

Neutrinoless double beta decay

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Study of the neutrinoless double beta decay and searches for the manifestation of the neutrino mass in ordinary beta decay are the main sources of information about the absolute neutrino mass scale, and the only practical source of information about the charge conjugation properties of the neutrinos. Thus, these studies have a unique role in the plans for better understanding of the whole fast expanding field of neutrino physics.

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INTRODUCTION

Despite the recent triumphs of neutrino physics, several fundamental questions remain to be answered to advance the field itself and its impact in general on the whole particle and nuclear physics, as well as astrophysics and cosmology. The studies of neutrinoless double beta decay and end-point anomalies in beta decay, in particular, are essential and unique in their potential to answer the first two of them and plays an important and equally unique role in the remaining ones:

- Are neutrinos their own anti-particles?
- What are the masses of the neutrinos?
- Do neutrinos violate the symmetry CP?
- Are neutrinos the key to the understanding of the matter-antimatter asymmetry of the Universe?
- What do neutrinos have to tell us about the intriguing proposals for new models of physics?

The present report is structured as follows: In this introductory section we provide the “Goal of the field” statement first in which we stress the fundamental importance of the distinction between the Dirac and Majorana neutrinos, and its relation to the existence of the neutrinoless double beta decay ($0\nu\beta\beta$).

In the next section “ $0\nu\beta\beta$ and β decays and Oscillations” we briefly summarize the status of the neutrino oscillation studies and the values of the corresponding mass differences Δm_{ij}^2 , and mixing angles. Next we discuss the relations and constraints provided by the results of oscillation studies and the neutrino mass parameters extracted from $0\nu\beta\beta$ and β decay experiments. We also show how this research fits into the larger picture of the whole neutrino field described in the other reports of this APS study.

For $0\nu\beta\beta$, the process that is observable only in heavy nuclei, the understanding of the nuclear structure plays an essential role in extracting the neutrino effective mass from the observed rate. We discuss the nuclear structure aspects in the section titled “Nuclear Structure Issues” and comment on the existing uncertainties as well as on the prospects of reducing them.

The rest of the report deals with the experiments. In the section titled “Experimental Prospects for $\beta\beta$ ” we summarize the situation in experimental $\beta\beta$ and briefly describe the numerous proposals.

Throughout the report we often use results reported in earlier reviews by some of us [1–4].

At present, we do not know the absolute scale of the neutrino mass. There is an upper limit, of \sim few eV from combining the limits from the tritium β decay with the Δm^2 values from the oscillation studies. For some, but not all, of the neutrinos there is also a lower limit, simply $\sqrt{\Delta m^2}$. These limits show that neutrinos, while massive, are very much lighter than the other fundamental constituents of matter, the charged leptons and quarks. While we do not understand the mass values of any fermion, the huge difference in masses of neutrinos and all charged fermions clearly requires an explanation. The usual one, like the see-saw mechanism, ties the neutrino mass with some very high mass scale. It also suggests that neutrinos, unlike all other fermions, are Majorana particles, i.e. they are their own antiparticles.

The research discussed here, if successful, would show whether these ideas are true or not. The observation of the $0\nu\beta\beta$ decay would prove that the total lepton number is not conserved and would establish a nonvanishing neutrino mass of Majorana nature. In other words, observation of the $0\nu\beta\beta$ decay, independently of its rate, would show that neutrinos, unlike all the other constituents of matter, are their own antiparticles. There is no other realistic way to

determine the nature - Dirac or Majorana, of massive neutrinos. This would be a discovery of major importance, comparable to the already discovered oscillations of atmospheric, solar and reactor neutrinos, and as important as a discovery of CP violation involving neutrinos. It would have impact not only on this fundamental question, but also on the determination of the absolute neutrino mass scale, and on the pattern of neutrino masses, and possibly on the problem of CP -violation in the lepton sector, associated with Majorana neutrinos.

At the same time, beta-decay endpoint measurements search for a kinematic effect due to neutrino mass and therefore are frequently referred to as "direct searches" for neutrino mass. This technique, which is essentially free of theoretical assumptions about neutrino properties, is not just complementary to the search of $0\nu\beta\beta$ decay. In fact, both types of measurements will be required to fully untangle the nature of the neutrino mass.

The following sections describe the status of the field, and plans for further experiments. Determining the absolute neutrino mass scale, and finding whether neutrinos are indeed Majorana particles and thus that the lepton number is not conserved, would represent a major advance in our understanding of particle physics.

$0\nu\beta\beta$ AND β DECAY AND OSCILLATIONS

Status of oscillation searches

As is well known, the concept of neutrino oscillations is based on the assumption that the neutrinos of definite flavor (ν_e, ν_μ, ν_τ) are not necessarily states of a definite mass $\nu_1, \nu_2, \nu_3, \dots$. Instead, they are generally coherent superpositions of such states,

$$|\nu_\ell\rangle = \sum_i U_{\ell i} |\nu_i\rangle. \quad (1)$$

When the standard model is extended to include neutrino mass, the mixing matrix U is unitary. As a consequence the neutrino flavor is no longer a conserved quantity and for neutrinos propagating in vacuum the amplitude of the process $\nu_\ell \rightarrow \nu_{\ell'}$ is

$$A(\nu_\ell \rightarrow \nu_{\ell'}) = \sum_i U_{\ell i} e^{-i \frac{m_i^2 L}{2E}} U_{\ell' i}^*, \quad (2)$$

The probability of the flavor change for $\ell \neq \ell'$ is the square of this amplitude, $P(\nu_\ell \rightarrow \nu_{\ell'}) = |A(\nu_\ell \rightarrow \nu_{\ell'})|^2$. It is obvious that due to the unitarity of U there is no flavor change if all masses vanish or are exactly degenerate. The idea of oscillations was discussed early on by Pontecorvo [5, 6] and by Maki, Nakagawa and Sakata [7]. Hence, the mixing matrix U is often associated with these names and the notation U_{MNS} or U_{PMNS} is used.

The formula for the probability is particularly simple when only two neutrino flavors, ν_ℓ and $\nu_{\ell'}$, mix appreciably, since only one mixing angle and two neutrino masses m_i, m_j are then relevant,

$$P(\nu_\ell \rightarrow \nu_{\ell' \neq \ell}) = \sin^2 2\theta \sin^2 \left[1.27 |\Delta m_{ji}^2| (\text{eV}^2) \frac{L(\text{km})}{E_\nu(\text{GeV})} \right], \quad (3)$$

where the appropriate factors of \hbar and c were included. Here $\Delta m_{ji}^2 \equiv m_j^2 - m_i^2$ is the mass squared difference. Due to the large difference in the two observed Δm^2 values, this simple formula adequately describes most of the experiments as of now.

In general, the mixing matrix of 3 neutrinos is parametrized by three angles, conventionally denoted as $\theta_{12}, \theta_{13}, \theta_{23}$, one CP violating phase δ and two Majorana phases α_1, α_2 [8–10]. Using c for the cosine and s for the sine, the mixing matrix U is parametrized as

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}e^{i\delta} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}e^{i\delta} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} \nu_1 \\ e^{i\alpha_2/2} \nu_2 \\ \nu_3 \end{pmatrix}. \quad (4)$$

The three neutrino masses m_i should be added to the parameter set that describes the matrix (4), representing therefore nine unknown parameters altogether.

The evidence for oscillations of solar (ν_e) and atmospheric (ν_μ and $\bar{\nu}_\mu$) neutrinos is compelling and generally accepted.

Evidence for oscillations of the solar ν_e have been reported first by the pioneering Davis et al. (Homestake) experiment [11]. It has been confirmed and reinforced later by Kamiokande, SAGE, GALLEX/GNO and Super-Kamiokande experiments [12, 13].

The SNO solar neutrino experiment [14, 15], in which it is possible to separately determine the flux of ν_e neutrinos reaching the detector (through the charged current reactions) and the flux of all active neutrinos (through the neutral current reactions), made the conclusion that solar neutrinos oscillate, inescapable.

Independently, KamLAND reactor antineutrino experiment has shown that $\bar{\nu}_e$ neutrinos oscillate as well [16, 17]. Moreover, the oscillation parameters extracted from that experiment agree perfectly with those from the solar ν_e experiments. This agreement, expected by the CPT-invariance, shows that the formalism of oscillations, including the matter effects, is well understood. Based on the combined analysis of these data the parameters Δm_{21}^2 (including its positive sign) and $\theta_{\odot} \sim \theta_{12}$ have been determined with a remarkable accuracy.

