Neutrino Mass Patterns and Future Double-Beta Decay Experiments

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The next generation of double-beta decay experiments have an excellent chance of providing data on the neutrino mass pattern. This presentation is a summary of what is currently known about the mass pattern and expectations from experiment. Uncertainties due to the precision in the oscillation parameters are not critical to the interpretation of a $\beta\beta(0\nu)$ measurement in terms of the mass pattern. Even though there is reason for optimism, the matrix element uncertainty is still a concern. A selected, representative group of the future experiments is discussed.

1. Introduction

Since an introduction to the science of double-beta decay ($\beta\beta$) was discussed by another speaker at this meeting,[1] only the critical points necessary for the discussion in this paper will be summarized here. Reference [2] is a recent review.

The zero-neutrino double-beta decay ($\beta\beta(0\nu)$) rate ($\Gamma$), is directly related to neutrino mass. $\Gamma$ is proportional to the square of the effective Majorana neutrino mass ($\langle m_{\beta\beta} \rangle$), an easily calculable phase space factor ($G$), and a difficult-to-calculate nuclear matrix element ($|M_{0\nu}|$);\[ \Gamma = G|M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2. \] (1)

The value for $\langle m_{\beta\beta} \rangle$ in turn, depends on the values of the individual neutrino mass eigenstates ($m_i$), the mixing matrix elements ($U_{ei}$) and the Majorana phases ($\alpha_i$);\[ \langle m_{\beta\beta} \rangle^2 = \sum_{i} |U_{ei}|^2 e^{i\alpha_i} m_i^2. \] (2)

To deduce information on $m_i$ from a measurement of $\Gamma$ the value of $|M_{0\nu}|$ and $|M_{0\nu}|$. In this report, we discuss how the uncertainties in these factors affect the conclusions on $m_i$. In addition we summarize the proposals for future $\beta\beta(0\nu)$ measurements.

2. Oscillations and $\beta\beta$ Decay

The results of the oscillation experiments provide data on the mixing matrix elements and the differences in the squares of the mass eigenvalues ($\delta m_{ij}^2 \equiv m_j^2 - m_i^2$). From the atmospheric neutrino data, we have $\delta m_{atm}^2 = 2.0^{+1.0}_{-0.7} \times 10^{-3}$ eV$^2$ (90% CL) and $\theta_{23} \approx 45$ degrees[3]. The combined results of the solar neutrino experiments and the reactor experiments[4] give $\delta m_{sol}^2 = 7.1^{+1.2}_{-0.6} \times 10^{-5}$ eV$^2$ and $\theta_{12} = 32.5^{+2.4}_{-2.3}$ degrees (68% CL). (Note that other authors have found modestly different results. See, e.g. Refs. [5,6].) From reactor experiments, we have a limit on $\delta m_{13} < 9$ degrees[7] (68% CL). If there are only 3 neutrinos, then these two $\delta m^2$ values define the mass spectrum given any one of the masses. However, the hierarchy of the mass spectrum is not yet known. In the convention used in this paper, $\nu_e$ is predominately composed of the mass eigenstate $\nu_1$. The hierarchy uncertainty can be simply stated: Is $\nu_1$ the lightest mass eigenstate?

The central values of these results and Eqn. 4 determine a range of $\langle m_{\beta\beta} \rangle$ values for a given value of $m_1$. Many authors have done this analysis (See, e.g. Refs. [8,9,10,11,12,13,14]) and Fig. 1 shows the result of the calculation. The bands indicate the range of possible values for arbitrary values of the phases. The borders indicate the CP conserving values of the phases, $e^{i\alpha} = \pm 1$.\}
3. UNCERTAINTIES IN $\langle m_{\beta\beta} \rangle$

The observation of $\beta\beta(0\nu)$ would have profound physics implications regardless of the size of the uncertainty in the deduced value of $\langle m_{\beta\beta} \rangle$. It would show that neutrinos are massive Majorana particles and that total lepton number is not a conserved quantity. But it is interesting to ask whether one can use a measurement of $\langle m_{\beta\beta} \rangle$ to discern these two hierarchies. At high values of the minimum neutrino mass, the mass spectrum is quasi-degenerate, and the bands are not resolved. At values of the minimum neutrino mass below $\approx 50$ meV, the degenerate band splits into two bands representing the normal ($m_1$ lightest) and inverted ($m_3$ lightest) hierarchy cases. Figure 1 indicates that it would be straight-forward to identify the appropriate band at these low mass values. However, there are uncertainties in the oscillation parameters and the matrix elements that are not represented in the figure.

