanism, and note that much of the discussion in this report is in the context of this mechanism. This mechanism is depicted in Fig. 4.1, at the level of the quarks within the nucleus. The exchanged neutrino includes all mass eigenstates that couple to the electron. The $\beta\beta$ decay amplitude thus involves a coherent sum over the mass eigenstates. This amplitude is embedded in the nucleus and evaluated in time-dependent perturbation theory, so that the virtual intermediate state includes the intermediate nucleus, as well as the electron and neutrino produced in the first β decay. The sum over neutrino momentum states dominates the propagator: effectively one can sum over nuclear states by closure. Details in the procedure involve approximations that account for the average excitation energy of the intermediate nucleus. One obtains in the end the transition probability

$$|\mathcal{M}|^2 = \frac{|\langle m\beta\beta\rangle|^2}{m_e^2}\ |M|^2. \tag{12}$$

The nuclear matrix element *M*, if the propagator is treated in the simplest way, without corrections for virtual nuclear excitations, has the form

$$M \sim -\langle 0_f^+ || \frac{1}{2}\sum_{i,j=1}^{A} \tau_+(i)\tau_+(j)\frac{1}{r_{ij}} ||0_i^+\rangle + g_A^2\langle 0_f^+ || \frac{1}{2}\sum_{i,j=1}^{A} \vec{\sigma}(i)\cdot\vec{\sigma}(j)\tau_+(i)\tau_+(j)\frac{1}{r_{ij}} ||0_i^+\rangle. \tag{13}$$

where g_A is the axial-vector coupling. Here we omit discussions of additional contributions that can contribute to the light neutrino exchange mechanism, such as those arising from lepton-number-violating left-right current interference terms or from mass terms where the couplings are right handed. The literature on such issues is extensive.

We will discuss the nuclear matrix elements, and also the approximations that lead to matrix elements of this form, later in this chapter, in order to focus here on the particle physics of the standard mechanism.

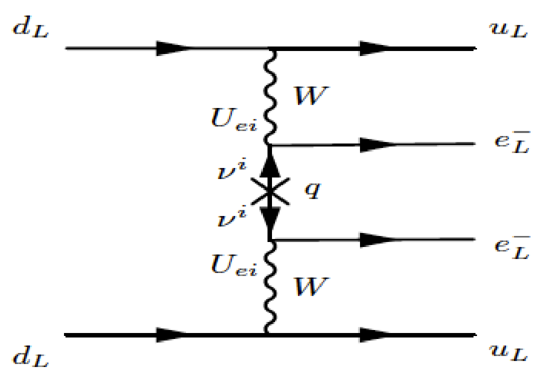

Figure 4.1: The quark-level "standard mechanism" contribution to neutrinoless $\beta\beta$ involving exchange of light Majorana neutrinos with standard-model weak couplings to the quarks.

For the case of *n* light neutrino generations and both Majorana and Dirac neutrino masses, the particle physics content of Fig. 4.1 can be expressed as the $\beta\beta$ decay Majorana mass, defined as

$$\langle m_{\beta\beta}\rangle = \sum_{i=1}^{2n} \lambda_i\ U_{ei}U_{ei}m_i \tag{14}$$

The mixing matrix elements and mass eigenstates for this case would be obtained from diagonalizing a $4n \times 4n$ mass matrix: the standard mechanism would correspond to a particularly simple form for this matrix that would generate three light Majorana neutrinos. When the matrix is diagonalized in the general case, one obtains $2n$ two-component eigenvectors with mass eigenvalues m_i. The coupling of the *i*th mass eigenstate to the electron is denoted by the mixing matrix element U_{ei}. The specific definition of the phase of the λ_i depends on conventions, but in a convention where in the limit of CP conservation the mixing matrix elements U_{ei} are real and the masses m_i are positive definite, would correspond to the CP eigenvalue of the *i*th mass eigenstate. Consequently the $\beta\beta$ decay mass includes interference terms that depend on the relative CP eigenvalues of the mass eigenstates. Many interesting limits can be considered. In the CP-conserving Dirac limit (that is, all Majorana terms in the mass matrix are set to zero), the mass eigenstates are pairwise degenerate and carry opposite CP. They cancel against one another in the $\beta\beta$ decay mass, so that $\langle m_{\beta\beta} \rangle = 0$. The pairwise degenerate two component spinors can be combined to form four-component Dirac spinors. A related limit is the pseudoDirac limit, in which the Majorana masses are not zero, but nevertheless small compared to the Dirac masses. In this case the eigenstates form into *n* doublets, and the $\beta\beta$ decay mass depends on the splitting within the doublets, not the doublet mass. Another interesting case is the Majorana limit, where the Dirac masses can be ignored. The mass matrix then takes on a block-diagonal form, corresponding to m_L and m_R discussed in the Science Introduction (which are now $n \times n$ matrices, where *n* is the number of neutrino generations). These blocks decouple, and there are two $\beta\beta$ decay masses generated by m_L and the U^L_{ei} (left-handed weak couplings) and m_R and the U^R_{ei} (right-handed couplings). The former is the standard mechanism: in this limit one can associate mass splittings and mixing amplitudes U^L_{ei} with those measured in oscillation experiments. For three light Majorana neutrinos one finds

