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Double beta decay and the quest for Majorana neutrinos

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Abstract. The observation of neutrinoless double beta ($0\nu\beta\beta$) decay remains crucial for understanding lepton number violation. The inverse half-life for $0\nu\beta\beta$-decay is given by the product of a phase space factor (PSF), a nuclear matrix element (NME), which both rely on theoretical description, and a function f containing the physics beyond the standard model. Phase space factors and nuclear matrix elements have been evaluated, or are under evaluation, systematically for all processes of interest. The nuclear matrix elements have been calculated within the framework of the microscopic interacting boson model (IBM-2), and phase space factors have been evaluated using exact Dirac electron wave functions. The current situation is then discussed by combining the theoretical results with experimental limits on the half-life of neutrinoless double beta decay. The extracted limits on the average light neutrino mass are addressed, complemented with a discussion of other possible $0\nu\beta\beta$-decay mechanisms and scenarios.

1. Introduction

The question of whether neutrinos are Majorana or Dirac particles and what are their average masses remains one of the most fundamental problems in physics today. Observation of neutrinoless double beta decay ($0\nu\beta\beta$) would verify the Majorana nature of the neutrino and constrain the absolute scale of the neutrino mass spectrum. The inverse half-life for $0\nu\beta\beta$-decay is given by

$$\left[\tau_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left|f(m_i, U_{ei})\right|^2, \tag{1}$$

i.e. it is a product of a phase space factor (PSF), a nuclear matrix element (NME), and a function f containing the physics beyond the standard model. PSF and NME both rely on theoretical description and their calculation serves the purpose of extracting physics beyond the standard model if $0\nu\beta\beta$-decay is observed, and of guiding searches if $0\nu\beta\beta$-decay is not observed.

In following sections recent calculations of phase space factors and nuclear matrix elements are being reviewed together with comparison to other available results. PSFs and NMEs have been evaluated, or are under evaluation, systematically for all processes of interest. The nuclear matrix elements have been calculated within the framework of the microscopic interacting boson model (IBM-2) [1, 2, 3, 4, 5, 6, 7], and phase space factors have been evaluated using exact Dirac electron wave functions as reported in [5, 8, 9, 10, 11]. The current situation is then discussed by

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combining the theoretical results with experimental limits on the half-life of neutrinoless double beta decay. The extracted limits on the average light neutrino mass are addressed, complemented with a discussion of other possible $0\nu\beta\beta$-decay mechanisms and scenarios, namely, existence of sterile neutrinos and inclusion of non-standard mechanisms of double beta decay.

2. Phase space factors

The key ingredient for the evaluation of phase-space factors in single- and double-β decay are the (scattering) electron wave functions (and for electron capture the bound wave functions). These energy dependent wavefunctions are then used to form mechanisms specific combinations f_{ij} and integrated over available electron energies. A general theory of phase space factors in DBD was developed years ago by Doi *et al.* [12, 13] following previous work of Primakoff and Rosen [14] and Konopinski [15]. It was reformulated by Tomoda [16] who also presented results in a selected number of nuclei. However, in these earlier calculations approximate expression for the electron wave functions at the nucleus was used. PSF have been recently recalculated [5, 8, 9, 10, 11] with exact Dirac electron wave functions and including screening by the electron cloud. These new PSFs are available from the webpage nucleartheory.yale.edu and by contacting jenni.kotila@jyu.fi.

3. Nuclear matrix elements

The total NME for $0\nu\beta\beta$-decay is a combination of Gamow-Teller (GT), Fermi (F), and tensor (T) matrix elements and can be written as:

$$\begin{aligned} M^{(0\nu)} &= M_{GT}^{(0\nu)} - \left(\frac{g_V}{g_A}\right) M_F^{(0\nu)} + M_T^{(0\nu)}, \\ M_{0\nu} &= g_A^2 M^{(0\nu)}. \end{aligned} \tag{2}$$

The reason for this separation is that the calculated single-β decay matrix elements of the GT operator in a particular nuclear model appear to be systematically larger than those derived from the measured ft values of the allowed GT transitions. The simplest way of taking into account this result is by introducing an effective $g_{A,eff}$, also sometimes written as $g_{A,eff} = qg_A$, where q is a quenching factor. The quenching of g_A is discussed in Sec. 4.