One can address this question by comparing the maximum value for the normal hierarchy ($\langle m_{\beta\beta} \rangle_{\text{Nor max}}$) with the minimum value for the inverted hierarchy ($\langle m_{\beta\beta} \rangle_{\text{Inv min}}$) that can result from the parameter uncertainties. When the lightest neutrino mass is small, one can write expressions for the maximum value for the normal hierarchy case and the minimum value for the inverted hierarchy case. When $m_1$ is near zero, $\langle m_{\beta\beta} \rangle_{\text{Nor max}}$ occurs for constructive interference between the contributions from the $m_2$ and $m_3$ terms when CP is conserved.

$$\langle m_{\beta\beta} \rangle_{\text{Nor max}} = \sqrt{\delta m^2_{\text{sol}} \sin^2 \theta_{\text{sol}} \cos^2 \theta_{13}}$$

$$+ \sqrt{\delta m^2_{\text{atm}} \sin^2 \theta_{13}}$$

From Eqn. 3 it is clear that $\langle m_{\beta\beta} \rangle_{\text{Nor max}}$ is maximal when $\theta_{13}$ is maximum, $\theta_{\text{sol}}$ is maximum and the $\delta m^2$ are maximum.

$\langle m_{\beta\beta} \rangle_{\text{Inv min}}$ is minimal with the same conditions on $\theta_{13}$ and $\theta_{\text{sol}}$, but for a minimum value for $\delta m^2_{\text{atm}}$.

$$\langle m_{\beta\beta} \rangle_{\text{Inv min}} = \sqrt{\delta m^2_{\text{atm}} \cos^2 \theta_{\text{sol}} \cos^2 \theta_{13}}$$

If we use the appropriate extremum values for the oscillation parameters in Eqns. 3 and 4 we find $\langle m_{\beta\beta} \rangle_{\text{Nor max}} \approx (9.1 \text{ meV}) (0.327)(0.976) + (55 \text{ meV})(0.024) = 4 \text{ meV}$ and $\langle m_{\beta\beta} \rangle_{\text{Inv min}} \approx (36 \text{ meV})(0.345)(0.976) = 12 \text{ meV}$. These numbers are sufficiently different, at least when using these low-CL uncertainty ranges, that it would appear one could discriminate between the two solutions.

Since the precision of the oscillation parameters is likely to improve with future experiments, they would not appear to be the primary concern. Even so, how critical each parameter is for this analysis can be determined by propagating its uncertainty to the $\langle m_{\beta\beta} \rangle$ uncertainty. Such a propagation-of-errors analysis is shown in Table 1 and it is clear that $\theta_{13}$ affects $\langle m_{\beta\beta} \rangle_{\text{Nor max}}$ a great deal. Its also clear that $\delta m^2_{\text{atm}}$ is critical for $\langle m_{\beta\beta} \rangle_{\text{Inv min}}$. Finally, $\theta_{\text{sol}}$ is important for both. This propagation-of-error analysis, however, doesn’t elucidate the effect that $\theta_{\text{sol}}$ also has on Fig. 1. The value of the lightest mass for which the cancellation drives $\langle m_{\beta\beta} \rangle$ to very small...
values depends critically on $\theta_{sol}$. But note that as long as the data indicates that the solar mixing is substantially separated from maximal, the cancellation is possible only over a narrow range of values for the lightest mass. All in all, the need to interpret $\Gamma$ provides additional motivation to improve the precision on $\theta_{13}$, $\theta_{sol}$ and $\delta m^2_{atm}$.

$|M_0|$ has been a source of concern for a long time. Typically, an uncertainty of a factor of 2-3 has been assumed for the determination of $\langle m_{\beta\beta}\rangle$ due to $|M_0|$. This uncertainty clearly dwarfs any uncertainty from the oscillation parameters and thus is the primary issue. Reference [10] gives an overview of the calculations, but there has been some recent progress.