$$
\begin{aligned}
|\langle m_{\beta\beta} \rangle| &\to \left|U^{L2}_{e1}\, m_1 + U^{L2}_{e2}\, e^{2i\Phi_1} m_2 + U^{L2}_{e3}\, e^{2i(\Phi_2-\delta)} m_3\right| \\
&= \left|c^2_{12}c^2_{13}m_1 + s^2_{12}c^2_{13}e^{2i\phi_1}m_2 + s^2_{13}e^{2i(\phi_2-\delta)}m_3\right|, \qquad (15)
\end{aligned}
$$

where $c_{12} \equiv \cos\theta_{12}$ etc. (see the Science Introduction). As noted there, all of the mixing angles are known from studies of neutrino oscillations, as are two mass differences $\delta m_{21} \equiv m_2^2 - m_1^2$ and $\delta m_{31} = m_3^2 - m_1^2$ (the latter up to a sign). The CP phases ϕ_1 and $\phi_2 - \delta$ are so far unconstrained experimentally.

This expression can be further simplified if we make assumptions about the pattern of neutrino masses. If the hierarchy is normal with $m_1 \sim 0$, the mass becomes

$$
\left|\langle m_{\beta\beta} \rangle\right|_{NH} \to \left|\sqrt{\delta m^2_{21}}s^2_{12}c^2_{13} + \sqrt{|\delta m^2_{31}|}s^2_{13}e^{i\phi}\right| \sim \left|4.8 + 1.2e^{i\phi}\right| meV \qquad (16)
$$

where ϕ is an unknown angle. Truly heroic next-to-next generation experiments would be needed to reach this level. If the hierarchy is inverted with $m_3 \sim 0$,

$$
\left|\langle m_{\beta\beta} \rangle\right|_{IH} \to \sqrt{\delta m^2_{31}}c^2_{13}\sqrt{1 - sin^2 2\theta_{12} sin^2\phi} \sim 34 \pm 15 \text{ meV} \qquad (17)
$$

This range for $\left|\langle m_{\beta\beta} \rangle\right|_{IH}$ establishes a target for next-generation experiments of lifetimes of ~ (few-10) × 10^{27} y. Finally, the quasi-degenerate case - the scale of the neutrino masses is large compared to the neutrino mass splittings – yields

$$
\left|\langle m_{\beta\beta} \rangle\right|_{degenerate} \to m_0 \left|c^2_{12}c^2_{13}e^{i\phi} + s^2_{12}c^2_{13}e^{i\phi\prime} + s^2_{13}\right| \sim m_0\, (0.68 \pm 0.32) \qquad (18)
$$

where the mass scale m_0 is constrained by direct neutrino mass measurements. Currently the most stringent of these comes from cosmology, where various analyses yield $\sum_i m_i \lesssim$ 200-600 meV. Thus conservatively, $m_0 \lesssim 200$ meV. If one instead relies only on laboratory limits of the absolute scale of neutrino mass, the best existing tritium beta decay results allow $m_0 \lesssim 2200$ meV. The goal of the ongoing tritium beta decay experiment KATRIN is to reduce this bound to ~ 200 meV. The quasi-degenerate scenario allows neutrinoless $\beta\beta$ decay to occur at rates consistent with current half life upper bounds of ~few × 10^{25}y. We stress that these values for m_0 are deduced under the assumption that the light neutrinos are Majorana: in the general case, we would not know how to relate kinematic measurements of neutrino mass to the mass relevant to neutrinoless $\beta\beta$ decay.

Heavy neutrino exchange: In treatment of the neutrino exchange mechanism for light Majorana neutrinos (see Fig. 4.1), the neutrino propagator was effectively approximated by

$$U_{ei}^L \frac{m_i}{p^2 + m_i^2} U_{ei}^L \sim U_{ei}^L \frac{m_i}{p^2} U_{ei}^L$$

so that the amplitude is proportional to the neutrino mass, and the nucleon-nucleon interaction falls off as $1/ r_{ij}$. If the exchange involves not a light neutrino, but a heavy one (relative to the nuclear momentum scale ~100 MeV), then

$$U_{eH} \frac{m_H}{p^2 + m_H^2} U_{eH} \sim U_{eH} \frac{1}{m_H} U_{eH}$$

so that the amplitude becomes inversely proportional to the heavy neutrino mass, and contact in nature. Consequently neutrinoless $\beta\beta$ decay not only places upper bounds on the masses of light Majorana neutrinos but also lower bounds on the masses of heavy Majorana neutrinos. Calculations of rates for the heavy-neutrino exchange mechanism are uncertain because they depend on poorly understood short-range hadronic physics, but current half life limits of ~ 10^{25} y require

$$m_H \gtrsim 3 \times 10^4 \text{ TeV } U_{eH}^2$$

Section1 describes a scenario, the seesaw model, where such heavy neutrinos arise in combination with the light neutrinos.