Oscillations of the atmospheric ν_{μ} ($\bar{\nu}_{\mu}$) have been most clearly observed in the Super-Kamiokande experiment. In particular the observed zenith angle dependence of the multi-GeV and sub-GeV μ -like events [18, 19] represents a compelling evidence. (Indication for the atmospheric neutrino oscillations, based mostly on the μ/e ratio, existed for a long time.) As is well known, the SK atmospheric neutrino data is best described in terms of dominant two-neutrino $\nu_{\mu} \rightarrow \nu_{\tau}$ ($\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{\tau}$) vacuum oscillations with maximal mixing. The analysis thus fixes the parameters $|\Delta m_{31}^2| \sim |\Delta m_{32}^2|$ and $\theta_{atm} = \theta_{23}$ (since $\cos \theta_{13} \sim 1$).

Finally, the remaining angle, θ_{13} remains unknown, but is constrained from above by the reactor neutrino CHOOZ and Palo Verde experiments [20, 21].

The Table I summarizes the present status of knowledge of the oscillation parameters (assuming three mass eigenstates, i.e. disregarding the possible existence of sterile neutrinos).

Thus, two of the three angles, and the two mass square differences have been determined reasonably well. The unknown quantities, accessible in future oscillation experiments (and discussed elsewhere in these reports) are the angle θ_{13} and the sign of the $\Delta m_{32}^2 \sim \Delta m_{31}^2$. If that sign is positive, the neutrino mass pattern is called a *normal mass ordering* ($m_1 < m_2 < m_3$) and when it is negative it is called *inverted mass ordering* ($m_3 < m_1 < m_2$). The extreme mass orderings, $m_1 < m_2 \ll m_3$ and $m_3 \ll m_1 < m_2$, are called the *normal* and, respectively, *inverted* hierarchies. In addition, the phase δ governing CP violation in the flavor oscillation experiments remains unknown, and a topic of considerable interest. Determination of the CP phase δ is again extensively discussed elsewhere in this report.

The remaining unknown quantities, the absolute neutrino mass scale, and the two Majorana phases α_1 and α_2 are not accessible in oscillation experiments. Their determination is the ultimate goal of $0\nu\beta\beta$ and β decay experiments.

Oscillations and direct neutrino mass measurements

Direct neutrino mass measurements are based on the analysis of the kinematics of charged particles (leptons, pions) emitted together with neutrinos (flavor states) in various weak decays. The most sensitive neutrino mass measurement to date, involving electron type neutrinos, is based on fitting the shape of the beta spectrum (see section VI below). In such measurements the quantity

$$m_{\nu_e} = \sqrt{\sum_i |U_{ei}|^2 m_{\nu_i}^2} \quad (5)$$

is determined or constrained, where the sum is over all mass eigenvalues m_{ν_i} that are too close together to be resolved experimentally.

TABLE I: Neutrino oscillation parameters determined from various experiments and their 95% confidence levels[22].

Parameter	Value $\pm 2\sigma$
Δm_{21}^2	$7.92(1 \pm 0.09) \times 10^{-5} \text{ eV}^2$
$\sin^2 \theta_{12}$	$0.314(1_{-0.15}^{+0.18})$
$ \Delta m_{32}^2 $	$2.4(1_{-0.26}^{+0.21}) \times 10^{-3} \text{ eV}^2$
$\sin^2 \theta_{23}$	$0.44(1_{-0.22}^{+0.41})$
$\sin^2 \theta_{13}$	$0.9_{-0.9}^{+2.3} \times 10^{-2}$

A limit on m_{ν_e} implies an *upper* limit on the *minimum* value $m_{\nu_{min}}$ of all m_{ν_i} , independent of the mixing parameters U_{ei} : $m_{\nu_{min}} \leq m_{\nu_e}$, i.e., the lightest neutrino cannot be heavier than m_{ν_e} . This is, in a sense, an almost trivial statement.

However, when the study of neutrino oscillations provides us with the values of *all* neutrino mass-squared differences Δm_{ij}^2 (including their signs) and the mixing parameters $|U_{ei}|^2$, and the value of $m_{\nu_e}^2$ has been determined in a future experiment, then the individual neutrino mass squares can be determined:

$$m_{\nu_j}^2 = m_{\nu_e}^2 - \sum_i |U_{ei}|^2 \Delta m_{ij}^2 \quad (\Delta m_{ij}^2 = m_{\nu_i}^2 - m_{\nu_j}^2) . \quad (6)$$

On the other hand, if only the absolute values $|\Delta m_{ij}^2|$ are known (but all of them), a limit on m_{ν_e} from beta decay may be used to define an *upper* limit on the *maximum* value $m_{\nu_{max}}$ of m_{ν_i} :

$$m_{\nu_{max}}^2 \leq m_{\nu_e}^2 + \sum_{i < j} |\Delta m_{ij}^2| . \quad (7)$$

In other words, knowing $|\Delta m_{ij}^2|$ one can use a limit on m_{ν_e} to constrain the heaviest active neutrino.

Oscillations, $0\nu\beta\beta$ decay, and neutrino mass

The neutrinoless double beta decay,

$$(Z, A) \rightarrow (Z + 2, A) + e_1^- + e_2^- \quad (8)$$

violates lepton number conservation. It can be recognized by its electron sum energy spectrum. Since the nuclear masses are so much larger than the decay Q value, the nuclear recoil energy is negligible, and the electron sum energy of the $0\nu\beta\beta$ is simply a peak at $T_{e1} + T_{e2} = Q$ smeared only by the detector resolution.

The $0\nu\beta\beta$ decay involves a vertex changing two neutrons into two protons with the emission of two electrons and nothing else. One can visualize it by assuming that the process involves the exchange of various virtual particles, e.g. light or heavy Majorana neutrinos, right-handed weak interaction mediated by the W_R boson, SUSY particles, etc. No matter what the vertex is, the $0\nu\beta\beta$ decay can proceed only when neutrinos are massive Majorana particles [23].

Of primary interest is the process mediated by the exchange of light Majorana neutrinos interacting through the left-handed $V - A$ weak currents. The decay rate is then,

$$[T_{1/2}^{0\nu}(0^+ \rightarrow 0^+)]^{-1} = G^{0\nu}(E_0, Z) \left| M_{GT}^{0\nu} - \frac{g_V^2}{g_A^2} M_F^{0\nu} \right|^2 \langle m_{\beta\beta} \rangle^2 , \quad (9)$$

where $G^{0\nu}$ is the accurately calculable phase space integral, $\langle m_{\beta\beta} \rangle$ is the effective neutrino mass, and $M_{GT}^{0\nu}$, $M_F^{0\nu}$ are the nuclear matrix elements. The problems associated with the evaluation of the nuclear matrix elements are discussed in Section IV, where also corrections to the nuclear structure dependent part of the decay rate are discussed.

If the $0\nu\beta\beta$ decay is observed, and the nuclear matrix elements are known, one can deduce the corresponding $\langle m_{\beta\beta} \rangle$ value, which in turn is related to the oscillation parameters by

$$\langle m_{\beta\beta} \rangle = \left| \sum_i |U_{ei}|^2 m_{\nu_i} e^{i\alpha_i} \right| , \quad (10)$$

where the sum is only over light neutrinos ($m_{\nu_i} < 10$ MeV). The Majorana phases α_i were defined earlier in Eq.(4). If the neutrinos ν_i are CP eigenstates, α_i is either 0 or π . Due to the presence of these unknown phases, cancellation of terms in the sum in Eq.(10) is possible, and $\langle m_{\beta\beta} \rangle$ could be smaller than any of the m_{ν_i} even if all neutrinos ν_i are Majorana particles.

We can use the values in Table I and express the $\langle m_{\beta\beta} \rangle$ in terms of the three unknown quantities: the mass scale, represented by the mass of the lightest neutrino $m_{\nu_{min}}$, and the two Majorana phases. In doing so, it is useful to distinguish three mass patterns: normal hierarchy (NH), $m_1 < m_2 \ll m_3$ (i.e. $m_{\nu_{min}} = m_1$), inverted hierarchy (IH), $m_3 \ll m_1 < m_2$ (i.e. $m_{\nu_{min}} = m_3$), and the quasi-degenerate spectrum (QD) where $m_{\nu_{min}} \gg \sqrt{|\Delta m_{32}^2|}$ as well as $m_{\nu_{min}} \gg \sqrt{|\Delta m_{21}^2|}$. Detailed discussion of the relation between the $\langle m_{\beta\beta} \rangle$ and the absolute neutrino mass scale can be found in numerous papers (see, e.g. some of the more recent references [24–29]).