$^{76}$Ge is a low-Z isotope relative to most other $\beta\beta$ isotopes. Hence it is a good candidate for shell model calculations of $|M_{0|\nu}|$. The sum over the huge intermediate space of $1^+$ states was done by Lanczos moments techniques for the neighboring $^{82}$Se $\beta\beta$ isotope [17]. The corresponding $^{76}$Ge calculation was done as a series, which is not exactly what is needed. But these calculations can be improved and new methods [13] might already be able to handle the full-shell model calculation for $^{76}$Ge. Such calculations are only as reliable as the input effective interaction and a recent calculation by Honma et al. [19] shows that the technology is very close to doing a Brown-Wildenthal style interaction calculation for Ge. A recent report [20], however, demonstrates that single-particle states relatively far from the Fermi level are important for $\beta\beta(0\nu)$ and therefore the required number of states is very large.

The quasiparticle random phase approximation (QRPA) is currently a popular technique used to estimate $|M_{0|\nu}|$. However, various implementations of QRPA by different authors have produced a spread of results. When this spread is interpreted as an uncertainty in $|M_{0|\nu}|$, it leads to a factor of 2 uncertainty in $\langle m_{\beta\beta}\rangle$. Recently however, it has been shown [21] that fixing the strength of the particle-particle interaction so the calculation produces the measured $\beta\beta(2\nu)$ result removes the variability between the various implementations. This exciting development will hopefully lead to a better understanding of the source of the spread.

4. FUTURE EXPERIMENTS

Table 2 summarizes the $\beta\beta$ proposals. The target $\langle m_{\beta\beta}\rangle$ sensitivity for the next generation of experiments is defined by $\sqrt{\delta m^2_{atm}} \approx 45$ meV. At this level, even null results will have a significant impact on our understanding of the mass spectrum if neutrinos are Majorana particles. This is especially true if the result is coupled with a kinematic measurement of neutrino mass from either tritium beta decay [22] or cosmology. (See e.g. Ref. [23].) To accomplish this goal requires approximately 1 ton of isotope.

Of the projects listed in Table 2, five are especially worthy of extra notice in my opinion. These five, CUORE, EXO, GENIUS, Majorana and MOON, have designs that meet the technical requirements for the 45-meV goal and, as a group, span the various techniques used for the study of $\beta\beta$. Since CUORE was described by another speaker [1], I will only describe the other four projects.

4.1. EXO

The Enriched Xenon Observatory (EXO) [30] proposes to use up to 10 t of 60-80% enriched $^{136}$Xe. The unique aspect of this proposal is the plan to detect the $^{136}$Ba daughter ion correlated with the decay. If the technique is perfected, it would eliminate all background except that associated with $\beta\beta(2\nu)$. The real-time optical detection of the daughter Ba ion, initially suggested in Ref. [31], might be possible if the ion can be localized and probed with lasers. The spectroscopy has been used for Ba$^+$ ions in atom traps. However, the additional technology to detect single Ba ions in a condensed medium or to extract single Ba ions from a condensed medium and trap them must be demonstrated for this application.

The EXO plan is to use Liquid Xe (LXe) scintillator. The LXe concept has the advantage of being much smaller than a gaseous TPC due to the high density of LXe. Once the Ba ion is localized via its scintillation and ionization, it might be extracted via a cold finger electrode coated in frozen Xe (M. Vient, unpublished observation, 1991). The ion is electrostatically attracted to the cold finger which later can be heated to evap-
Table 1
A summary of the impact on the values for $\langle m_{\beta\beta} \rangle$ in the normal and inverted hierarchies due to the oscillation parameter uncertainties. For the central values of the parameters, the nominal values of $\langle m_{\beta\beta} \rangle_{\text{Nor max}}$ and $\langle m_{\beta\beta} \rangle_{\text{Inv min}}$ are 2.4 meV and 19 meV, respectively. See Ref. [15] for a previous similar analysis.