Several methods have been used for evaluation of NMEs, including Quasiparticle Random Phase Approximation (QRPA) [18], Shell Model (ISM) [19], Interacting Boson Model (IBM-2) [6], Density Functional Theory (DFT) [20] among others. For $0\nu\beta\beta$-decay the scenario that has attracted most attention is the emission and re-absorption of a light neutrino, $m_{light} \ll 1$ keV, for which

$$f = \frac{\langle m_\nu \rangle}{m_e} = \sum_{k=light} (U_{ek})^2 \frac{m_k}{m_e}, \tag{3}$$

and experimental half-life offers thus direct information about average light neutrino mass. Recent results for light neutrino exchange NME for some of the models are summarized in figure 1. By combining the PSF with the NME, one can set limits on neutrino masses. Fig. 2 shows current limits on light neutrino masses for present PSF, IBM-2 NME, and bare value of g_A=1.269.

4. Quenching of g_A

As mentioned results in figures 1 and 2 are obtained using the free value of the axial vector coupling constant as obtained from neutron decay, $g_A = 1.269$. However, it is well known from single-β-decay and electron capture that g_A is renormalized in models of nuclei. Two reasons for this renormalization are: (i) the limited model space in which the calculation is done, giving

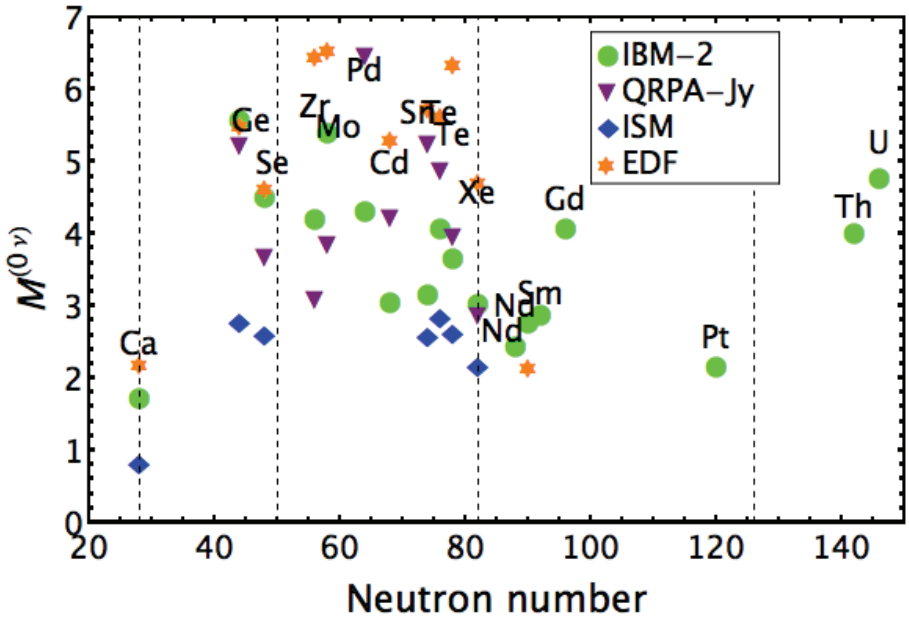

Figure 1. Comparison of IBM-2 [6, 17], QRPA-Jy [18], ISM [19], and EDF [20] $0\nu\beta\beta$-decay NMEs for light neutrino exchange.