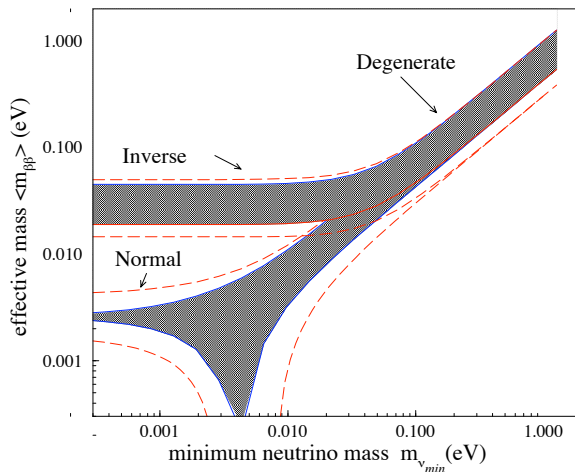


FIG. 1: Effective Majorana mass $\langle m_{\beta\beta} \rangle$ versus the minimum mass $m_{\nu_{min}}$. The different mass patterns are indicated. The shaded region corresponds to the best values of oscillation parameters, and $\theta_{13} = 0$. The dashed lines indicate the expanded range corresponding to the 1σ errors of the oscillation parameters and the maximum allowed θ_{13} . Note that the uppermost line is unchanged (within this scale) in that case.

In Fig.1 we show the plot of $\langle m_{\beta\beta} \rangle$ versus $m_{\nu_{min}}$ using the oscillation parameters in Table I, and allowing for the maximum value of θ_{13} and one σ variations of them. One can clearly see the three regions (NH, IH, QD). Thus, determination of the $\langle m_{\beta\beta} \rangle$ value would allow, in general, to distinguish between these patterns, and to determine a range of $m_{\nu_{min}}$. One should keep in mind, however, that there are caveats to this statement for the situations where the corresponding bands merge (e.g. the IH and QD near $m_{\nu_{min}} \sim 0.05$ eV).

Despite this caveats, obviously, if one can experimentally establish that $\langle m_{\beta\beta} \rangle \geq 50$ meV, one can conclude that the QD pattern is the correct one, and one can read off an allowed range of $m_{\nu_{min}}$ values from the figure. (The sign of $\Delta m_{31}^2 \sim \Delta m_{32}^2$ will remain undetermined in that case, however.)

On the other hand, if $\langle m_{\beta\beta} \rangle \sim 20$ -50 meV only an upper limit for the $m_{\nu_{min}}$ can be established, and the pattern is likely IH, even though exceptions exist. However, if (and that is unlikely in a foreseeable future) the value of $m_{\nu_{min}}$ can be determined independently, the pattern can be resolved.

Finally, if one could determine that $\langle m_{\beta\beta} \rangle \leq 10$ meV but nonvanishing (which is again is unlikely in a foreseeable future), one could conclude that the NH pattern is the correct one.

Altogether, observation of the $0\nu\beta\beta$ decay, and accurate determination of the $\langle m_{\beta\beta} \rangle$ value would not only establish that neutrinos are massive Majorana particles, but would contribute considerably to the determination of the absolute neutrino mass scale. Moreover, if the neutrino mass scale would be known from independent measurements, one could possibly obtain from the measured $\langle m_{\beta\beta} \rangle$ also some information about the CP violating Majorana phases.

Absolute neutrino mass scale

As shown above, $0\nu\beta\beta$ and β decays both depend on different combinations of the neutrino mass values and oscillation parameters. The $0\nu\beta\beta$ decay rate is proportional to the square of a coherent sum of the Majorana neutrino masses because $\langle m_{\beta\beta} \rangle$ arises from exchange of a virtual neutrino. On the other hand, in beta decay one can determine an incoherent sum because a real neutrino is emitted.

Quite different source of information is based on cosmological and astrophysical observations where the density of the primordial neutrino sea is determined or constrained and thus a parameter proportional to the sum of the neutrino masses is determined.

It is worthwhile to stress that the various methods that depend on the neutrino absolute mass scale are complementary. If, ideally, a positive measurement is reached in all of them ($0\nu\beta\beta$ β decay, cosmology) one can test the results for consistency and perhaps determine the Majorana phases. The idea is illustrated in Ref. [3]. Many authors have examined the potential to combine measurements from $\beta\beta$ decay, tritium β decay, and cosmology to determine the Majorana phases. (See e.g. [30–32].)

NUCLEAR STRUCTURE ISSUES

The observation of $0\nu\beta\beta$ decay would immediately tell us that neutrinos are Majorana particles and give us an estimate of their overall mass scale. But without accurate calculations of the nuclear matrix elements that determine the decay rate it will be difficult to reach quantitative conclusions about masses and hierarchies.

Theorists have tried hard to develop many-body techniques that will allow such calculations. In order to test the calculations they have tried to calibrate them against related observables: $2\nu\beta\beta$ decay, ordinary β^+ and β^- decay, Gamow-Teller strength distributions, odd-even mass differences and single-particle spectra. They have tried to exploit approximate isospin and $SU(4)$ symmetries in the nuclear Hamiltonian and to extend well-known many-body methods in novel ways. In spite of all this effort, we know the matrix elements with only limited accuracy. In this section we review the state of the nuclear-structure calculations and discuss ways to improve them.

Most recent attempts to calculate the nuclear matrix elements have been based on the neutron-proton Quasiparticle Random Phase Approximation (QRPA) or extensions to it. Of those that haven't, the most prominent are based on the shell model (SM). While the two methods have much in common — their starting point is a Slater determinant of independent nucleons — the kinds of correlations they include are complementary. The QRPA treats a large fraction of the nucleons as “active” and allows these nucleons a large single-particle space to move in. But RPA correlations are of a specific and simple type best suited for collective motion. The shell model, by contrast, treats a small fraction of the nucleons in a limited single-particle space, but allows the nucleons there to correlate in arbitrary ways. That these very different approaches yield similar results indicates that both capture most of the important physics. That, by itself, is encouraging and restricts the possible values of nuclear matrix elements considerably.

QRPA

The application of QRPA to $\beta\beta$ decay began with the realization by [33] that in the QRPA the neutron-proton (np) particle-particle (i.e. pairing-like) interaction, which has little effect on the collective Gamow-Teller resonance, suppresses $2\nu\beta\beta$ rates considerably. Soon afterward, [34] and [35] demonstrated a similar though smaller effect on $0\nu\beta\beta$ decay. It was quickly realized, however, that the QRPA was not designed to handle realistic np pairing; the calculated half-lives were unnaturally sensitive to the strength of the pairing interaction. As a result, the rates of $\beta\beta$ decay, particularly $2\nu\beta\beta$ decay, were hard to predict precisely because a small change in a phenomenological parameter (the strength of np isoscalar pairing) caused a large change in the lifetimes and eventually the breakdown (called a “collapse”) of the entire method when the parameter exceeds some critical value. Most recent work in the QRPA has aimed at modifying the undesirable aspects of the method so that its sensitivity to np pairing becomes more realistic.

There has been a large number of attempts to extend the validity of QRPA. We will not list them here, or discuss them in detail. Comprehensive discussion can be found in [3]. Earlier and even more complete discussion of the issues involved can be found in [36].

Shell Model

The obvious alternative to QRPA, and the current method of choice for nuclear structure calculations in heavy nuclei where applicable, is the shell model. It has ability to represent the nuclear wave function to arbitrary accuracy, provided a large enough model space is used. This caveat is a huge one, however. Current computers allow very large bases (millions of states), but in heavy nuclei this is still not nearly enough. Techniques for constructing “effective” interactions and operators that give exact results in truncated model spaces exist but are hard to implement. Even in its crude form with relatively small model spaces and bare operators, however, the shell model seems to offer some advantages over the QRPA. Its complicated valence-shell correlations, which the QRPA omits (though it tries to compensate for them by renormalizing parameters) apparently affect the $\beta\beta$ matrix elements [38].

The first modern shell-model calculations of $\beta\beta$ decay date from the work Haxton and Stephenson [39] and references therein. Only a few truly large-scale shell model calculations have been performed. The heavy deformed $\beta\beta$ nuclei, ^{238}U , and ^{150}Nd , for example, require bases that are too large to expect real accuracy. Realistic work has thus been restricted to few nuclei, in particular to ^{48}Ca , ^{76}Ge , and ^{136}Xe , though less comprehensive calculations have been carried out in several other nuclei [36].