| Oscillation Parameter | Range          | Range in $\langle m_{\beta\beta} \rangle_{\text{Nor max}}$ | Range in $\langle m_{\beta\beta} \rangle_{\text{Inv min}}$ |
|----------------------|----------------|-------------------------------------------------------------|-------------------------------------------------------------|
| $\sqrt{\delta m^2_{\text{sol}}}$ | 8.1 - 9.1 meV  | 2.3 - 2.6 meV                                               | N.A.                                                        |
| $\sqrt{\delta m^2_{\text{atm}}}$ | 36 - 55 meV    | 3.2 - 3.7 meV (with $\theta_{13} = 9^\circ$)                | 15.2 - 23.2 meV                                             |
| $\theta_{\text{sol}}$ | 30.1 - 34.9 deg | 2.1 - 2.7 meV                                               | 15.5 - 22.4 meV                                             |
| $\theta_{13}$       | 0 - 9 deg      | 2.4 - 3.5 meV                                               | 18.6 - 19.0 meV                                             |

orotate the Xe and release the Ba ion into a radio frequency quadrupole trap. At that point, the Ba$^{++}$ is neutralized to Ba$^+$, laser cooled and optically detected.

The collaboration has recently performed experiments to optimize the energy resolution[41]. By measuring both scintillation light and ionization simultaneously, they have achieved energy resolution sufficient for the experiment. Tests to determine the viability of the Ba extraction process are also being performed. The EXO collaboration has received funding to proceed with a 200-kg enriched Xe detector without Ba tagging. This initial prototype will operate at the Waste Isolation Pilot Plant (WIPP) in southern New Mexico.

4.2. GENIUS
The progress and understanding of Ge detectors has been developed over more than 30 years of experience. The potential of these detectors lie in their great energy resolution, ease of operation, and the extensive experience relating to the reduction of backgrounds. This potential is not yet exhausted as is evidenced by the GENIUS and Majorana proposals.

The GENIUS (GERmanium NItrogen Underground Setup) [33] proposal has evolved from the Heidelberg-Moscow (HM) experiment. The driving design principle behind this proposed Ge detector array experiment is the evidence that the dominant background in the HM experiment was due to radioactivity external to the Ge. (The reader should contrast this with the motivation for the design of the Majorana proposal described below.) An array of 2.5-kg, p-type Ge crystals would be operated "naked" within a large liquid nitrogen (LN) bath. By using naked crystals, the external activity would be moved to outside the LN region. Due to its low stopping power, roughly 12 m of LN is required to shield the crystals from the ambient $\gamma$-ray flux at the intended experimental site at Gran Sasso. A test of the naked operation of a crystal in a 50 l dewar has been successful [42,43].

The proposal anticipates an energy resolution of $\approx 6$ keV FWHM (0.3%) and a threshold of 11 keV. The value of this low threshold is set by $x$ rays from cosmogenic activities. Using 1 t of 86% enriched Ge detectors, the target mass is large enough for dark matter studies. In fact a 10-kg $\text{nat}$Ge proof-of-principle experiment for dark matter studies has begun at Gran Sasso [44].

4.3. Majorana
The Majorana Collaboration plans to use $\approx 500$, 86% enriched, segmented Ge crystals for a total of 500 kg of detector [36,37]. The cryostat would be formed from very pure electroformed Cu [45]. Their analysis indicated that $^{68}$Ge contained within the Ge detectors was the limiting background for their $\beta\beta$(0$\nu$) search. (Contrast this with the GENIUS approach described above.) The proposal’s design therefore emphasizes segmentation and pulse shape discrimination to reject this background. $^{68}$Ge produces a background that deposits energy at multiple sites in the detector. In contrast, a $\beta\beta$(0$\nu$) event will have a localized energy deposit. Segmentation of the crystals permits a veto of such events. Furthermore, distinct ionization events will have a
Table 2
A summary of the double-beta decay proposals. The quoted sensitivities are those quoted by the proposers but scaled for 5 years of run time. These sensitivities should be used carefully as they depend on background estimates for experiments that don’t yet exist.

