Neutrinoless double beta decay

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Abstract. Present status of the search for $0\nu\beta\beta$ decay and of the related theoretical questions is reviewed. The mechanism of the decay, and how to recognize it, is discussed first, followed by the relation of the effective neutrino Majorana mass and the oscillation parameters, and the problems of nuclear matrix elements. The planned $\sim$ 100 kg experiments are briefly described.

Keywords: Double β decay, neutrino mass, Majorana particles
PACS: 14.60.Pq, 23.40.-s, 23.40.Hc

INTRODUCTION

Thanks to the discoveries of recent years we know that neutrinos have mass and that they are mixed. The three mixing angles have been reasonably well determined (even though for the angle θ_{13} only the small upper limit exists) and the two mass square differences Δm^2_{21} and $|\Delta m^2_{31}|$ are also known. The extent of our present knowledge of the oscillation parameters is summarized in Fig. 1. For further discussion the important point is that the electron neutrino ν_e is dominantly an unequal superposition of two close lying states ν_1 and ν_2, with a small, perhaps vanishing, admixture of the further away state ν_3. Despite these triumphs there are questions that ought to be answered before we might be able to formulate what is sometimes called a “New Standard Model" that would properly incorporate these new discoveries:

- Are neutrino Majorana particles or Dirac particles like the other fermions?
- What is absolute neutrino mass?
- What is the mass pattern, normal or inverted hierarchy (see Fig.1)?
- Is CP symmetry violated in the lepton sector?
- Is there a relation between all of this and the baryon asymmetry of the Universe?

Study of neutrinoless double beta decay could, and hopefully will in a foreseeable future, help in answering the first two questions on the above list.

What is double beta decay? It is the nuclear transition, typically involving the ground states of even-even nuclei (Z,A) and $(Z+2,A)$ in which two neutrons are simultaneously transformed into two protons and two electrons (and perhaps something else). Such process is possible because the even-even nuclei are more bound than the odd-odd ones with the same number A of nucleons, as illustrated in Fig. 2. The transition changing protons into neutrons, with the emission of positrons or with electron captures, is also possible as could be deduced from Fig.2, but in the following we concentrate on the decay with the emission of electrons. Note that the depicted situation is not unique,

CP870, *Intersections of Particle and Nuclear Physics: 9th Conference,*
edited by T. M. Liss

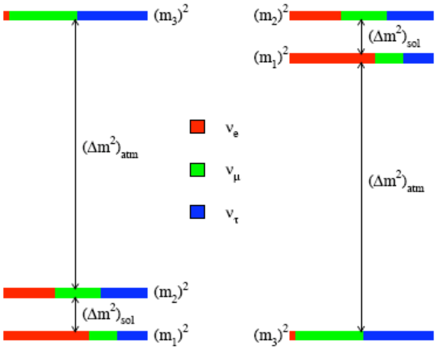

FIGURE 1. Normal (left) and inverted (right) hierarchies, with the flavor composition of the mass eigenstates shown. The ν_e component of ν_3 with the mass m_3 is just an upper limit. Note that Δm^2 are not to scale.

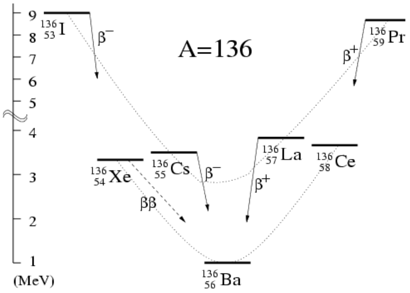

FIGURE 2. Masses of nuclei with 136 nucleons, with the y-axis shifted arbitrarily. The two faint parabolas connect the even-even and odd-odd nuclei, respectively. ^{136}Xe and ^{136}Ce are stable against the ordinary β decay, but can decay by emission of two electrons (^{136}Xe) or two positrons (^{136}Ce).

there are eleven ‘candidate nuclei’ pairs, analogous to the $^{136}\text{Xe} \rightarrow {}^{136}\text{Ba}$, with the Q value, i.e., available kinetic energy, in excess of 2 MeV.