Large spaces challenge us not only through the problem of diagonalizing large matrices, but also by requiring us to construct a good effective interaction. The bare nucleon-nucleon interaction needs to be modified in truncated spaces

(this is an issue in the QRPA as well, though a less serious one). Currently, effective interactions are built through a combination of perturbation theory, phenomenology, and painstaking fitting. The last of these, in particular, becomes increasingly difficult when millions of matrix elements are required.

Related to the problem of the effective interaction is the renormalization of transition operators. Though the problem of the effective Gamow-Teller operator which enters directly into $2\nu\beta\beta$ decay, has drawn some attention, very little work has been done on the renormalization of the two-body operators that govern $0\nu\beta\beta$ decay. Shell model calculations won't be truly reliable until they address this issue, which is connected with deficiencies in the wave function caused by neglect of single-particle levels far from the Fermi surface. Ref. [40] suggests that significant improvement on the state of the art will be difficult but not impossible in the coming years.

Constraining Matrix Elements with Other Observables

The more observables a calculation can reproduce, the more trustworthy it becomes. And if the underlying model contains some free parameters, these observables can fix them. The renormalization of free parameters can make up for deficiencies in the model, reducing differences between, e.g., the QRPA and RQRPA once the parameters of both have been fit to relevant data. The more closely an observable resembles $0\nu\beta\beta$ decay, the more relevant it is.

Gamow-Teller distributions, both in the β^- and β^+ directions, enter indirectly into both kinds of $\beta\beta$ decay, and are measurable through (p, n) and analogous nucleon exchange reactions. Ref.[41] is particularly careful to reproduce those transitions as well as possible. Pion double charge exchange, in which a π^+ enters and a π^- leaves, involves the transformation of two neutrons into two protons, like $\beta\beta$ decay, but the nuclear operators responsible aren't the same in the two cases. Perhaps the most relevant quantity for calibrating calculations of $0\nu\beta\beta$ decay is $2\nu\beta\beta$ decay, which has now been measured in 10 different nuclei. A discussion of such possibilities was compiled in the report by Zuber *et al.*[42].

Two recent papers have tried to use $2\nu\beta\beta$ decay to fix the strength of np pairing in QRPA-based calculations. Ref. [43] used it only for the $J^\pi = 1^+$ channel relevant for $2\nu\beta\beta$ decay, leaving the np pairing strength unrenormalized in other channels. By contrast, Ref [44] renormalized the strength in all channels by the same amount. The results of the two procedures were different; the former reference found that the $0\nu\beta\beta$ matrix elements depended significantly on the theoretical approach, while the later one found almost no dependence on model-space size, on the form of the nucleon-nucleon interaction, or on whether the QRPA or RQRPA was used. The authors argued that fixing the np pairing strength to $2\nu\beta\beta$ rates essentially eliminates uncertainty associated with variations in QRPA calculations of $0\nu\beta\beta$ rates, though they left open the question of how close to reality the calculated rates were.

The conclusion of [44] is supported by the work [45] where the $2\nu\beta\beta$ was also used to fix the relevant parameter and essentially no difference between QRPA, RQRPA, and the new variant developed there was found. Moreover, when the fact that higher order terms are not included in [45], but are included in [44] (a reduction by $\sim 30\%$) are taken into account, these two calculations agree quite well. Another case is the work [46] which uses yet another variant of the theory and seemingly disagrees drastically with other calculations for the case of ^{76}Ge $0\nu\beta\beta$ decay. However, in an earlier work using the same method and parameters [47], it is clear that the rate of the $2\nu\beta\beta$ decay is incorrect by a large factor. When the relevant parameters are adjusted to give the correct $2\nu\beta\beta$ rate, the result again agrees quite well with [44].

While this question remains open, it is clear that only calculations of the $0\nu\beta\beta$ nuclear matrix elements that also describe other relevant nuclear properties should be included in the estimate of the uncertainty.

EXPERIMENTAL PROSPECTS FOR $\beta\beta$

If an experiment observes $0\nu\beta\beta$ it will have profound physics implications. Such an extraordinary claim will require extraordinary evidence. The recent claim[48] for an observation of $0\nu\beta\beta$ has been controversial (See discussion below). Also previous "false peaks" in $\beta\beta$ spectra have appeared near a $0\nu\beta\beta$ endpoint energy (see discussion in [49], page 273). One must ask the question: What evidence is required to convincingly demonstrate that $0\nu\beta\beta$ has been observed? Low-statistical-significance peaks ($\approx 2\sigma$) have faded with additional data, so one must require strong statistical significance (perhaps 5σ). (See Fig. 2.) This will require a large signal-to-noise ratio that will most likely be accomplished by an ultra-low-background experiment whose source is its detector. Such experiments are usually calorimetric and provide little information beyond just the energy measurement.

How does an experiment demonstrate that an observed peak is actually due to $\beta\beta$ decay and not some unknown radioactivity? Additional information beyond just an energy measurement may be required. For example, although

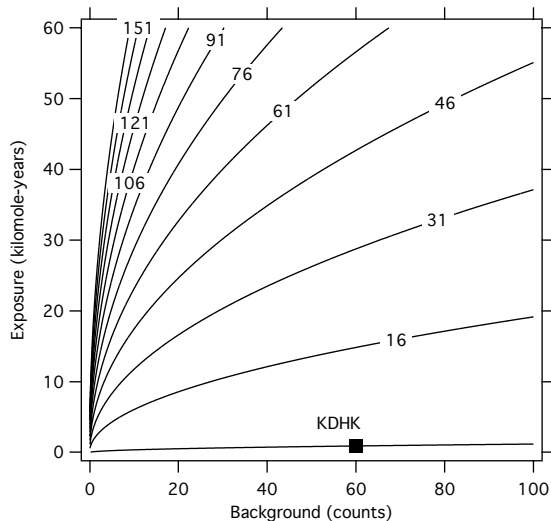


FIG. 2: This contour plot shows the half life, in units of 10^{25} y, for a peak of 5σ significance for a given exposure and background. The KDHK point is shown.

there is some uncertainty associated with the matrix elements, it is not so large that a comparison of measured rates in two different isotopes could not be used to demonstrate consistency with the Majorana-neutrino hypothesis. Alternatively, experiments that provide an additional handle on the signal, for example by measuring a variety of kinematical variables, demonstrating that 2 electrons are present in the final state, observing the γ rays associated with an excited state, or identifying the daughter nucleus, may lend further credibility to a claim. Experiments that provide this extra handle may require a significantly more complicated apparatus and therefore face additional challenges.

The exciting aspect of $\beta\beta$ research today is that many proposed experiments intend to reach a Majorana mass sensitivity of $\sqrt{\delta m_{\text{atm}}^2}$. Several different isotopes and experimental techniques are being pursued actively and many of the programs look viable. In this section we describe the current situation in experimental $\beta\beta$ decay .

Results to date

Table II lists the recent $0\nu\beta\beta$ results. The best limits to date come from the enriched Ge experiments. The two experiments had comparable results although the Heidelberg-Moscow result was marginally better. The $T_{1/2}^{0\nu}$ limits near 2×10^{25} y results in a $\langle m_{\beta\beta} \rangle$ limit near 300 meV, with an uncertainty of about a factor of 3 because of the uncertainty in $|M_{0\nu}|$. One recent paper[60] performed a joint analysis of the two experiments and found $T_{1/2}^{0\nu} > 2.5 \times 10^{25}$ y.

A claim for the observation of $0\nu\beta\beta$

In early 2002, a claim for the observation of $0\nu\beta\beta$ was published (Klapdor-Kleingrothaus *et al.*2002a). The paper made a poor case for the claim and drew strong criticism[60–62]. The initial response to the criticism was emotional[63]. In addition, one of the original co-authors wrote a separate reply[64] that mostly defended the claim yet acknowledged some significant difficulty with the analysis. This author’s name doesn’t appear on later papers. More recently, however, supporting evidence for the claim has been presented and we recommend the reader study Ref. [65] for a good discussion of the initial evidence and Ref. [48] for the most recent data analysis. Importantly, this later paper includes additional data and therefore an increase in the statistics of the claim. In this subsection we summarize the current situation. (We use the shorthand KDHK to refer to the collection of papers supporting the claim.)

Figure 3 shows the spectrum corresponding to 71.7 kg-y of data from the Heidelberg-Moscow experiment between 2000 and 2060 keV[48]. This spectrum is shown here to assist the casual reader in understanding the issues. However,

TABLE II: A summary of the recent $0\nu\beta\beta$ results. The $\langle m_{\beta\beta} \rangle$ limits are those deduced by the authors. All limits are at 90% confidence level unless otherwise indicated. The columns providing the exposure and background are based on arithmetic done by the authors of this paper, who take responsibility for any errors in interpreting data from the original sources.