Alternative mechanisms: The exchange of a heavy neutrino is an example of an alternative mechanism for neutrinoless $\beta\beta$ decay, many of which have been suggested over the years. As in the example just described, they typically involve the exchange of a Majorana particle other than a light neutrino. Such mechanisms arise in left-right symmetric models, in supersymmetric models with R-parity violation, and in the Higgs triplet model. As an example, Fig. 4.2 shows one contribution to neutrinoless $\beta\beta$ decay arising within the left-right symmetric model. For a comprehensive discussion of the phenomenology we refer the reader to [12]. As we noted in the discussion of heavy Majorana neutrino exchange, the short-range nature of such exchanges inherently leads to uncertainties in the nuclear physics: there exist very few experimental probes of internucleon physics at high momentum scales, to guide theory.

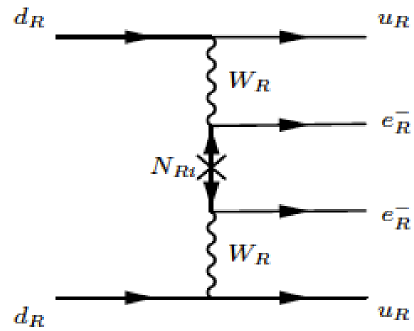

Figure 4.2: A quark-level "alternative mechanism" contribution to neutrinoless $\beta\beta$ within the left-right symmetric model, involving both heavy Majorana neutrino exchange and new right-handed weak gauge bosons W_R.

As discussed in this report, the experimental goal of probing light neutrino masses at the bottom of the inverted hierarchy band requires a sensitivity to neutrinoless $\beta\beta$ decay half lives of (few-10) $\times\, 10^{27}$y. This target implies considerable discovery potential beyond the standard light-neutrino-exchange mechanism. That is, even if the light neutrinos have a normal hierarchy with $m_1 \sim 0$, it is still quite possible that a nonzero rate will be obtained in experiments, because some other mechanism mediates the lepton-number-violating decay. In fact, observable signals are predicted in a number of well motivated models of short-distance lepton number violation with particles in the multi-TeV range. The plausibility of alternative mechanisms involving new TeV-scale particles provides additional motivation for high-sensitivity searches for neutrinoless $\beta\beta$ decay.

If a nonzero rate is observed in future experiments, there will be keen interest in identifying the underlying mechanism. There are a few observables that could be exploited, such as the angular correlation between the emitted electrons and the single-electron spectrum, provided experiments capable of tracking the final-state electrons are available. Such a discovery would generate intense interest in searches for other lepton-number- and family-number violating processes, such as muon-to-electron conversion in nuclei. It would also intensify efforts at the LHC and elsewhere to search for and identify new heavy particles that might mediate lepton number violation.

Nuclear matrix elements

In recent years we have witnessed a renaissance of nuclear structure theory which has been driven by progress in solving the nuclear many-body problem by ab-initio methods like effective field theory (EFT) and nuclear lattice EFT, Green's Function Monte Carlo (GFMC), no-core shell model, and coupled-cluster approaches and by deriving NN and 3N interactions systematically on the basis of the symmetries of QCD. Some of these approaches hold the promise to describe nuclear properties including a consistent estimate of the theoretical uncertainties. However, despite the exciting advances, these methods cannot yet be applied to the complex heavy nuclei of experimental interest in $\beta\beta$ decay. Hence $\beta\beta$ decay matrix element evaluations must be taken from models like the configuration-mixed shell model, the QRPA, and others that employ truncated bases and depend on empirical methods to determine the effective interaction and effective operators. It is difficult to assign uncertainties to the resulting matrix elements because the methods are not based on systematic approximation schemes, and because ββ matrix elements are inherently sensitive to details of the wave functions: the $0^+ \rightarrow 0^+$ ground state transitions of interest are highly exclusive, typically exhausting only a fraction of one percent of the double Gamow-Teller sum rule, 6(N-Z)(N-Z+1), for the dominant operator. Furthermore, certain assumptions that are common among competing calculations could be a source of systematic uncertainty. However, as we will outline below, there are opportunities to improve the modeling and to cross-check some of the assumptions now made in the models.