There are two modes of the $\beta\beta$ decay. In the $2\nu\beta\beta$ mode two e^- and two $\bar{\nu}_e$ are emitted simultaneously, and in the $0\nu\beta\beta$ mode only the two e^- and nothing else is emitted. The $2\nu\beta\beta$ decay is a standard allowed process, only slow because it is of the second order weak. It has been observed in a number of cases, with the typical half-life of $T_{1/2} \sim 10^{20}$ years. The sum-electron kinetic energy spectrum of the $2\nu\beta\beta$ decay is continuous, peaked below the midpoint of the Q value.

In contrast, the $0\nu\beta\beta$ decay violates the lepton number conservation law that is a symmetry of the Standard Model. Hence, its observation would signal a presence of ‘new physics’, namely that neutrinos are massive Majorana particles, and it would answer the first question on the list above. That existence of the total lepton number violation and the statement that neutrinos are massive Majorana particles are equivalent follows from the theorem initially formulated by Schechter and Valle long time ago [1] and illustrated symbolically in Fig.3.

Since the nuclei are very heavy compared to the Q value of the $\beta\beta$ decay, the nuclear recoil energy is negligible. In the $0\nu\beta\beta$ decay the sum-electron spectrum is therefore a δ-function peak, smeared only by the resolution of a detector. By determining the sum of the electron energies, one can separate the $0\nu\beta\beta$ from the $2\nu\beta\beta$ decay mode, even if the rates differ by as much as 10^6, the goal of the near term plans.

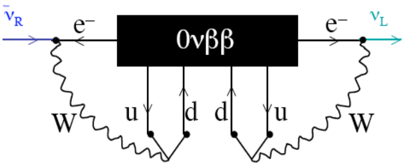

FIGURE 3. By adding standard weak interactions in loops to the $0\nu\beta\beta$ elementary amplitude (black box) one obtains the neutrino Majorana mass term.

MECHANISM OF THE $0\nu\beta\beta$ DECAY

The $0\nu\beta\beta$ decay can be caused by the virtual exchange between the two participating nucleons of light Majorana neutrinos, the same ones that are known to be massive and oscillating. This is the simplest assumption about the mechanism involved in the 'black box' in Fig.3. However, there are other possibilities as well. The virtual exchange might involve various so far hypothetical heavy particles (right-handed neutrinos, W_R, supersymmetric particles, etc.). In that case, the six-fermion vertex in the 'black box' has a dimension $d = 9$ and scales like $1/\Lambda^5$, where Λ is the typical scale of the heavy particles involved. By observing the $0\nu\beta\beta$ decay as a peak in the sum-electron spectrum, one cannot determine the mechanism that caused it. That would be the case even if more detailed information becomes available (e.g. the single electron spectra, or the angular distribution of the electrons), at least for some of the possible mechanisms. The two competing mechanisms, the light neutrino exchange (when the amplitude scales as mass $\langle m_{\beta\beta}\rangle$) and the heavy particle exchange (scale Λ^{-5}) have similar rates for $\langle m_{\beta\beta}\rangle \sim 0.3$-$1.0$ eV and $\Lambda \sim$ few TeV [2]. This is the range of Λ values where confusion might exist; smaller Λ are already experimentally excluded, much heavier ones are irrelevant due to the steep $1/\Lambda^5$ dependence.

If the $0\nu\beta\beta$ decay is observed, how could we tell which mechanism is responsible? One possibility, suggested in Ref.[3], is the relation between the Lepton Number Violation (LNV) and Lepton Flavor Violation (LFV). The best constrained LFV processes are $\mu \rightarrow e+\gamma$ and $\mu \rightarrow e$ conversion in a nuclear field. Plans exist for a major improvement in the sensitivity in the search for both these processes [4, 5].