| Experiment | Source | Detector Description | Sensitivity to $T_{1/2}^{0\nu}$ (y) |
|------------|--------|----------------------|------------------------------------|
| CAMEO [27] | $^{116}$Cd | 1 t CdWO$_4$ crystals in liq. scint. | $1 \times 10^{27}$ |
| CANDLES [28] | $^{48}$Ca | several tons of CaF$_2$ crystals in liq. scint. | $1 \times 10^{26}$ |
| COBRA [24] | $^{130}$Te | 10 kg CdTe semiconductors | $1 \times 10^{24}$ |
| CUORE [29] | $^{130}$Te | 750 kg TeO$_2$ bolometers | $2 \times 10^{26}$ |
| DCBA [25] | $^{150}$Nd | 20 kg enrNd layers between tracking chambers | $2 \times 10^{25}$ |
| EXO [30] | $^{136}$Xe | 1 t enrXe TPC (gas or liquid) | $8 \times 10^{26}$ |
| GEM [32] | $^{76}$Ge | 1 t enrGe diodes in liq. nitrogen | $7 \times 10^{27}$ |
| GENIUS [33] | $^{76}$Ge | 1 t 86% enrGe diodes in liq. nitrogen | $1 \times 10^{28}$ |
| GSO [34,35] | $^{160}$Gd | 2 t Gd$_2$SiO$_5$:Ce crystal scint. in liq. scint. | $2 \times 10^{26}$ |
| Majorana [36] | $^{76}$Ge | 0.5 t 86% segmented enrGe diodes | $3 \times 10^{27}$ |
| MOON [38] | $^{100}$Mo | 34 t natMo sheets between plastic scint. | $1 \times 10^{27}$ |
| NEMO 3 [26] | $^{100}$Mo | 10 kg of $\beta\beta(0\nu)$ isotope (7 kg Mo) with tracking | $4 \times 10^{24}$ |
| Xe [39] | $^{136}$Xe | 1.56 t of enrXe in liq. scint. | $5 \times 10^{26}$ |
| XMASS [40] | $^{136}$Xe | 10 t of liq. Xe | $3 \times 10^{26}$ |

different pulse shape than a localized event. Thus pulse shape analysis can also reject background.

The collaboration is fielding a close-packed array of 18 Ge detectors, 16 of which will share a lone cryostat. This prototype, called MEGA [46], will demonstrate the cryogenic cooling design for multiple crystals in a single low-background cryostat. It will also permit a study of crystal-to-crystal coincidence suppression of backgrounds for $\beta\beta$ and dark matter. Finally, the operation of MEGA at WIPP will provide an excellent material screening facility in addition to a very sensitive apparatus for studying $\beta\beta$ to excited states. These later experiments will be conducted by placing samples within the MEGA detector arrangement. The high efficiency for $\gamma$-ray detection will provide the sensitivity for observing the two $\gamma$ rays from the excited state relaxation.

In addition, the collaboration is studying the performance of several segmented detector configurations. This program, called SEGA [47], will establish the background rejection capabilities of segmented detectors experimentally and confirm the previous Monte Carlo studies. Pulse shape discrimination tends to identify multiple energy deposits along the radial direction in crystals whereas the segmentation tends to identify multiple deposits axially and azimuthally. The SEGA program will measure the orthogonality of these cuts. There are 3 segmented geometries that will be studied: (1) a custom designed, isotopically enriched, 12-segment detector (2) a stock-item commercially available Clover (TM) detector from Canberra and (3) a many-segmented detector originally obtained for studies for the GRETA project [48]. The 12-segmented enriched detector will also operate at WIPP, both as a stand-alone unit and also as one of the detectors comprising the MEGA apparatus.

4.4. MOON
The MOON (Mo Observatory Of Neutrinos) proposal [38] plans to use $^{100}$Mo as a $\beta\beta(0\nu)$ source and as a target for solar neutrinos. This dual purpose and a sensitivity to low-energy su-
pernova electron neutrinos\textsuperscript{[49]} make it an enticing idea. $^{100}$Mo has a high Q-value (3.034 MeV), which results in a large phase space factor and places the $\beta\beta(0\nu)$ peak region well above most radioactive backgrounds. It also has hints of a favorable $|M_{0\nu}|$ but unfortunately it has a relatively short $T^{2\nu}_{1/2}$. The experiment will make angular correlation studies of $\beta\beta$ to select $\beta\beta(0\nu)$ events and to reject backgrounds. The planned MOON configuration is a supermodule of scintillator and Mo ensembles. One option is a module of plastic fiber scintillators with thin (20 mg/cm$^2$) layers of Mo, arranged to achieve a position resolution comparable to the fiber diameter (2-3 mm).