There are very few experimental tests of transitions that change nuclear charge by two units. Suggestions, for example, that double pion charge exchange might be used to test $\beta\beta$ decay transition matrix elements were rather quickly debunked, due to the very different nature of the operators and momentum transfers. Perhaps the most helpful experimental constraint is the two-neutrino $\beta\beta$ decay rate, which is known for almost all nuclear cases of experimental interest. Yet this is of limited value: while certain aspects like the effect of correlations on two-neutrino and neutrinoless matrix elements are similar , there are also fundamental differences between these two processes, for example caused by the vastly different momentum transfers involved. In particular, it is not reasonable to approximate the intermediate states in neutrinoless $\beta\beta$ decay matrix elements by the sum over 1^+ states that saturate the dominant two-neutrino spin matrix element.

In deriving the form of the $\beta\beta$ decay rate, most treatments of $0^+ \rightarrow 0^+$ ground-state-to-ground-state transitions make a set of common assumptions:

- The weak currents are evaluated in the allowed limit, which eliminates the $(v/c)^2$ effects of the parity-changing axial-charge and vector three-current operators. Retained are the double Fermi and Gamow-Teller operators. Clearly there are no interference terms for $0^+ \rightarrow 0^+$ transitions. The double Fermi matrix element, in the case of two-neutrino $\beta\beta$ decay, acts on the initial state to produce the double isobaric analog state, and thus contributes to the ground-state transition only through isospin mixing corrections. This matrix element is problematic in calculations that violate isospin artificially, e.g., through basis truncation.

- As described previously, the electron wave functions are treated as relativistic plane waves, then corrected to account for the strong Coulomb distortions in the nuclear field.

- The amplitude is evaluated in time-dependent perturbation theory. In the more difficult case of two-neutrino $\beta\beta$ decay, there exist modern techniques for performing the inverse-energy-weighted sum over intermediate nuclear states *n*
$$\sum_n \frac{|1_n^+\rangle\langle 1_n^+|}{E_i - \epsilon_e - \epsilon_\nu - E_n}$$
where ϵ_e and ϵ_ν are the energies of the leptons emitted in the first beta decay (usually approximated by an average value), though these methods are not always employed. In the case of neutrinoless $\beta\beta$ decay, as noted earlier, an integration over virtual

neutrino momenta is done, taking into account the average effects of the accompanying excited intermediate nucleus.

These approximation have been checked in certain cases, e.g., contributions of first-forbidden nuclear operators have been estimated. Even with the simplifying assumptions above, a significant level of complexity arises in calculations that treat general lepton-number-violating effective interactions -- with left- (Fig. 4.1) and right-handed (Fig. 4.2) mass terms, left-right current interference terms, and possible non-standard interactions.

Shell Model and QRPA Matrix Elements: To evaluate the resulting matrix elements, nuclear wave functions must be generated. Several approaches have been pursued. The nuclear shell model (NSM) has been utilized extensively. It is a microscopic model, with interactions generally taken from realistic potentials for which ladder sums have been evaluated to all orders, augmented by phenomenological corrections of the potential that are adjusted to reproduce spectra and other nuclear properties. Shell model wave functions have good quantum numbers for particle number, isospin and angular momentum. An important strength of the NSM is its ability to account for the details of spectra and transitions near the ground state, provided appropriately renormalized operators are being used. Hence one is more confident that the basic degrees of freedom and the relevant many-nucleon correlations important to ground state properties of both the parent and daughter nuclei have been included. Several of the experimentally important $\beta\beta$decay isotopes, such as ^{76}Ge, ^{82}Se, and ^{100}Mo, reside in regions of the (*N*,Z) plane where shapes change, e.g., spherical to deformed. Ground states can evolve rapidly in these regions, and microscopic models must incorporate the necessary degrees of freedom if they are to be regarded as realistic. For example, in the Ge isotopes, shapes changes are associated with neutron occupation of the $1g_{9/2}$ shell. As neutrons begin to fill this shell, a strong attractive interaction arises between the neutrons and any protons occupying the $1f_{5/2}$ shell (both orbitals have a single node). Protons that otherwise would occupy a spherical closed $2p_{3/2}$ shell, are instead excited: three low-lying 0^+ bands are associated with the 0particle-0hole (spherical), 2p2h, and 4p4h excitations out of the $2p_{3/2}$ shell into the $1f_{5/2}$ shell. The NSM does a good job in reproducing this polarization, predicting band energies and *B(E*2) values, reproducing level crossing that mark shape changes in this region, and reproducing the rather dramatic changes in proton and neutron spectroscopic factors that have been mapped out experimentally as a function of *N*. NSM diagonalization methods, such as the Lanczos method, can be adapted to do the sum over intermediate nuclear states by moments expansions, as an explicit enumeration of such states would be infeasible.