A typical theoretical prediction of the corresponding branching ratios is that $B_{\mu\rightarrow e}/B_{\mu\rightarrow e+\gamma} \sim \alpha/\pi \sim 10^{-2} - 10^{-3}$. However, in models (e.g. the left-right symmetric model or R-parity violating supersymmetry) where low scale LNV exists, the corresponding ratio is $\gg 10^{-2}$ [3]. Thus, the eventual observation of these LFV processes can be used a diagnostic tool for the presence of low-scale LNV with $\Lambda \sim$ TeV that could cause confusion in interpreting the future $0\nu\beta\beta$ decay observation. (There are important caveats to that rule, but they involve 'fine tuning' and thus are less likely.) If the LFV is not seen in the next round of experiments, it is also unlikely that the models with low scale LNV are viable.

$0\nu\beta\beta$ DECAY AND OSCILLATION PARAMETERS

Lets assume that the simplest scenario is the correct one, i.e., that the $0\nu\beta\beta$ decay is caused by the exchange of light Majorana neutrinos. In that case the decay rate is

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

where $G^{0\nu}(E_0,Z)$ is the easily and accurately calculable phase space factor, $M^{0\nu}$ is the nuclear matrix element, discussed below, and $\langle m_{\beta\beta}\rangle$ is the effective neutrino Majorana mass

$$\langle m_{\beta\beta}\rangle = \Sigma_i |U_{ei}|^2 m_i e^{i\alpha_i} \ , \tag{2}$$

where U_{ei} is the first row of the neutrino mixing matrix, m_i are the absolute (nonnegative) neutrino masses of the mass eigenstates $|i\rangle$, and α_i are unknown Majorana phases that cannot be determined in oscillation experiments. (Naturally, for 3 neutrinos only 2 phase differences are physical.)

The relation between the quantity $\langle m_{\beta\beta}\rangle$ and other related observables is depicted in Fig.4. One can see that in the case of inverted hierarchy (red diagonal shading) there is a lower limit on $\langle m_{\beta\beta}\rangle \sim 20$ meV for the best fit oscillation parameters, extended to ~ 10 meV when the error bars are included. For the normal hierarchy (blue horizontal shading) there is no lower limit for the $\langle m_{\beta\beta}\rangle$. If $\theta_{13} = 0$ that quantity would vanish if $\alpha_2 - \alpha_1 = \pi$ and

$$m_{min} = m_1 = \frac{\sin^2\theta_{12}\sqrt{\Delta m^2_{21}}}{\sqrt{\cos 2\theta_{12}}} \sim 4.5 \text{ meV} \ . \tag{3}$$

If $\theta_{13} \neq 0$ the interval of vanishing $\langle m_{\beta\beta}\rangle$ widens. Thus $\langle m_{\beta\beta}\rangle$ can exactly vanish, and the $0\nu\beta\beta$ decay can be unobservable, even though all three mass eigenstates $|i\rangle$ represent massive Majorana neutrinos. Obviously, this possibility, while not excluded, represents 'fine tuning', unless some symmetry dictates it.

As seen in Fig. 4 by observing the $0\nu\beta\beta$ decay we cannot, in general, decide on the mass hierarchy. Note that the degenerate mass pattern, $\langle m_{\beta\beta}\rangle \geq\sim$ 50-100 meV could, and probably will be, accessible to the tritium β-decay experiments and/or 'observational cosmology'. These probes of neutrino mass are insensitive to the difference between Majorana and Dirac neutrinos. If the degenerate mass scenario is the correct one, we will be able, in near future, to compare the two or three possible mass determinations, and using the bands in Fig.4 check their consistency.

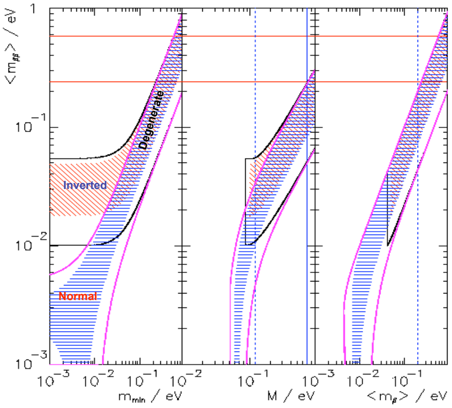

FIGURE 4. The relation between the effective neutrino mass $\langle m_{\beta\beta} \rangle$ and other absolute neutrino mass related observables. m_{min} is mass of the lightest neutrino, $M = \Sigma_i m_i$ is the sum of neutrino masses, constrained or determined by 'observational cosmology', and $\langle m_\beta \rangle^2 = \Sigma_i |U_{ei}|^2 m_i^2$ is observable in β decay. Shaded bands are for the best values of U_{ei}, lines include the 95% CL errors. The width of the shaded bands reflects the uncertainty related to the unknown Majorana phases.

