Neutrinoless Double Beta Decay in Particle Physics

Werner Rodejohann
Max–Planck–Institut für Kernphysik, Postfach 103980, D–69029 Heidelberg, Germany

Abstract

Neutrinoless double beta decay is a process of fundamental importance for particle physics. It can be mediated by light massive Majorana neutrinos (standard interpretation) or by something else (non-standard interpretations). We review its dependence on the neutrino parameters, its complementarity to other observables sensitive to neutrino mass, and emphasize its ability to distinguish different neutrino mass models. Then we discuss mechanisms different from light Majorana neutrino exchange, and show what can be learned from those and how they could be tested.

Keywords: lepton number violation, neutrino mass, double beta decay

1. Introduction

Neutrinoless double beta decay ($0\nu\beta\beta$) experiments are much more than neutrino experiments. Searches for $0\nu\beta\beta$ are fundamental physics because they probe the presence of lepton number violation, which is on equal footing to baryon number violation, i.e. proton decay. Once a (positive or negative) result from $0\nu\beta\beta$ experiments is present, one can go on and (assuming that lepton number is violated in Nature) interpret the outcome in two ways:

1. Standard Interpretation:
   neutrinoless double beta decay is mediated by light, active and massive Majorana neutrinos (the ones which oscillate) and all other mechanisms potentially leading to $0\nu\beta\beta$ give negligible or no contribution;

2. Non-Standard Interpretations:
   neutrinoless double beta decay is mediated by some other lepton number violating process, and light, active and massive Majorana neutrinos (the ones which oscillate) potentially leading to $0\nu\beta\beta$ give negligible or no contribution.

In the first interpretation $0\nu\beta\beta$ is a neutrino physics experiment, in the second one a broader particle physics experiment with emphasis on the particular lepton number violating physics under study. Of course, the observation of $0\nu\beta\beta$ implies the Majorana nature of neutrinos (to be precise, a tiny 4-loop induced Majorana mass term), a fact known as the black-box, or Schechter-Valle, theorem.

We will discuss in this contribution some of the physics potential of the two interpretations given above. For experimental aspects, see the contributions in [1], nuclear physics issues are dealt with in [3].

2. Standard Interpretation

The first interpretation is most common, and in the light of neutrino oscillations arguably the best motivated one. Assuming light massive Majorana neutrino exchange, the amplitude for $0\nu\beta\beta$ is proportional to

$$
\mathcal{A} \propto G_F^2 \frac{\langle m_{ee} \rangle}{q^2} \text{ with } \langle m_{ee} \rangle \equiv \sum U_{ei}^2 m_i = |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{2i\alpha} + |U_{e3}|^2 m_3 e^{2i\beta}.
$$

(1)
Here \( q^2 \approx (0.1 \text{GeV})^2 \) is the typical momentum exchange in the reaction, \( m_1 \) are the neutrino masses, |\( U_{ei} \)| the PMNS matrix elements of the first row (depending on \( \theta_{12} \) and \( \theta_{13} \)) and \( \alpha, \beta \) are the two Majorana phases. The coherent sum \( \langle m_{ee} \rangle \) is usually called the effective mass and contains 7 of the 9 parameters of the neutrino mass matrix, which in the fundamental Lagrangian fully describes neutrino mass and lepton mixing. Two of those 9 parameters, the Majorana phases, show up only in the effective mass. It contains therefore a large amount of information. Its geometrical interpretation is shown in the left part of Fig. 1 if the three complex terms in \( \Sigma U_{ei}^2 m_i \) cannot form a triangle, the effective mass is non-zero. Fig. 1 also displays plots of the effective mass versus the other two complementary mass observables. Those are

\[
m_\beta = \sqrt{\sum |U_{ei}|^2 m_i^2} \quad \text{and} \quad \sum m_i = m_1 + m_2 + m_3 ,
\]

measurable in beta decays [4] and in cosmology [5], respectively. We refer to the cited contributions presented at this conference for their current status and future prospects.

What is noteworthy from the plots of neutrino mass observables is that the effective mass can vanish in case of the normal neutrino mass ordering. While it seems at first sight unnatural that 7 parameters conspire in order to let a particular combination of them become zero, it should be kept in mind that \( \langle m_{ee} \rangle \) is the ee element of the fundamental low energy Majorana neutrino mass matrix. This matrix is generated by the underlying theory of mass generation, and texture zeros occur frequently in such (flavor) models. We recall here that the dependence on \( \langle m_{ee} \rangle \) of the amplitude is in fact stemming from the term \( \Sigma U_{ei}^2 m_i (q^2 - m_i^2) \), and the limit \( q^2 \gg m_i^2 \) is taken in the fermion propagator to obtain Eq. (1). If \( \Sigma U_{ei}^2 m_i = 0 \), then there is a term of order \( U_{ei}^2 m_i^2 / q^2 \), which will in general not vanish. It is however suppressed by a factor \( m_i^2 / q^2 \lesssim 10^{-16} \).