The NSM also has significant shortcomings. Although NSM methods, in terms of tractable basis dimensions, have advanced by five orders of magnitude since the first serious applications of the method to $\beta\beta$ decay 30 years ago, the method is still limited numerically. Typically calculations are done within a single major shell, e.g., the $1g_{7/2}2d_{5/2}2d_{3/2}3s_{1/2}1h_{11/2}$ model space between magic shells at neutron/proton numbers 50 and 82 for the nuclei ^{128,130}Te and ^{136}Xe, and all possible configurations of the valence particles in this model space are taken into account. However, this model space omits the $1g_{9/2}$ and $1h_{9/2}$ spin-partners of the $1g_{7/2}$ and

$1h_{11/2}$ orbits. The Gamow-Teller sum rule important for both two-neutrino and neutrinoless $\beta\beta$ decay matrix elements is thus violated. Similarly, neutrinoless $\beta\beta$ operators include higher multipoles that can reach outside this model space.

The other method most frequently used in $\beta\beta$ decay is the quasiparticle random phase approximation (QRPA) or renormalized QRPA (RQRPA). The interactions used, while sometimes based on phase-shift-constrained potentials, generally contain adjustable parameters. Frequently in $\beta\beta$ decay applications, particle-particle channel interactions are scaled by a parameter g_{pp} ,which is then tuned to reproduce the experimental value of the two-neutrino matrix element. This adjustment is often quite delicate: small changes in g_{pp} can lead to large changes in matrix elements. In fact, if the renormalization of g_{pp} required to match experiment is too large, it can induce an instability associated with the breakdown of the small-amplitude-vibrations assumption underlying QRPA. Particle number, isospin, and angular momentum are conserved only on average. The included excitations may extend over several shells, addressing a short-coming of the NSM, but within each shell only selected configurations are used. For example, in applications to ^{76}Ge, configurations analogous to the 4p4h excitations discussed above are absent, even though such configurations play an important role in ground-state structure. The method is not well suited to regions of rapid shape change. Numerically QRPA basis sizes do not scale with mass number as rapidly as those of the SM, so the method can be used even in the heaviest nuclei.

Other methods are in use -- the interacting boson model, where basis truncations are implemented by retaining only S and D nucleon pairs; projected Hartree-Fock-Bogoliubov methods with schematic pairing+quadrupole interactions; generator coordinate methods with projection on good angular momentum and particle number which made possible the first application to the strongly deformed nucleus ^{150}Nd – but the bulk of effort over the years has been invested in the NSM and QRPA approaches.

Phenomenological adjustments: Certain obvious shortcomings of these methods have been addressed through ad hoc adjustments of matrix elements. NSM wave functions are embedded in low-momentum Hilbert spaces, while the *NN* interaction is repulsive and very strong at distances $\lesssim$0.5fm, capable of causing scattering to states far outside the NSM Hilbert space. The NSM wave function is not meant to represent the true wave function $|\Psi\rangle$ but rather the projection of the true wave function onto a low-momentum space, $P|\ \Psi\rangle$, which has a nontrivial normalization < 1, as all high-momentum components are missing. Consequently, just as one obtains the correct projection $P|\ \Psi\rangle$ only if the correct effective interaction is employed in the NSM, one obtains correct matrix elements only if the proper effective operators are used between the NSM wave functions $P|\ \Psi\rangle$. It is not feasible to identify these effective operators from first principles, as this is equivalent to exactly solving the many-body problem. Instead, phenomenological corrections are used. Two are extensively discussed in the $\beta\beta$ decay literature, g_A^{eff} and correlation functions.

It has been known for some time from studies of single β decay and of Gamow-Teller distributions obtained from charge-exchange data that both NSM and QRPA transition strengths systematically overestimate Gamow-Teller transition strengths. This is not surprising, as NSM and QRPA practitioners typically use their wave functions as if they were $|\Psi\rangle$, with unit normalization, instead of restricted wave functions $P|\ \Psi\rangle$. To correct for the discrepancies, the bare Gamow-Teller operator $g_A\vec{\sigma}(i)\tau_\pm(i)$ is replaced by an effective one $g_A^{eff}\vec{\sigma}(i)\tau_\pm(i)$ with the effective axial coupling g_A^{eff} then adjusted to reproduce the data. The approach is very successful numerically in shell model applications, though the required normalization depends on the model space. In the $2s1d$ and $2p1f$ shells, where there are no missing spin partners, g_A^{eff}~$0.79g_A$ and ~$0.74g_A$ respectively. In the $2p_{3/2}1f_{5/2}2p_{1/2}1g_{9/2}$ shell appropriate for calculations of ^{76}Ge or ^{82}Se, the exclusion of some spin orbit partners leads to an underestimation of tensor correlations and consequently g_A^{eff}~$0.60g_A$. A definition of g_A^{eff} in QRPA calculations is aggrevated by the limited consideration of configurations within the model space.