$0\nu\beta\beta$ DECAY NUCLEAR MATRIX ELEMENTS

Clearly, if the goal is a determination of the effective mass $\langle m_{\beta\beta} \rangle$, then an uncertainty in the nuclear matrix elements $M^{0\nu}$ causes corresponding uncertainty in $\langle m_{\beta\beta} \rangle$. Unfortunately, the nuclear many-body system does not allow (at least not now) exact solutions, and approximations must be used. Treating the nucleus as A nucleons bound in a mean field and interacting through effective residual force is a common, and presumably good approximation. Next, one has to decide how wide interval of single-particle states around the Fermi level to include in a calculation of $M^{0\nu}$, and how complicated configurations of the valence nucleons should be taken into account. In that respect the two common methods, the nuclear shell model (SM) and the quasiparticle random phase approximation (QRPA) represent almost opposite extremes. In SM only a narrow interval (one shell or less) can be used, but all (or almost all) configurations are included, in QRPA an arbitrary number of single particle states can be included, but only simple particle-hole (or two-quasiparticle) configurations and their iterations are included. Since QRPA is much simpler computationally, most of the published calculations use that methods or its modifications. The issues involved are reviewed in Refs.[6, 7].

Alas, the published results often do not agree with each other. That was rather eloquently pointed out in Ref.[8] where the spread of the published results (overwhelmingly based on QRPA) was used as a measure of the uncertainty. If that would be the case, the uncertainty would be quite large, a factor of 3-5. In contrast, our paper, Ref. [9], devoted to the assessment of the uncertainties inherent in QRPA comes to the conclusion that the uncertainties specific to QRPA and its modifications are much smaller, perhaps $\sim 30\%$ or so. So, who is right?

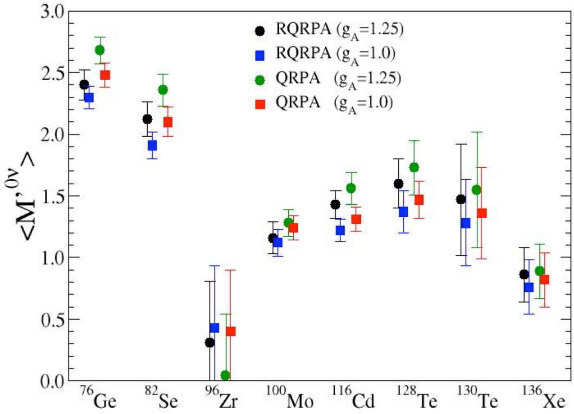

FIGURE 5. Nuclear matrix elements from the work of Rodin et al. [9]. Four variants of the QRPA method are shown; for each the average and variance are shown, obtained from three evaluations each with different numbers of single-particle states included.

There is a lively debate in the nuclear structure community of these issues. It turns out (there is no unanimity on that, however) that the spread of published calculated values is not inherent in the QRPA method and not even it is caused by the choice of poorly known parameters (even though they have an effect). Rather, the spread is caused by different a priori assumptions, in particular how to treat (or whether to neglect) the short range nucleon-nucleon repulsion and to a lesser extent whether to include or not the induced weak currents (in particular the pseudoscalar). It is hoped that a consensus would emerge, supported by results of solvable models and evaluation of various experimentally known quantities. Unfortunately, so far no observable that would be directly related to $M^{0\nu}$ have been identified. $M^{2\nu}$ shares with $M^{0\nu}$ the same initial and final states, but has a simpler structure (pure Gamow-Teller) while in $M^{0\nu}$ all multipoles contribute a comparable amount.