Isotope	Exposure (kmole-y)	Background (counts)	Half-Life Limit (y)	$\langle m_{\beta\beta} \rangle$ (meV)
^{48}Ca	5×10^{-5}	0	$> 1.4 \times 10^{22}$	$< 7200 - 44700$ [50]
^{76}Ge	0.467	21	$> 1.9 \times 10^{25}$	< 350 [51]
^{76}Ge	0.117	3.5	$> 1.6 \times 10^{25}$	$< 330 - 1350$ [52]
^{76}Ge	0.943	61	$= 1.2 \times 10^{25}$	$= 440$ [48]
^{82}Se	0.022	7	$> 2.1 \times 10^{23}$	$< 1200 - 3200$ [57]
^{100}Mo	0.131	14	$> 5.8 \times 10^{23}$	$< 600 - 2700$ [57]
^{116}Cd	1×10^{-3}	14	$> 1.7 \times 10^{23}$	< 1700 [53]
^{128}Te	Geochem.	NA	$> 7.7 \times 10^{24}$	$< 1100 - 1500$ [54]
^{130}Te	0.07	12	$> 2.4 \times 10^{24}$	$< 400 - 1400$ [56]
^{136}Xe	7×10^{-3}	16	$> 4.4 \times 10^{23}$	$< 1800 - 5200$ [58]
^{150}Nd	6×10^{-5}	0	$> 1.2 \times 10^{21}$	< 3000 [59]

the critical reader is encouraged to read the papers listed in the references as the authors analyze several variations of this data using different techniques. The fit about the expected $0\nu\beta\beta$ peak energy yields 28.75 ± 6.86 counts assigned to $0\nu\beta\beta$. The paper claims a significance of approximately 4σ for the peak, where the precise significance value depends on the details of the analysis. The corresponding best-fit lifetime, $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ years[48], leads to a $\langle m_{\beta\beta} \rangle$ of 440 meV with the matrix element calculation of Ref. [66] chosen by the authors.

The next round of proposed $0\nu\beta\beta$ experiments are designed to reach $\sqrt{\delta m_{\text{atm}}^2}$ and therefore will quickly confirm or repudiate this claim. This is fortunate since the feature near 2039 keV in the KDHK claim will likely require an experimental test. These experiments should provide a detailed listing of all identified systematic uncertainties and a quantified estimate of their size. Furthermore, because the stakes are very high and there will be many people who are biased, either for or against the KDHK claim, blind analyses should also become part of the experimental design.

Towards a 100-kg experiment

The KDHK spectrum shows a feature very close to the $0\nu\beta\beta$ endpoint. This intriguing result will need to be confirmed or refuted experimentally. One can see the required operation parameters for a confirmation experiment from the KDHK result. One needs about 75 kg-y of exposure, and a background lower than about 0.5 counts/(kg y). Note that most of the proposals described above will all accomplish this very early on in their program if they meet their design goals. If instead one designs an experiment only to test the claim (not to provide a precise measurement of the $T_{1/2}^{0\nu}$) then a 100-kg experiment could provide the answer after a modest run time.

If the KDHK result holds up, it will be a very exciting time for neutrino-mass research. A $\langle m_{\beta\beta} \rangle$ near 400 meV means that β -decay experiments and cosmology will be sensitive to the mass. As a result, one can certainly imagine a not-too-distant future in which we know the neutrino mass and its Majorana-Dirac character. Towards this goal, a precision measurement of $\langle m_{\beta\beta} \rangle$ will be required. To accomplish this, we will need more than one $\beta\beta$ experiment, each with a half-life measurement accurate to 10-20%. At this level the uncertainty will be dominated by the matrix element uncertainty even if future calculations can be trusted to 50%. With two experiments utilizing different isotopes, one might disentangle the uncertainty in $|M_{0\nu}|$. Furthermore, efforts to study statistical distributions of the kinematic parameters, such as the opening angle or the individual electron energies, will be desired.

Towards a 100-ton experiment

The next generation of experiments hopes to be sensitive to $\sqrt{\delta m_{\text{atm}}^2}$. If they fail to see $0\nu\beta\beta$ at that level, the target for the succeeding generation of efforts will be $\sqrt{\delta m_{\text{sol}}^2}$. This scale is an order of magnitude lower and hence

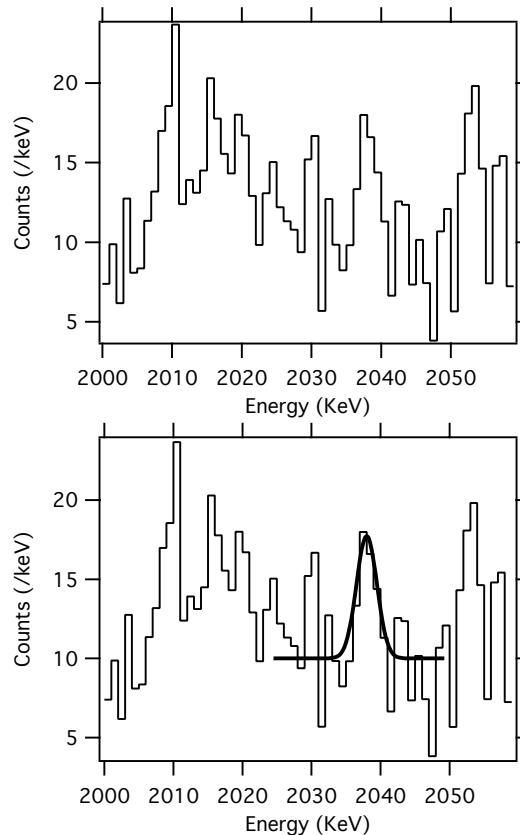


FIG. 3: The spectrum from the Heidelberg-Moscow experiment upon which the claim for $0\nu\beta\beta$ is based. The data in the two panels are identical. The lower panel has a Gaussian curve to indicate the strength of the claimed $0\nu\beta\beta$ peak.

will require two orders of magnitude more isotopic mass, approximately 100 tons of isotope.

Proposed Experiments for $\beta\beta$ Decay

The recent reviews by Elliott and Vogel[1] and Elliott and Engel[3] describe the basics of experimental $0\nu\beta\beta$ decay in some detail. Therefore, we refer the reader to those articles and only summarize the status of the various projects. Table III lists the proposals.

CANDLES

The CANDLES (CALcium fluoride for studies of Neutrino and Dark matters by Low Energy Spectrometer) collaboration has recently published the best limit on $0\nu\beta\beta$ decay of 1.4×10^{22} y in ^{48}Ca [50]. Using the ELEGANTS VI detector, this experiment consisted of 6.66 kg of $\text{CaF}_2(\text{Eu})$ crystals surrounded by CsI crystals, a layer of Cd, a layer of Pb, a layer of Cu, and a layer of LiH-loaded paraffin, all enclosed within an air-tight box. This box was then surrounded by boron-loaded water tanks and situated underground at the Oto Cosmo Observatory. This measurement successfully demonstrated the use of these crystals for $\beta\beta$ studies.

An improved version of this crystal technology, the CANDLES-III detector[68], is presently being constructed with 191 kg of CaF_2 crystals. These crystals have better light transmission than the $\text{CaF}_2(\text{Eu})$ crystals. This design uses sixty 10-cm^3 CaF_2 crystals, which are immersed in liquid scintillator. The collaboration has also proposed a 6.4-t experiment that hopes to reach 100 meV for $\langle m_{\beta\beta} \rangle$.

TABLE III: A summary of the $0\nu\beta\beta$ proposals. Background estimates were not available for all projects. The quantity of isotope includes the estimated efficiency for $0\nu\beta\beta$.