The single β decay values for g_A^{eff} are generally used in both two-neutrino and neutrinoless ββ decay calculations. In the case of two-neutrino ββ decay, with its inverse-energy-weight sum over intermediate nuclear states, this procedure can be justified by arguing that the important β decay transitions are low in energy, similar to the transitions from which g_A^{eff} is derived. The correction, of course, has a significant effect on predictions: ββ decay rates depend on $(g_A^{eff})^4$. Using this value shell model calculations describe the experimental two-neutrino ββ decay matrix element quite well, giving further validity to this renormalization approach in two-neutrino ββ decay. However, its justification for neutrinoless *ββ* decay is questionable as the renormalization of g_A should depend on the momentum transfer, which is vastly different in the two ββ decay modes. Furthermore, the Gamow-Teller transitions for which the renormalization has been established do not dominate the neutrinoless ββ decay amplitude, while the other contributing multipoles are not known to require any renormalization.

Correlation functions are another issue. Model spaces restricted to low-momentum spaces lack the degrees of freedom necessary to resolve short-distance behavior. Thus the "hole" in the two-nucleon relative wave function that would exist in a complete nuclear calculation is absent in the softer wave function $P|\ \Psi\rangle$. The idea of a correlation function is that a reasonable phenomenological approximation to the full wave function is

$$|\Psi\rangle \sim \left[\prod_{i<j} F_{\mathrm{P}}(r_{ij})\right]\ P|\ \Psi\rangle$$

One inserts by hand the most important omitted high-momentum components in the wave function by modifying all two-nucleon relative-pair wave functions. Correlation functions have been used in double ββ decay calculations for a very long time, and there has been some debate about which correlation function is best. The subject has progressed recently by estimating the short-range correlations on the basis of the Unitary Correlation Operator Method (UCOM), leading to significantly smaller corrections of order 10%.

Matrix element estimates: Despite the potential pitfalls, it is difficult to identify any means of estimating neutrinoless ββ decay matrix element uncertainties other than through a comparison of competing calculations. In part because the NSM and QRPA methods have been employed by many investigator over decades - this has helped develop some consensus on appropriate spaces and interactions - we focus on a comparison of these methods here, for the standard mechanism neutrinoless ββ matrix element. We stress again the primary difference between the models: the shell model uses a smaller set of single particle orbitals than QRPA, but then considers all configurations spanned by these orbitals, while in the QRPA only a a selected set of configurations is being used. Indicative studies have shown that increasing the set of single particle orbitals in NSM calculations has the tendency to increase the neutrinoless ββ decay matrix element, while the inclusion of correlations neglected in QRPA studies reduces the matrix element. Consequently, one might argue that the shell model and QRPA matrix elements are lower and upper limits, respectively. Additional uncertainties are connected with the renormalization of g_A and the effects of short-range correlations and two-body currents.

Transition	Method	$G^{0\nu}(10^{-14}/y)$	$M^{0\nu}$	$\left[\frac{\langle m_{\beta\beta}\rangle}{20\text{ meV}}\right]^2 \left[\frac{g_A^{eff}}{g_A}\right]^4 \tau_{1/2}^{0\nu}(10^{27}y)$
$^{48}Ca \rightarrow {}^{48}Ti$	SM-UCOM	2.481	0.85	14.0
$^{76}Ge \rightarrow {}^{76}Se$	SM-UCOM QRPA-UCOM	0.236	2.81 4.19-5.36	13.5 3.71-6.08
$^{82}Se \rightarrow {}^{82}Kr$	SM-UCOM QRPA-UCOM	1.016	2.64 2.94-3.72	3.55 1.79-2.87
$^{130}Te \rightarrow {}^{130}Xe$	SM-UCOM QRPA-UCOM	1.422	2.65 3.48-4.22	2.52 0.99-1.46
$^{136}Xe \rightarrow {}^{136}Ba$	SM-UCOM QRPA-UCOM	1.458	2.19 2.38-2.80	3.60 2.20-3.05

Table 4.1: Scaled neutrinoless $\beta\beta$ decay half-lives assuming $\langle m_{\beta\beta}\rangle$ ~ 20 meV, close to the lower boundary of the inverted hirarchy band, as a function of the quenching factor g_A^{eff}/g_A. See text for references and further explanation.

To illustrate the uncertainties associated with nuclear models we write the neutrinoless ββ decay half-life as

$$\left[\tau_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}\left(g_A^{eff}\right)^4 \left|M_{0\nu}\right|^2 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$

and display in Table 4.1 results for the shell model and QRPA. The calculations listed in Table 4.1 employ the same prescription for short-range correlations, the unitary correlation operator method [13], removing differences associated with this correction. We have also made the dependence on g_A^{eff} explicit, given the concern that values taken from studies of low-energy β decay BGT values may significantly overestimate the degree of quenching for neutrinoless $\beta\beta$ decay [14]. The ratio $g_A^{\rm eff}/g_A$, where $g_A \sim 1.269$ is the free nucleon value, is commonly referred to as the quenching factor. The phase-space factors in Table 4.1 come from [15], using the normalizations of [16], while the matrix elements come from the compilation of [11]. Half-lives are given as a function of $|\langle m_{\beta\beta}\rangle|^2$, normalized to the value of 20 meV characteristic of the lower bound of the inverted hierarchy band. The calculated half-lives in Table 4.1 are consistent with those in Fig. 3.1, where a lower $\langle m_{\beta\beta}\rangle$ value was used.