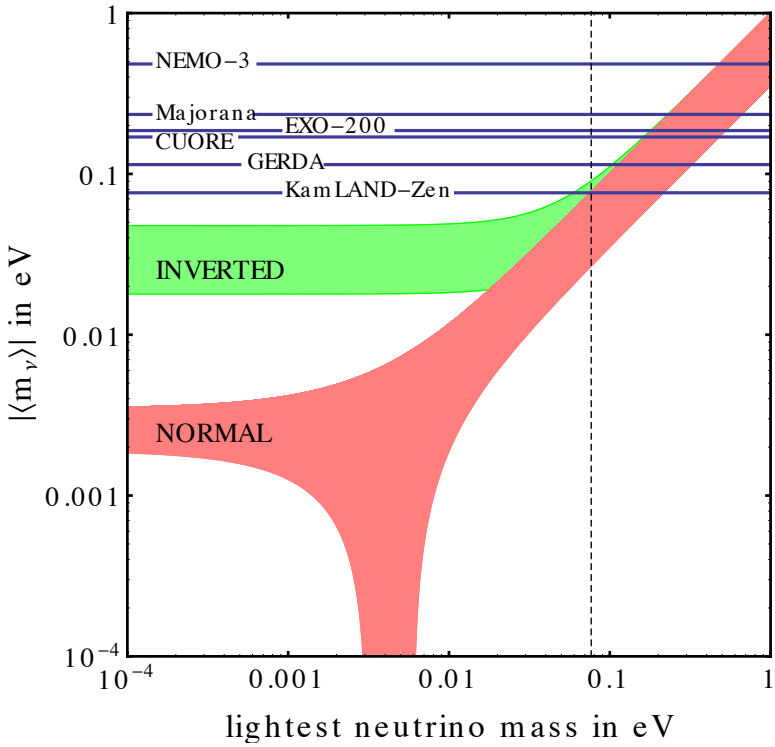

Figure 2. Current limits to $\langle m_\nu \rangle$ from CUORE [21], GERDA [22], EXO-200 [23], KamLAND-Zen [24], NEMO-3 [25], and Majorana [26], with IBM-2 NME and $g_A = 1.269$. The limit from Planck Collaboration [27] is shown by vertical line.

rise to a quenching factor $q_{N_{ex}}$ and (ii) the omission of non-nucleonic degrees of freedom, giving rise to a quenching factor q_Δ. Since g_A appears to the second power in the NME, and hence to the fourth power in the half-life, its quenching will have a dramatic effect on double-beta decay.

Quenching of g_A in $2\nu\beta\beta$-decay, consistent with single-beta decay, has been observed (see figure 5 of [2]). The question of whether or not g_A in $0\nu\beta\beta$-decay is renormalized as much as in $2\nu\beta\beta$-decay is of much debate. The two processes differ by the momentum transferred to leptons; in $2\nu\beta\beta$ this is of the order of few MeV, while in $0\nu\beta\beta$ it is of the order of 100 MeV. Also, in $2\nu\beta\beta$ only 1^+ and 0^+ states in the intermediate odd-odd nucleus contribute to the decay, while in $0\nu\beta\beta$ all multipoles play a role. This problem is currently being addressed from various sides both experimentally and theoretically (for a review see [28]) due to the fact that, if g_A is renormalized to maximal quenching, obtained from $2\nu\beta\beta$, estimates for half-lives should be increased by a factor of ∼4-34 and limits on the average neutrino mass should be increased by a factor ∼1.6-6, making it very difficult to reach in the foreseeable future even the inverted region.