Lets point out that the few existing shell model results are in a reasonable accord with the results of Ref.[9]. The relation between these two complementary method certainly deserves a more detailed study.

NEAR TERM PROSPECTS

At present, the most sensitive experiments used enriched ^{76}Ge. The Heidelberg-Moscow [10] and IGEX [11] experiments used $\sim$ 10 kg of the source each and reached a lower limit $T_{1/2} \geq 1.9 \times 10^{25}$ years [10] based on $\sim$ 70 kg-years exposure. Subsequently, a subset of the Heidelberg-Moscow collaboration reanalysed the data obtained in the experiment, and concluded that the peak at the Q-value corresponding to the $0\nu\beta\beta$ decay is in fact present, and determined the half-life as $T_{1/2} = 1.5^{+7.55}_{-0.71} \times 10^{25}$ y [12]. If that claim could be independently verified, we would have to conclude that the neutrino mass pattern is the degenerate one. Clearly, such an extraordinary claim requires detailed scrutiny, and eventual independent verification. Several experiments are poised to not only accomplish that (and if true reduce the error bars substantially), but to explore fully the degenerate neutrino mass region.

I briefly describe four of these proposed experiment, CUORE, EXO, GERDA, and Majorana [1] They are at different stages of development. Some of them are funded and building the apparatus, some are funded partially, and some await approval. All hope to reach sensitivity to $0\nu\beta\beta$ decay half-life of $\sim 10^{26}$ years, an improvement by an order of magnitude. All of them are also potentially scalable to a $\sim$ ton size experiments, provided the envisioned background suppression is achieved in the first phase. The results are expected by $\sim$2010.

CUORE[14] is a cryogenic experiment using crystals of natural TeO_2. It will be placed in the Gran Sasso Laboratory and will contain 0.78 tons of TeO_2, i.e. $\sim$ 200 kg of ^{130}Te. The prototype experiment CUORICINO reached sensitivity 1.8×10^{24} until now.

EXO is a liquid xenon time-projection chamber to measure $0\nu\beta\beta$ decay. The ultimate EXO experiment [15] should include positive identification of the presence of a ^{136}Ba ion, thus making it essentially free of background. That is a formidable technological challenge. Therefore, the prototype EXO-200 experiment, using 200 kg of the already enriched ^{136}Xe will not contain this feature. EXO-200 will be placed in the WIPP site in Carlsbad, NM by the end of 2006, the data taking should begin the following year.

GERDA[16] and Majorana [17] are experiments using enriched ^{76}Ge. They differ in the way the desired background suppression is achieved. GERDA, which will be situated in Gran Sasso, will use 'naked' Ge detectors, placed in a large container of liquid nitrogen (perhaps later replaced by liquid Argon). Majorana instead uses more traditional scheme, with segmented crystals and pulse shape capabilities. Both plan to use substantially larger amounts of ^{76}Ge than precious experiments, which combined with better background suppression should allow each of them to reach sensitivity to $T_{1/2} > 10^{26}$ years after about two years of running.

Thus, within this decade, we should be able to fully explore the degenerate neutrino mass region, $\langle m_{\beta\beta} \rangle \geq\sim$ 100 meV. The strength of this program is based on using several different methods and different candidate nuclei, thus reducing the dependence on the nuclear matrix elements and systematic errors. If the $0\nu\beta\beta$ decay is found in this phase, we would have answers to the first two questions in the Introduction. If not, larger, ton-

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[1] Other proposals and ideas have been discussed. Some are based on existing experiments, others are new. A partial list, slightly out of date by now, can be found in Ref. [13].

size experiments are needed. The experience gained with these $\sim$ 100 kg experiments will then serve as a guide for the selection and funding of those even more challenging tasks.

ACKNOWLEDGMENTS

I appreciate and really enjoyed collaboration with Vincenzo Cirigliano, Steve Elliott, Amand Faessler, Andriy Kurylov, Michael Ramsey-Musolf, Vadim Rodin and Fedor Šimkovic with whom the results reported here were obtained.

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