Collaboration	Isotope	Detector Description
CANDLES[68]	^{48}Ca	CaF_2 crystals in liq. scint.
COBRA[69]	^{116}Cd	CdTe semiconductors
CUORE[70]	^{130}Te	TeO_2 bolometers
DCBA[71]	^{82}Se	Nd foils and tracking chambers
EXO[72]	^{136}Xe	Xe TPC
GeH_4 [73]	^{76}Ge	GeH_4 tracking ionization chamber
GEM[74]	^{76}Ge	Ge detectors in LN
GSO[77, 78]	^{160}Gd	Gd_2SiO_5 crystals in liq. scint.
Majorana[79]	^{76}Ge	Segmented Ge detectors
MOON[80]	^{100}Mo	Mo foils and plastic scint.
GERDA[81]	^{76}Ge	Ge detectors in LN
Nano-crystals[82]		suspended nanoparticles
SeF_6 [83]	^{82}Se	negative ion drifting SeF_6 TPC
Super-NEMO[84]	^{82}Se	foils with tracking
Xe[85]	^{136}Xe	Xe dissolved in liq. scint.
XMASS[86]	^{136}Xe	liquid Xe

COBRA

The COBRA experiment[69] uses CdZnTe or CdTe semiconductor crystals. These crystals have many of the advantages of Ge detectors but, in addition, operate at room temperature. Because the crystals contain Cd and Te, there are 7 $\beta\beta$ and $\beta^+\beta^+$ isotopes contained. The final proposed configuration is for 64000 1-cm³ crystals for a total mass of 418 kg. The collaboration has already obtained 30-keV resolution at 2.6 MeV with these detectors and has published initial $\beta\beta$ -decay studies[87]. Background studies are the current focus of the efforts. Although it is tempting to focus on the naturally isotopic abundant ^{130}Te for $0\nu\beta\beta$ decay, the presence of the higher Q-value ^{116}Cd creates a serious background from its $2\nu\beta\beta$ decay. Detectors enriched to 90% in ^{116}Cd are planned.

CUORE

CUORE and CUORICINO are based on the technique of cryogenic detectors. When operated at low temperature, the absorbers of these detectors have a heat capacity so low that even the small energy released by a single radioactive decay event can be observed and measured by means of a suitable thermal sensor. With crystals of mass near to a kilogram, with NTD Ge (Neutron Transmutation Doped germanium) thermistors, an energy resolution similar to that of germanium diodes has been achieved. In addition, thermal detectors allow a wide choice of nuclei to be used for double beta decay searches. The experiment CUORICINO is located in the Gran Sasso underground laboratory and it is a prototype for CUORE (Cryogenic Underground Observatory for Rare Events). CUORICINO is an array of 44 crystals of TeO_2 each 5x5x5 cm and 18 crystals each 3x3x6 cm. With its mass of approximately 40 kg, CUORICINO is by far the most massive cryogenic set-up in operation. Due the large isotopic abundance (34%) of the double beta decay candidate ^{130}Te , no isotopic enrichment is required, but two of the 3x3x6 cm crystals are enriched in ^{130}Te and two other in ^{128}Te to investigate $2\nu\beta\beta$. In only three months of operation, CUORICINO has obtained a 90% c.l. limit on the lifetime against neutrinoless double beta decay of 2.4×10^{24} yr[56], corresponding to an upper limit on the average neutrino mass ranging from 0.4 to 1.4 eV depending on the choice of matrix element. This result rivals the best limits obtained from many years of searches for the double beta decay of ^{76}Ge . CUORE will consist of an array consisting of 19 columns of 13 planes of 4 TeO_2 crystals each 5x5x5 cm of for a total of 988 crystals with a mass around 741 kg (200 kg of ^{130}Te). Each tower will therefore be similar to the single tower of CUORICINO,.

DCBA

A momentum analyzer called the Drift Chamber Beta-ray Analyzer (DCBA)[71] is a tracking detector operated in a uniform magnetic field of around 1 kG. Various isotopes can be installed within the detector, if the source can be fabricated into a thin plate. Presently, the collaboration is considering ^{82}Se , ^{100}Mo , and ^{150}Nd because of their high Q-values. A tracking region on each side of a source plate includes anode-, potential- and cathode-wires. The drift region is filled with 1-atm helium gas mixed with small amounts of a quench gas. A β ray emitted from a source plate makes a helical track in the region between anode and cathode wire planes. Anode signals are read out with Flash Analog to Digital Converter (FADC). The three-dimensional reconstruction of a helical track is available using data from the electron drift time (corresponding to the X-coordinate), an anode wire position (Y) and the ratio of signals from both sides of an anode wire (Z). Momentum of each β ray is derived from the curvature of the track. Electron tracks of 1 MeV were studied using internal conversion electrons from ^{207}Bi , which was installed in a prototype called DCBA-T. The collaboration is making efforts to improve the Z-position resolution so as to obtain better energy resolution. Another developing item is to accommodate source plates, as much as possible, in a limited chamber volume. Research into cleaning the source material is also proceeding.

The future DCBA experiment will consist of 40 modules. One module comprises a drift chamber of about 1.8 m³ volume containing the source plates surrounded by a solenoid magnet with maximum field of 1.6 kG. In the chamber, 30 tracking regions cover 29 source plates. The total source-plate area is 25 m² in each module. For a source-plate thickness of 60 mg/cm², the source weight is 15 kg for each module. Therefore total source weight is 600 kg, corresponding to about 6600 mol and 5400 mol for ^{82}Se and ^{100}Mo , respectively, which are enriched to 90%. For a natural Nd source, about 200 mol of ^{150}Nd will be installed. Assuming an efficiency of event detection of 0.3, a background rate of 1 event/module/year, and a measuring time of 5 years; the half-life sensitivities are approximately calculated to be 3×10^{26} yr for ^{82}Se , 2×10^{26} yr for ^{100}Mo and 9×10^{24} yr for ^{150}Nd in natural Nd. If 90% enriched ^{150}Nd is available in the future by the method of Atomic Vapor Laser Isotope Separation, it is possible to obtain 1×10^{26} yr for ^{150}Nd .

EXO

The **Enriched Xenon Observatory**[72] is being set-up to study the double beta decay of ^{136}Xe . The collaboration aims to use up to 10 tons of isotopically enriched ^{136}Xe to build a redundant and background-free detector using good energy resolution, pattern recognition and the identification of the atomic species produced by the double-beta decay. A concise description of the project and its plans to test Majorana neutrino masses as small as 10 to 40 meV using this scheme has been published in [72].

The final state atom tagging is possible because of the simple and well known atomic spectroscopy of Ba⁺ ions. Such spectroscopy has enabled the observation of individual ions illuminated with appropriate wavelengths since about 20 years. The specific wavelengths needed to produce atomic fluorescence ensure extreme selectivity of this technique. Ba happens to be the atomic species produced in the double beta decay of ^{136}Xe . In EXO the Xenon will be used as an active target in a Time Projection Chamber (TPC) either in liquid (LXe) or gas (GXe) phase. In the GXe case the laser beams would be steered to the location where a candidate decay has occurred. In the LXe case the Ba-ion candidate would be extracted and brought into an ion trap where the fluorescence would be observed. The possibility of observing the fluorescence of the Ba directly in the liquid is also being investigated by one of the EXO groups. While R&D is proceeding at different institutions for both liquid and gas phase TPC, a LXe TPC for 200 kg of ^{136}Xe is being built as a prototype and as a first step towards the very large detector.

^{136}Xe is a particularly convenient isotope for a very large double beta decay experiment. It combines a large Q-value with ease (and low cost) enrichment, the absence of long lived radioactive isotopes, ease of purification and the possibility of transfer from one detector to another in the case new technology would become available. In addition purification can be achieved on-line so that more refined purification system may be introduced as they become needed. Finally, together with the enabling possibility of final state identification that is the hallmark of EXO, ^{136}Xe has the longest $2\nu\beta\beta$ half life among all high Q-value $\beta\beta$ -unstable nuclides (at least factor 6.5 longer than e.g. ^{76}Ge).

With its 200 kg of source strength the EXO prototype detector will already represent the largest existing double beta decay experiment. Recently evidence for a Majorana neutrino mass of $0.44_{-0.20}^{+0.14}$ eV (errors given at 3σ c.l.) has been claimed by a part of the Heidelberg component of the Heidelberg-Moscow experiment [48]. Should this claim turn out to be correct the EXO prototype expects to observe 43_{-30}^{+33} $0\nu\beta\beta$ decays per year when using the same matrix element calculation as reference [48]. The prototype detector is being commissioned at Stanford and plans to be transferred to WIPP in 2006. The development of the barium extraction and tagging will continue in parallel,

together with the work on a GXe TPC. After initial operation of the prototype the technology for the large detector will be chosen and its design finalized.

MOON

MOON (Molybdenum Observatory Of Neutrinos)[80] is a "hybrid" $\beta\beta$ and solar ν_e experiment with ^{100}Mo . It aims at studies of $\langle m_{\beta\beta} \rangle$ with a sensitivity near 30 meV by measuring $0\nu\beta\beta$ decays of ^{100}Mo and the charged current ^7Be solar ν_e with an accuracy of about 10% by inverse β decays of ^{100}Mo . The $\beta\beta$ decays to the ground and excited states are measured in prompt coincidence for the $0\nu\beta\beta$ studies. The large $Q=3.034$ MeV results in a large phase-space factor to enhance the $0\nu\beta\beta$ rate and a large energy to place the $0\nu\beta\beta$ signal above most background. MOON is a spectroscopic study of two β rays. As such, its capability to measure the energy and angular correlations for the two β rays can help identify the $0\nu\beta\beta$ mechanism. Its capability for a tight localization of $\beta\beta$ events in space and time is crucial for selecting $0\nu\beta\beta$ and reducing background.