In contrast to the normal ordering, the effective mass cannot vanish for the inverted mass ordering. The lower limit of \( \langle m_{ee} \rangle \) can be expressed as

\[
\langle m_{ee} \rangle^{\text{IH}}_{\text{min}} = \left( 1 - |U_{e3}|^2 \right) \sqrt{|\Delta m_{\odot}^2| (1 - 2 \sin^2 \theta_{12} )} .
\]

If the inverted ordering is to be ruled out, limits below \( \langle m_{ee} \rangle^{\text{IH}}_{\text{min}} \) have to be reached. Among the parameters governing \( \langle m_{ee} \rangle^{\text{IH}}_{\text{min}} \), the largest dependence is induced by the solar neutrino parameter \( \sin^2 \theta_{12} \), and quantifies to an uncertainty of about a factor of 2 for \( \langle m_{ee} \rangle^{\text{IH}}_{\text{min}} \). This factor of 2 introduces therefore about the same uncertainty as the nuclear matrix elements (NMEs), and motivates solar neutrino precision experiments in order to reduce it.

The three types of neutrino mass observables are obviously highly complementary. Ordinary beta decay is basically a model-independent probe of neutrino mass, whereas the extraction of the cosmological observable \( \sum m_i \) is sensitive to the data sets used, and little is known what happens to limits when non-standard cosmological models different from the ΛCDM framework are applied. As mentioned above, neutrino mass limits from 0νββ require the assumption of lepton number violation and in addition, as we will see below, that no other mechanism contributes.

At the end of this decade, \( m_\beta \) will be known to be larger or smaller than about 0.3 eV, standard cosmology will be sensitive to smaller values of \( \sum m_i \), while \( \langle m_{ee} \rangle \) can also be probed down to the 0.1 eV regime. All three observables
3. Non-Standard Interpretations

A clear experimental signature for a non-standard contribution to $0\nu\beta\beta$ would be for instance no signal in KATRIN and/or cosmology, and a life-time measurement in $0\nu\beta\beta$ which would be interpreted as an effective mass of 0.5 eV or so. There are several candidates for non-standard contributions: Higgs triplets, right-handed currents, heavy Majorana neutrinos, supersymmetric particles, etc. Limits from $0\nu\beta\beta$ can be translated into limits on the couplings and masses associated with these mechanisms. The limits from the literature, which often take nuclear physics aspects into
account, can be approximately reproduced by rather simple arguments on the amplitude level. For instance, heavy Majorana neutrinos (for which in the propagator the limit $M_
u^2 \gg q^2$ applies) will have an amplitude proportional to $\mathcal{A} \propto G_F^2 m_{\nu \nu} / M_{\nu \nu}$, where $M_{\nu \nu}$ are heavy neutrino masses with coupling $S_{\nu \nu}$ to electrons. Setting this amplitude equal to the light neutrino amplitude from Eq. (1), and using $\langle m_{\nu \nu} \rangle \leq 0.5$ eV gives $S_{\nu \nu}^2 / M_{\nu \nu} \leq 5 \times 10^{-8}$ GeV$^{-1}$, which is in fact the limit given in [17]. (Left-handed) Higgs triplet exchange has an amplitude $\mathcal{A} \propto G_F^2 h_{\nu \nu} v_{L \nu} / M_{\nu \nu}$, where $h_{\nu \nu}$ is its coupling to two electrons, $v_L$ its vev, and $M_{\nu \nu} \gg q$ its mass. Note that $h_{\nu \nu} v_{L \nu}$ is the contribution of the triplet to neutrino mass. Therefore, if the triplet would be responsible for neutrino mass, its contribution to $0\beta\beta$ would be suppressed by a factor $q^2 / M_{\nu \nu}$. On the other hand, the triplet can only give the leading contribution to $0\beta\beta$ if $\langle m_{\nu \nu} \rangle$ is extremely small.