5. Other possible scenarios

Besides light neutrinos, neutrino masses could also be degenerate and large. This possibility is however, in tension with the cosmological bound on the sum of neutrino masses, $\sum m_i \leq 0.230$ eV, obtained by the Planck collaboration [27]. Other scenarios like Majoron emission, sterile neutrinos, ..., are also possible. Here Majoron means a massless neutral boson [10] and sterile means a neutrino with no standard model interaction. The scenario of sterile neutrinos is currently being extensively investigated both experimentally, with planned experiments at FERMILAB and CERN-LHC, and theoretically. NME for sterile neutrinos of arbitrary mass can be calculated by using a neutrino potential that depends on the effective mass of sterile neutrinos, m_{ν_I}, and $f = m_{\nu_I}/m_e$. IBM-2 matrix elements for this scenario have been calculated in Ref. [7]. Contribution of all hypothetical neutrinos can be written in the general form

$$[\tau_{1/2}^{0\nu}]^{-1} = G_{0\nu} \left| \frac{1}{m_e} \left[\sum_{k=1}^{3} U_{ek}^2 m_k + \frac{1}{m_e} \sum_i U_{ei}^2 m_i + \sum_j U_{ej}^2 m_j \right] |M_{0\nu}|^2 + m_p \left[\sum_N U_{eN}^2 \frac{m_N}{\langle p^2 \rangle + m_N^2} + \sum_{k_h=1}^{3} U_{ek_h}^2 \frac{1}{m_{k_h}} \right] \left| M^{0\nu_h} \right|^2 \right|, \tag{4}$$

where the first three terms represent the contribution of light neutrinos (known with $m_\nu < 0.1$ eV, unknown with $m_i \sim 1$ eV, unknown with $m_j \sim 1$ keV) and the last two terms represent contributions of heavy neutrinos (unknown with mass $m_N \sim 1$ MeV , unknown with mass $m_{\nu_h} > 1$ GeV).

Several types of sterile neutrinos have been suggested: heavy sterile neutrinos with masses in the keV-GeV range and light sterile neutrinos with masses in the eV range to account for the reactor anomaly in oscillation experiments. The presence of sterile neutrinos changes completely the picture: for example with light sterile neutrino and $g_A = 1.269$, the inverted hierarchy is reachable by GERDA-PHASE II and CUORE.

6. Non standard mechanisms

It could also be that other, non-standard mechanisms contribute [11, 29]. Here non-standard means mechanisms other than V-A. Non-standard mechanisms are also currently being