The project needs Mo and scintillator radioactive impurity levels less than 1 mBq/ton. This can be achieved by carbonyl chemistry for Mo and plastics can be produced cleanly. The simulations of the scintillator-film sandwich design indicate that the energy resolution for the $\beta\beta(0\nu)$ peak will be $\approx$5% FWHM, which is at the upper end of the range of feasibility for a sub 50 meV $\langle m_{\beta\beta}\rangle$ experiment. Metal-loaded liquid scintillator and bolometer options are also being considered. The bolometer option would remove the resolution concerns. Use of enriched $^{100}$Mo is feasible, as it can be enriched by either gas centrifuge or laser ionization separation. Enrichment would reduce the total volume of the apparatus resulting in a lower internal radioactivity contribution to the background by an order of magnitude.

4.5. OTHER PROPOSALS

There are too many additional proposals in Table 2 for detailed description but I mention the remaining ones here. The CAMEO proposal\textsuperscript{[24]} would use 1000 kg of scintillating $^{116}$CdWO$_4$ crystals situated within the Borexino apparatus. The Borexino liquid scintillator would provide shielding from external radioactivity and light piping of crystal events to the photomultiplier tube (PMT) array surrounding the system. Similarly, the CANDLES proposal\textsuperscript{[28]} (CAlcium floride for study of Neutrino and Dark matter by Low Energy Spectrometer) plans to immerse CaF$_2$ in liquid scintillator. The scintillation light from the $\beta\beta$ of $^{48}$Ca will be detected via PMTs. Two groups\textsuperscript{[34,35]} have been studying the use of GSO crystals (Gd$_2$SiO$_5$:Ce) for the study of $\beta\beta$ in $^{136}$Cd.

COBRA (CdTe O neutrino double Beta Research Apparatus)\textsuperscript{[21]} would use CdTe or CdZnTe semiconductors to search for $\beta\beta(0\nu)$ in either Cd or Te. 1600 1-cm$^3$ crystals would provide 10 kg of material. GEM is a proposal\textsuperscript{[32]} that is very similar to that of GENIUS. However, much of the LN shielding would be replaced with pure water.

The Drift Chamber Beta-ray Analyzer (DCBA) proposal\textsuperscript{[25]} is for a three-dimensional tracking chamber in a uniform magnetic field. Thin plates of Nd would form the source. The series of NEMO experiments is progressing with NEMO-3\textsuperscript{[24]} that began operation in 2002. The detector contains a source foil enclosed between tracking chambers that is itself enclosed within a scintillator array. NEMO-3 can contain a total of 10 kg of source and plans to operate with several different isotopes, but with $^{100}$Mo being the most massive at 7 kg. The collaboration is also discussing the possibility of building a 100-kg experiment that would be called NEMO-4.

There are two additional groups proposing to use $^{136}$Xe to study $\beta\beta(0\nu)$. Caccianiga and Giammarchi\textsuperscript{[39]} propose to dissolve 1.56 t of enriched Xe in liquid scintillator. The XMASS\textsuperscript{[40]} collaboration proposes to use 10 t of liquid xenon for solar neutrino studies. The detector would have sensitivity to $\beta\beta(0\nu)$.

5. CONCLUSIONS

This is a very exciting time for $\beta\beta$. The next generation of experiments will be sensitive to a mass region where neutrino masses are known to exist. As a result, even null experiments will have an impact on our understanding of the mass spectrum. The subtleties associated with the uncertainties in $|U_{ei}|$ and $|M_{0\nu}|$are of secondary importance. If $\beta\beta(0\nu)$ is observed, the physics learned will be revolutionary as it would establish the neutrino as a massive Majorana particle.

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