R-parity violating SUSY can also mediate the process (see e.g. [18] [19]), in two classes of diagrams. First, in the usual diagram of $0\beta\beta$ the W bosons can essentially be replaced by selectrons and the Majorana neutrino by a neutralino or gaugino. The amplitude is then given by $\mathcal{A} \propto g^2 \sqrt{x_{11}^2 / \Lambda_{SUSY}}$, where $g \equiv \sqrt{0.1}$ is a (combination of) gauge coupling(s). $x_{11}^2$ stems from the vertex of the selectron with the up- and down quarks and the power of $\Lambda_{SUSY}$ is easily understood by the propagators for one fermion and two bosons, whose masses are assumed to be $\Lambda_{SUSY} \gg q$. By comparing again with the amplitude in Eq. (1), it follows $x_{11}^2 / \Lambda_{SUSY} \lesssim 7 \times 10^{-17}$ GeV$^{-5}$ [19]. Interestingly, the same couplings describe resonant selectron production at the LHC [20], which allows to test this mechanism. For instance, one can show that certain regions in SUSY parameter space are in conflict with existing $0\beta\beta$-limits, or that detection of resonant selectron production at the LHC in other regions would rule out any considerable contribution of this mechanism to $0\beta\beta$ [20]. Another class of R-parity violating diagrams involves neutrino and virtual squark exchange. The amplitude goes as $\mathcal{A} \propto G_F m_d x_{11}^2 / \Lambda_{SUSY}$, where $m_d$ is the down-type quark mass of the $k$th generation. It enters the game because mixing between left- and right-handed squarks is involved, which is proportional to this mass. The $\lambda'_{112} \lambda'_{112}$ term is irrelevant due to $K^0 - \bar{K}^0$ constraints, and the $\lambda'_{111} \lambda'_{111}$ contribution is sub-leading with respect to the diagram discussed above [22]. Anyway, depending on whether it is the down-, strange- or bottom (s)quark, by comparing the amplitudes limits of $(1 \times 10^{-11}, 6 \times 10^{-13}$ or $1 \times 10^{-14}$) GeV$^{-3}$ arise, compared with the actual literature values of $(7.7 \times 10^{-12}, 4.0 \times 10^{-13}$ or $1.7 \times 10^{-14}$) GeV$^{-3}$.

---

[1] LHC-related phenomenology of non-standard mechanisms in left-right symmetric theories has recently been discussed in [23].
Figure 4: Left: constraints at 1σ on the model parameters from an observation of $0\nu\beta\beta$ of $^{82}$Se at half-life $10^{25}$ y (outer blue elliptical area) and $10^{26}$ y (inner blue elliptical area). Adding the reconstruction of the angular (outer, lighter green) and energy difference (inner, darker green) distribution drastically shrinks the allowed parameter space. Right: adding information from the decay of $^{150}$Nd. In this example, 30% admixture of right-handed currents is assumed. Taken from [27].

Again, the simple estimates are rather close to the limits involving nuclear physics.

However, there is nuclear physics, and in fact it can help to distinguish the different mechanisms. This has been dealt with recently in Refs. [24][25][26]. For instance, one can within a typical NME calculation fix the particle physics parameters such that for $^{76}$Ge the life-time is the same for all popular non-standard mechanisms. Triggered by nuclear details, the life-time in other nuclei can however differ by up to one order of magnitude. Typically, multi-isotope determination of $0\nu\beta\beta$ in three to four different elements is necessary in order to single out the true mechanism [24].

We have seen up to know that non-standard mechanisms can be pinned down either by looking for other places in which they show their presence, or by probing $0\nu\beta\beta$ in different nuclei. The third possibility is to take a closer look at the decay products, namely the two final state electrons. The SuperNEMO experiment is currently the only one able to probe in particular the energy of the individual electrons and their angular distribution [27]. A recent analysis by the collaboration assumes the simultaneous presence of the standard mechanism (with the particle physics parameter $\langle m_{ee}\rangle$) and a right-handed current contribution ($\lambda = \frac{m_W}{m_{W_R}}^2 U_{ei} V_{ei}$, with $V$ being the right-handed analogon of the PMNS matrix). Fig. 4 shows an example of the results from [27].

4. Summary

Neutrinoless double beta decay will be intensively searched for in the current decade. The interesting complementarity with the other neutrino mass-related observables can shed some light on the question of neutrino mass generation and on the cosmological model. Perhaps even more interesting is the possibility of other mechanisms leading to $0\nu\beta\beta$, which have phenomenological consequences in a variety of fields, such as lepton flavor violation or accelerator physics.

Acknowledgments

This work was supported by the ERC under the Starting Grant MANITOP and by the DFG in the project RO 2516/4-1 as well as in the Transregio 27.