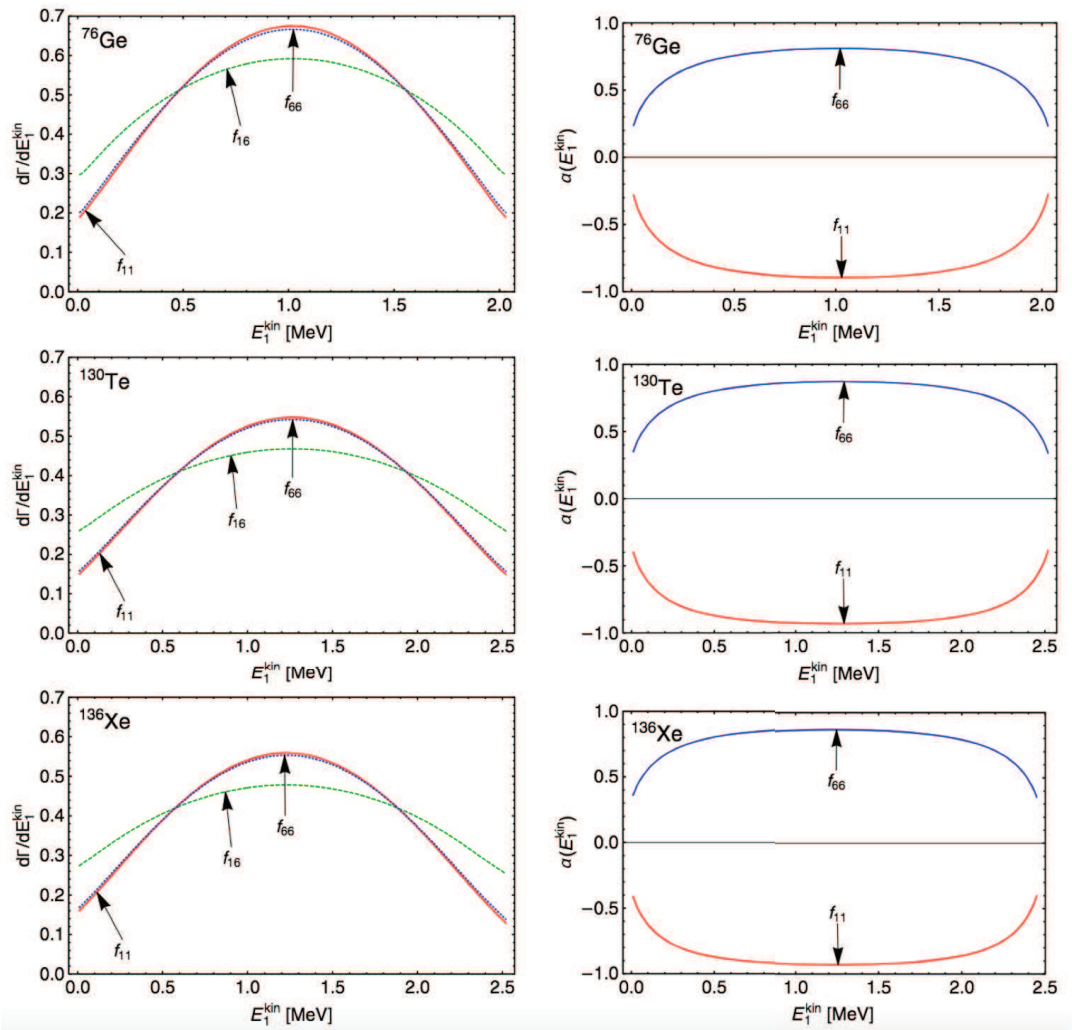

Figure 3. Left panel: Single electron energy distribution as a function of kinetic energy. Right panel: Energy-dependent angular correlation between the two electrons as function of the kinetic energy.

investigated both long-range [29], with Lagrangian

$$\mathcal{L}_{\text{long}} = \frac{G_F}{\sqrt{2}} \left[J^{\dagger}_{V-A,\mu} j^{\mu}_{V-A} + \sum_{\alpha,\beta} \epsilon_{\alpha,\beta} J^{\dagger}_{\alpha} j_{\beta} \right], \tag{5}$$

and short-range [11, 30], with Lagrangian

$$\mathcal{L}_{\text{short}} = \frac{G_F}{\sqrt{2}} \left[\epsilon_1 J J j + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^{\mu} J_{\mu} j + \epsilon_4 J^{\mu} J_{\mu\nu} j^{\nu} + \epsilon_5 J^{\mu} J j_{\mu} \right], \tag{6}$$

where J and j are the hadronic and leptonic currents with definite tensor structure and chirality.

On principle, a given underlying particle physics model may give rise to several contributions. To determine the numerical sensitivity to the ϵ coefficients, it is common to simplify the situation by considering the contribution of only one mechanism at the time. As an example, Fig. 3 shows short range mechanism energy distributions f_{11}, f_{66}, and f_{16} [11]. Notable is that

angular correlation has different signs for f_{11} and f_{66} which allows one to potentially distinguish the scenarios resulting in f_{66} from standard mass mechanism as well as from other scenarios corresponding to f_{11}.

7. Conclusions

No matter what the mechanism of $0\nu\beta\beta$-decay is, its observation will answer the fundamental questions: What is the absolute mass scale of neutrinos? Are neutrinos Dirac or Majorana particles? How many neutrino species are there? Indeed, if observed, $0\nu\beta\beta$-decay may provide evidence for physics beyond the standard model other than the mass mechanism. Conversely, its non-observation will set stringent limits on other scenarios (sterile, ...), and on non-standard mechanisms. In this sense, $0\nu\beta\beta$-decay is a search for lepton number violation rather than a measurement of the neutrino mass.

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