A possible configuration of the MOON apparatus is a super module of hybrid plate and fiber scintillators with ^{100}Mo isotope mass totaling about 1 ton. One module of this apparatus consists of a thin (20 mg/cm²) Mo film interleaved between X-Y fiber planes and a plate scintillator. The fiber scintillators enable one to get the position resolution ($1/K < 10^{-8}$ pixels per ton) and the scintillator plate provides an energy resolution ($\sigma \approx 2.2\%$ at 3 MeV). A different detector option under consideration consists of foils within liquid Ar to obtain better energy resolution. Research has shown (1) that for the small plate scintillator, $\sigma = 2.2\%$, FWHM: 5% for $0\nu\beta\beta$ including light attenuation, for MOON, (2) the position resolution of 3.2×10^9 , and (3) the feasibility of using centrifugal separation of MoF₆ gas to produce ^{100}Mo enrichment of 85-90% in ton-scale quantities. MOON-I has been deployed at the Oto Underground Laboratory in Japan using 3 layers for a total of 142 g of 94.5% enriched ^{100}Mo . It has been operating since April 2005. A proposal for MOON is planned by 2006.

The MOON sensitivity can be evaluated as follows. The source is 1 ton of Mo with 85% ^{100}Mo . The $0\nu\beta\beta$ efficiency after energy and angle cuts is 0.28. The background from $2\nu\beta\beta$ in the $0\nu\beta\beta$ window during 5 years after cuts is 5.5(42) events for an energy resolution of $\sigma=2.2(3)\%$ (FWHM 5(7)%). Here $\sigma=2.2\%$ is estimated based on the R&D data from a small-scale prototype and ELEGANT V, while 3% is a conservative value including a 50% factor. The background from cosmogenic isotopes and natural isotopes are less than 0.5 events. Then the $0\nu\beta\beta$ yield of $\sqrt{\text{background}}$ is 2.3(6.4), corresponding to a half life 22 (7.7) $\times 10^{26}$. The mass sensitivities are, respectively, 13 (22) meV. Here the matrix element of $|M_{0\nu}| = 3$ is estimated by referring to the recent 3 calculations. The MOON apparatus has the $\beta\beta$ source separated from the detector, and therefore can be used for other $\beta\beta$ isotopes such as ^{82}Se , ^{150}Nd and ^{116}Cd as well by replacing Mo isotopes with other isotopes.

Majorana

The Majorana Collaboration proposes to field 120 kg of 86% enriched Ge detectors[79]. By using segmented crystals and pulse-shape analysis, multiple-site events can be identified and removed from the data stream. Internal backgrounds from cosmogenic radioactivities will be greatly reduced by these cuts and external γ -ray backgrounds will also be preferentially eliminated. Remaining will be single-site events like that due to $\beta\beta$. The sensitivity is anticipated to be $\approx 10^{26}$ y.

Several research and development activities are currently proceeding. The collaboration is building a multiple-Ge detector array, referred to as MEGA, that will operate underground at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM USA. This experiment will investigate the cryogenic cooling of many detectors sharing a cryostat in addition to permitting studies of detector-to-detector coincidence techniques for background and signal identification. A number of segmented crystals are also being studied to understand the impact of segmentation on background and signal. Recently, these segmented detectors have shown that the radial information provided by PSD is indeed independent to the azimuthal information provided by the segmentation. The segmentation studies, or SEGA program, consists of one 12-segment enriched detector and a number of commercially available segmented detectors. Presently, commercially available segmented detectors are fabricated from n-type crystals. Such crystals are much more prone to surface damage and thus more difficult to handle when packaging inside their low-background cryostats. Hence the collaboration is also experimenting with segmenting p-type detectors.

The Majorana design uses Ge detectors within a low-mass, electroformed Cu cryostat. Electroformed Cu is very free of radioactive contaminants. However, just how radio-pure the Cu is remains unknown. Hence, the collaboration plans to form Cu underground and study its radiopurity to a sensitivity below previous limits.

Bare Ge Crystals

The GENIUS collaboration[75] proposed to install 1 t of enriched bare Ge crystals in liquid nitrogen. By eliminating much of the support material surrounding the crystals in previous experiments, this design is intended to reduce backgrounds of external origin. Note how this differs from the background-reduction philosophy associated with pulse-shape analysis coupled with crystal segmentation. The primary advocates for this project indicate[48] that its motivation has been questioned by their own claim of evidence for $0\nu\beta\beta$ decay. Even so, the GENIUS test facility[76] is being operated to demonstrate the effectiveness of operating crystals naked in liquid cryogen.

Another collaboration, GERDA (GERmanium Detector Array), however, is proposing to pursue a similar idea. They have recently submitted a Letter of Intent[81] to the Gran Sasso Laboratory. They propose to collect the enriched Ge crystals from both the Heidelberg-Moscow and IGEX experiments and operate them in either liquid nitrogen or liquid argon. As a second phase of the proposal, they plan to purchase an additional 20-kg of enriched, segmented Ge detectors and operate with a total of 35-40 kg for about 3 years. These initial two phases are presently under construction. Finally, they eventually plan to propose a large ton-scale experiment. It should be noted that this collaboration and the Majorana collaboration are cooperating on technical developments and if a future ton-scale experiment using ^{76}Ge proceeds these two groups will most likely merge and optimally combine the complementary technologies of bare-crystal operation and PSA-segmentation.

Nanocrystals

Some elements may be suitable for loading liquid scintillator with metallic-oxide nanoparticles. Since Rayleigh scattering varies as the sixth power of the particle radius, it can be made relatively small for nanoparticles of radii below 5 nanometers. Particles of this size have been developed and commercial suppliers of ZrO_2 , Nd_2O_3 etc. are available. Absorption of the materials must also be taken into account, but some of the metal oxides such as ZrO_2 and TeO_2 are quite transparent in the optical region because of the substantial band gaps in these insulators. Some members of the SNO collaboration[82] have been studying a configuration equivalent to filling the SNO cavity with a 1% loaded liquid scintillator or approximately 10 t of isotope after the present heavy water experiment is completed. The group is currently researching the optical properties of potential nano-crystal solutions. In particular, one must demonstrate that sufficient energy resolution is achievable with liquid scintillator.

Gas TPCs

Two ideas being discussed hope to track electrons well enough to show there are 2 and perhaps measure the opening angle. One of these ideas is to use a gridded ionization chamber with GeH_4 gas[73]. Such ionization chambers have demonstrated remarkable energy resolution. The other idea is to use a negative ion-drifting TPC containing the gas SeF_6 [83]. Both of these ideas are in the concept stage, but clearly point the way to alternative techniques that may permit measurements of kinematic variables beyond just the sum energy of the two electrons.

Super-NEMO

The currently operating NEMO-3 detector uses a tracking-calorimeter technique to detect $\beta\beta$. The source, is not the detector, but rather a thin foil located in the middle of a tracking chamber. This tracking chamber, which is made of geiger-drift cells, is surrounded by a calorimeter (scintillators with low radioactivity PMTs). The first of two long runs to search for $0\nu\beta\beta$ decay began in February of 2003 with 7 kg of ^{100}Mo and 1kg of ^{82}Se . Additionally, 2 kg of various foils were placed in the detector to study $2\nu\beta\beta$ decay and backgrounds. The first run will last approximately five years. So far a comprehensive study of the effects of various shields has been undertaken. The second run, again for five years, is currently planned to operate with 20 kg of ^{82}Se . The ^{82}Se is of particular interest because the $2\nu\beta\beta$ decay lifetime is 10 times that of ^{100}Mo and thus may contribute less as a background to $0\nu\beta\beta$ decay.

The recent progress of the NEMO-3 program[84] has culminated in excellent $2\nu\beta\beta$ results. In particular, the energy spectra from ^{100}Mo contain approximately 10^5 events and are nearly background free. These data permit, for the first time, a precise study of the spectra. In fact, there is hope that the data (Sutton 2004) will demonstrate whether the $2\nu\beta\beta$ transition is primarily through a single intermediate state or through a number of states[88].

A much bigger project is currently being planned that would use 100 kg of source. The apparatus would have a large footprint however and the Frejus tunnel where NEMO-3 is housed would not be large enough to contain it. Currently the collaboration is studying the design of such a detector.