References

[1] M. Pavan; M. Dolinski; K. Nakamura; R. Saakyan; M. Barnabe-Heider, these proceedings.
[2] J. Schechter, J. W. F. Valle, Neutrino Masses in $SU(2) \times U(1)$ Theories, Phys. Rev. D22 (1980) 2227.
[3] F. Simkovic, these proceedings.
[4] T. Thümmler; J. Formaggio, these proceedings.
[5] Y. Y. Y. Wong, these proceedings.
[6] F. Fereggia, A. Strumia, F. Vissani, Neutrino oscillations and signals in β and 0νββ experiments, Nucl. Phys. B637 (2002) 345–377.
[7] A. de Gouvea, J. Jenkins, Non-oscillation probes of the neutrino mass hierarchy and vanishing $|U_{e3}|$, [arXiv:hep-ph/0507702].
[8] M. Lindner, A. Merle, W. Rodejohann, Improved limit on $\theta_{13}$ and implications for neutrino masses in neutrino-less double beta decay and cosmology, Phys. Rev. D73 (2006) 053005.
[9] S. Pascoli, S. T. Petcov, Majorana Neutrinos, Neutrino Mass Spectrum and the $\langle m_\nu \rangle \sim 10^{-3} \text{eV}$ Frontier in Neutrinoless Double Beta Decay, Phys. Rev. D77 (2008) 113003.
[10] G. L. Fogli, et al., Observables sensitive to absolute neutrino masses (Addendum), Phys. Rev. D78 (2008) 033010.
[11] S. Pascoli, S. T. Petcov, T. Schwetz, The Absolute Neutrino Mass Scale, Neutrino Mass Spectrum, Majorana CP Violation and Neutrinoless Double-Beta Decay, Nucl. Phys. B734 (2006) 24–49.
[12] W. Maneschg, A. Merle, W. Rodejohann, Statistical Analysis of future Neutrino Mass Experiments including Neutrino-less Double Beta Decay, Europhys. Lett. 85 (2009) 51002.
[13] J. Valle; M.C. Chen, these proceedings.
[14] J. Barry, W. Rodejohann, Neutrino Mass Sum-rules in Flavor Symmetry Models, Nucl. Phys. B842 (2011) 33–50.
[15] G. Karagorgi; R. van de Water, these proceedings.
[16] S. Goswami, W. Rodejohann, MiniBooNE Results and Neutrino Schemes with 2 sterile Neutrinos: Possible Mass Orderings and Observables related to Neutrino Masses, JHEP 10 (2007) 073.
[17] H. Klapdor-Kleingrothaus, H. Pas, Neutrinoless double beta decay and new physics in the neutrino sector, [arXiv:hep-ph/0002109].
[18] R. N. Mohapatra, New contributions to neutrinoless double-beta decay in supersymmetric theories, Phys. Rev. D34 (1986) 3457–3461.
[19] M. Hirsch, H. Klapdor-Kleingrothaus, S. Kovalenko, Supersymmetry and neutrinoless double beta decay, Phys.Rev. D53 (1996) 1329–1348.
[20] B. Allanach, C. Kom, H. Pas, Large Hadron Collider probe of supersymmetric neutrinoless double beta decay mechanism, Phys.Rev.Lett. 103 (2009) 091801.
[21] V. Tello, M. Nemevsek, F. Nesti, G. Senjanovic, F. Vissani, Left-Right Symmetry: from LHC to Neutrinoless Double Beta Decay, [arXiv:1011.3522].
[22] B. C. Allanach, C. H. Kom, H. Pas, LHC and B physics probes of neutrinoless double beta decay in supersymmetry without R-parity, JHEP 10 (2009) 026.
[23] A. Faessler, T. Gutsche, S. Kovalenko, F. Simkovic, Pion dominance in RPV SUSY induced neutrinoless double beta decay, Phys. Rev. D77 (2008) 113012.
[24] V. Gehman, S. Elliott, Multiple-Isotope Comparison for Determining 0 nu beta beta Mechanisms, J.Phys.G G34 (2007) 667–678.
[25] F. Deppisch, H. Pas, Pinning down the mechanism of neutrinoless double beta decay with measurements in different nuclei, Phys.Rev.Lett. 98 (2007) 232501.
[26] G. Fogli, E. Lisi, A. Rotunno, Probing particle and nuclear physics models of neutrinoless double beta decay with different nuclei, Phys.Rev. D80 (2009) 015024.
[27] R. Arnold, et al., Probing New Physics Models of Neutrinoless Double Beta Decay with SuperNEMO, [arXiv:1005.1241].