Table 4.1 indicates the range of uncertainties associated with the use of the two most frequently used models, the shell model and QRPA, and provides target half-lives, subject to the prescription used to determining the quenching appropriate to neutrinoless $\beta\beta$ decay -- a topic that we feel requires further study. For most targets, covering the hierarchy band requires reaching half-life limits of a (few-10)$\times 10^{27}$ y. Typically there is a factor-of-three spread between the NSM and QRPA half-life predictions.

As discussed recently in [16], if one converts the half lives into sensitivities per ton of enriched isotope, the parameter generally used in experimental comparisons, the differences between isotopes in Table 1 is reduced. In the QRPA calculations, which include spin partners, a uniform $g_A^{eff} \sim 1$ is typically used [4] (based, as we have stressed, on β decay comparisons that may not be as relevant to neutrinoless $\beta\beta$ decay). Consequently, for isotopic mass number *A*, the figure of merit one finds for the QRPA calculations is

$$\left[\frac{\langle m_{\beta\beta}\rangle}{20\ \mathrm{meV}}\right]^2 \left[\frac{A}{100}\right] \tau^{0_\nu}_{1/2}(10^{27} y) = \begin{cases} (7.32 - 11.97) & {}^{76}\mathrm{Ge} \\ (3.81 - 6.10) & {}^{82}\mathrm{Se} \\ (3.35 - 4.93) & {}^{130}\mathrm{Te} \\ (7.77 - 10.75) & {}^{136}\mathrm{Xe} \end{cases}$$

Theory Outlook: There are a number of possible improvements that could be made in theory. There is certainly an asymmetry between the effort typically invested in effective interactions, which are frequently derived from realistic bare interactions and then tuned to reproduce a large body of spectroscopic data, versus that invested in effective operators. This of course reflects the absence of any measurements that directly constrain neutrinoless $\beta\beta$ decay matrix elements. However, effective operator theory can be rather rigorously formulated for the NSM, and despite the absence of data, one could envision numerical experiments to test some of the assumptions currently being made. These tests could be performed in very light systems where $\beta\beta$ decay does not occur, but where nevertheless analogous ground-state transition matrix elements could be explored. By comparing against the quasi-exact methods available for such nuclei, one could determine the needed quenching factors for simple SM spaces, to determine whether the notion of a common g_A^{eff} for single β , two-neutrino $\beta\beta$ decay, and neutrinoless $\beta\beta$ decay is reasonable. Similarly, the naive treatments of correlation functions -- usually a single schematic correlation function is applied to all relative-coordinate states - could be vastly improved, given the extensive body of work on variational methods in light nuclei (where correlation functions carrying multiple quantum labels have been carefully tuned to help in the minimization procedure).

Another shortcoming, given that the spread among theoretical calculations is commonly adopted as a measure of theoretical uncertainties, is that there is no procedure within the community to systematically evaluate theory. No consensus has arisen as to what constitutes a reasonable calculation - what criteria should be met for a calculation to be accepted as valid. This refers not only to technical aspects of calculations, but also to ancillary work that should be carried out to test the quality of calculations, including level spectra, B(E2) values, and spectroscopic factors. Without protocols for determining which calculations are technically valid, adequately vetted against experimental data, and otherwise state-of-the-art - thereby eliminating calculations that are dated or poorly documented - the spread among theory calculations will continue to widen. Consequently so will the estimate of errors. In lattice QCD the community has developed criteria for evaluating calculations - has the stability of the result to changes in lattice size or lattice spacing been demonstrated, etc? One could envision better organization among double beta decay theorists to develop similar criteria to establish the quality of calculations. This could in turn encourage more focus on some of the less tested assumptions in $\beta\beta$ decay calculations. Continued support from community theory organizations like the INT, which has hosted several programs that delved into double beta decay, could be helpful in promoting the needed organization. As a first step an initiating workshop is planned at the Extreme Matter Institute, an interdisciplinary Topical Center in Darmstadt, for later this year.

The subcommittee recommends establishing a theory task force that aims at:

1.) developing criteria to establish and rank the quality of existing and future calculations,
2.) identifying methods to constrain the less tested assumptions in existing approaches.

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APPENDIX A: Charge to NSAC

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

December 5, 2013

Dr. Donald Geesaman
Chair, DOE/NSF Nuclear Science Advisory Committee
Argonne National Laboratory
9800 South Cass Avenue
Argonne, Illinois 60439

Dear Dr. Geesaman:

This letter is to request that the DOE/NSF Nuclear Science Advisory Committee (NSAC) form a Subcommittee to provide guidance to the DOE and NSF regarding an effective strategy for implementing a possible second generation U.S. experiment on neutrino-less double beta decay (NLDBD) capable of reaching the sensitivity necessary to determine whether the nature of the neutrino is Majorana or Dirac. While the Office of Nuclear Physics is the Office of Science steward for NLDBD, this scientific question is of broad interest to both the Nuclear Science and High Energy Physics communities, and NSAC should solicit input from the High Energy Physics Advisory Panel (HEPAP) as well as the nuclear science community in formulating the membership of this Subcommittee.