XMASS

The XMASS collaboration[86] plans to build a 10 t natural Xe liquid scintillation detector. They expect an energy resolution of 3% at 1 MeV and hope to reach a value for $T_{1/2}^{0\nu} > 3.3 \times 10^{27}$ y. This detector would also be used for solar-neutrino studies and a search for dark matter.

Borexino CTF

In August of 2002, operations at the Borexino experiment resulted in the spill of scintillator. This led to the temporary closure of Hall C in the Gran Sasso Laboratory and a significant change in operations at the underground laboratory. As a result, efforts to convert the Counting Test Facility (CTF) or Borexino itself into a $0\nu\beta\beta$ experiment[67, 85] have been suspended[89].

How many $\beta\beta$ Experiments are Required?

In view of the importance and scale of new generation $0\nu\beta\beta$ experiments, internationally cooperative efforts in both experiment and theory are quite important. Thus it is reasonable to suggest a concentration of the limited resources on a few $\beta\beta$ experiments. However, it is critical to use different experimental techniques and isotopes to demonstrate the effect has really been seen and also to extract the most critical physics conclusions. It is therefore necessary to build a number of detectors and the reasons are enumerated here.

1. The observation of a statistically significant signal in a single experiment might not be considered a discovery without clear confirmation from other independent experiments utilizing different isotopes.
2. A nuclear matrix element is necessary to deduce $\langle m_{\beta\beta} \rangle$ from a measured $0\nu\beta\beta$ rate. Since theoretical calculations of $|M_{0\nu}|$ may include a substantial uncertainty, one needs experiments on different isotopes to extract a reliable value for the effective mass.
3. Although light-neutrino exchange is the most natural explanation for $0\nu\beta\beta$ if it exists, there are other possibilities. The relative matrix element values for different nuclei depend on the mechanism. Furthermore the matrix element situation is encouraging and one can anticipate a great improvement in the calculation precision. Therefore, measurements in several nuclei might be the most straight-forward way to provide insight into the mechanism of $0\nu\beta\beta$.
4. There are a number of different techniques being proposed for future experiments. Each has been previously used as effective prototypes for the proposals and therefore remains a strong candidate for future effort. However, the sensitivity of any given proposal depends strongly on its background estimate. It remains to be seen which of the technologies will successfully attain the required background. In addition, certain technologies provide capabilities such as measurements of the opening angle, individual electron energies, or the daughter production. These will not only help understand and remove background but they may also provide insight into the mechanism of $0\nu\beta\beta$.

FACILITY REQUIREMENTS

There are a large number of proposed double beta decay experiments worldwide. Any number of these might eventually be sited at DUSEL. Here we present a brief discussion of the requirements for the lab based on these proposals. We have chosen 3 of the proposals to elucidate the requirements. These 3 span the space of requirements because the other projects can be considered to have similar requirements to one of these three. Majorana is a solid-state calorimeter experiment, EXO is a liquid cryogen TPC experiment, and MOON is a large foil-tracking detector experiment.

Background reduction is the clear need for future $\beta\beta$ experiments. DUSEL can help achieve this requirement by providing cleanroom laboratories, machine shops, chemical facilities, assembly facilities deep underground. Such facilities will be required if the $\beta\beta$ experiments of the future hope to reach half-life sensitivities indicated by the atmospheric-oscillation mass scale. Majorana background estimates suggest that 4500 mwe would be an adequate depth, though the collaboration favors a deeper site, if available, to provide some margin of safety. MOON depth requirements are still quite uncertain, with the possibility that very great overburdens of 6000 mwe will be necessary. Provided the laser tagging is perfected and the prototype experiment reveals no unanticipated cosmogenic backgrounds, EXO could function at depths as shallow as 2000 mwe. Greater depth reduces the cosmic-ray μ flux at the experimental site. Hence depth is an obvious way to decrease the flux of high-energy neutrons that such neutrons produce. A detailed study of this problem [90] indicates that 5000 mwe would satisfy the needs for a compact calorimeter experiment, although expansive shield designs can help mitigate this problem.

Double beta decay space requirements: The space requirements for the experiments, given as length x width x height, are:

- Majorana: 5 x 4 x 3 m³ apparatus and 4 x 4 x 3 m³ control systems.
- EXO: 5 x 5 x 5 m³ apparatus, 5 x 4 x 3 m³ control systems, and 4 x 4 x 3 m³ cryogenic purification systems.
- MOON: 5 x 8 x 5 m³ apparatus and 8 x 11 x 6 m³ lab area and control systems.

Basic facilities needs: Most of the general site requirements of double beta decay experiments are modest. They include:

- Power requirements of 10-25 kW.
- Stable temperatures, usually 20 C or less, with air conditioning.
- Scrubbed air, with residual radon levels below 1Bq/m³.
- A clean room for preparations, assembly and cleaning.
- De-ionized water system.
- Cranes for assembly and manipulation of detector and shielding elements.
- Radon-free materials storage area.
- Machine shop, both general and for ultra-low background work.
- Low-level counting capabilities for materials screening.
- A source of radon-free liquid nitrogen or nitrogen gas. (Most experiments have a critical volume needing to be purged of radon. Pure nitrogen purge gas is commonly used, e.g., boil-off N₂ gas from liquid nitrogen.)

Special facilities needs (experiment specific): Majorana and EXO have identified special facilities needs and special safety concerns.

- An underground copper electroforming facility. The acids and plating baths used in the electroforming require special safety procedures. (Majorana)
- Possibly, underground Ge crystal growth and detector preparation facilities. (Majorana)
- Large-volume liquid Xe containment. Large quantities of liquid cryogenics present an oxygen displacement.

CONCLUSIONS

Study of the neutrinoless double beta decay and searches for the manifestation of the neutrino mass in ordinary beta decay are the main sources of information about the absolute neutrino mass scale, and the only practical source of information about the charge conjugation properties of the neutrinos. Thus, these studies have a unique role in the plans for better understanding of the whole fast expanding field of neutrino physics.

In this report we summarized the various aspects of the problem. We explained first the relation of the information that can be obtained from the analysis of $0\nu\beta\beta$ and β decay experiments with the parameters describing neutrino

oscillations and the absolute neutrino mass scale. We then discussed the nuclear structure issue and the uncertainty in determining the neutrino mass from a measured $0\nu\beta\beta$ decay rate. We also briefly discussed the role of neutrino mass in cosmology, and the corresponding constraints on neutrino masses based on astrophysical observations.

The remaining part of the report was devoted to the description of the existing and planned experiments. We described the present situation in $0\nu\beta\beta$ and tritium beta decay, and in particular the recent, so far unverified, claim of the $0\nu\beta\beta$ decay discovery. We concentrated then on the future plans for both areas of research.

The situation in the direct neutrino mass searches using tritium β decay is relatively simple. There is only one realistic plan a very large new beta spectrometer which is being built in Germany. This KATRIN experiment has a design sensitivity approaching 200 meV. If the neutrino masses are quasi-degenerate, as would be the case if the recent double-beta decay claim proves true, KATRIN will see the effect. Although KATRIN is predominately a European effort, there is significant US participation. The design and construction of this experiment is proceeding well and we enthusiastically recommend the continuing strongly support of this program.

There are many proposals, and even more ideas, for much larger $0\nu\beta\beta$ decay experiments than the existing ones. We outlined and justified in the report the strategy that we believe should be followed:

1. A substantial number (preferably more than two) of 200-kg scale experiments (providing the capability to make a precision measurement at the quasi-degenerate mass scale) with large US participation should be supported as soon as possible. We estimate that the timescale of such experiments is 3-5 years, and that each such experiment will cost approximately \$10M-\$20M.
2. Concurrently, the development toward ~ 1 -ton experiments (*i.e.* sensitive to $\sqrt{\Delta m_{\text{atm}}^2}$) should be supported, primarily as expansions of the 200-kg experiments. The corresponding plans for the procurement of the enriched isotopes, as well as for the development of a suitable underground facility, should be carried out. The US funding agencies should set up in a timely manner a mechanism to review and compare the various proposals for such experiments which span research supported by the High Energy and Nuclear Physics offices of DOE as well as by NSF. Each such experiment will cost approximately \$50M-\$100M and take 5-10 years to implement.
3. A diverse R&D program developing additional techniques of $0\nu\beta\beta$ decay study should be supported.

The field of neutrino physics has made great strides recently. We believe that the study of $0\nu\beta\beta$ decay in particular could very well be the next one where significant discoveries will be made.

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