As you may know, in 2005 the Neutrino Scientific Assessment Group (NuSAG) jointly established by NSAC and HEPAP provided recommendations for a phased program of sensitive searches for NLDBD. Specifically, it recommended 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 ($m_{\beta\beta} > 100$ 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 ($m_{\beta\beta} > 10{-}20$ meV) with a single experiment."

Consistent with this recommendation, a number of first-phase experiments exploring complementary approaches were undertaken with support from the DOE Nuclear Physics and High Energy Physics Offices and the NSF Particle Astrophysics Program. Early results from these experiments are or will be available in the foreseeable future.

2

The NSAC Subcommittee is requested, in the context of ongoing and planned U.S. efforts as well as international competitiveness, to assess:

- The scientific merit of pursuing a second-generation NLDBD experiment;
- The status of ongoing and planned first phase NLDBD experiments toward achieving their goals, including major remaining challenges;
- The science-driven down-select criteria for arriving at the most promising approach to a second generation experiment, including a sensitivity goal that, at a high level of confidence, based on present understanding, would be expected to answer the question of the Majorana vs. Dirac nature of neutrinos for the inverted mass hierarchy scenario when combined with the results from other experiments that aim at establishing the hierarchy and masses of the three known neutrino flavors.
- Status and expected progress in theoretical calculations that are needed to determine the sensitivity limits that can ultimately be reached in NLDBD experiments.

We expect that this panel will be a standing Subcommittee of NSAC, constituted for an initial period of two years and request that the Subcommittee submit its first report to the Office of Science and NSF by the end of April 2014. Subsequent reports to assess annual progress and the most promising candidate approaches capable of achieving necessary down select criteria should follow.

We are aware that this charge represents an additional burden on your time. However, the involvement of the research community is essential to inform the Agencies' decisions regarding investments in this potentially transformative scientific endeavor.

Sincerely,

Patricia M. Dehmer
Acting Director
Office of Science

F. Fleming Crim
Assistant Director
Directorate for Mathematical and Physical Sciences

cc: Professor Andrew Lankford
Chair, DOE/NSF HEPAP

APPENDIX B: Subcommittee Membership

NSAC NLDBD Subcommittee Membership

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APPENDIX C: Meeting Agendas

Agenda
NLDBD Meeting, 2/24-25/2014

Monday Feb. 24

8:30 am	Executive Session	60 min
9:30 am	CUORE	45 min
10:15 am	Coffee Break	
10:30 am	Discussion	30 min
11:00 am	Majorana Demonstrator	30 min
11:30 am	Discussion	15 min
11:45 pm	GERDA	30 min
12:15 pm	Discussion	15 min
12:30 pm	Working lunch for Subcommittee	60 min
1:30 pm	Large Ge Experiment (GERDA/Majorana)	15 min
1:45 pm	Discussion	15 min
2:00 pm	EXO/NEXO	45 min
2:45 pm	Discussion	30 min
3:15 pm	Coffee Break	
3:45 pm	NEXT	45 min
4:30 pm	Discussion	30 min
5:00 pm	KamLAND-Zen	45 min
5:45 pm	Discussion	30 min

Tuesday Feb. 25

8:30 am	SuperNEMO	45 min
9:15 am	Discussion	30 min
9:45 am	SNO+	45 min
10:30 am	Coffee Break	
10:45 am	Discussion	30 min
11:15 am	LUCIFER	30 min
11:45 am	Discussion	15 min
12:00 pm	Working Lunch	60 min
1:00 pm	Supplemental discussion/questions for the collaborations	60 min
2:00 pm	Nuclear Theory (P. Vogel)	45 min
2:45 pm	Discussion	15 min
3:00 pm	Coffee Break	15 min
3:15 pm	Particle Theory (A. de Gouvea)	45 min
4:00 pm	Discussion	15 min
4:15 pm	Executive session	105 min
6:00 pm	Adjourn	

Agenda
NLDBD Meeting, 3/7-8/2014

Friday Mar. 7

9am-12pm	Discussion of Science Overview Section	180 min
12:00 pm	Working lunch	60 min
1pm-3pm	Discussion of Current Project Section	120 min
3pm-6pm	Discussion of Criteria/Goals Section	180 min

Saturday Mar. 8

9-10am	Discussion of Future Projects Section	60 min
10am-12pm	Discussion of Criteria/Goals Cont'd	120 min
12pm	Working Lunch	60 min
1pm-3pm	Discussion of Theory Section	120 min
3-5pm	Wrap up remaining issues	120 min