Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 61 (2015) 223 – 226

Physics Procedia

Non-Standard Mechanisms for Neutrinoless Double Beta Decay

Frank F. Deppisch

Department of Physics and Astronomy, University College London, UK

Abstract

Neutrinoless double beta decay is a powerful tool to probe not only for Majorana neutrino masses but for lepton number violating physics in general. We discuss relations between lepton number violation, double beta decay and neutrino mass, provide an overview of the general Lorentz invariant parametrization of the double beta decay rate and highlight a number of different new physics models showing how different mechanisms can trigger double beta decay.

Selection and peer review is the responsibility of the Conference lead organizers, Frank Avignone, University of South Carolina, and Wick Haxton, University of California, Berkeley, and Lawrence Berkeley Laboratory

Keywords: Double beta decay, Lepton number violation, Physics beyond the Standard Model
PACS: 23.40.BW, 11.30.Fs, 14.80

1. Introduction

The search for neutrinoless double beta decay ($0\nu\beta\beta$) - the simultaneous transformation of two neutrons into two protons, two electrons and nothing else - is the most sensitive tool for probing Majorana neutrino masses. However, while this so-called mass mechanism is certainly the best known example triggering the decay, Majorana neutrino masses are not the only element of beyond Standard Model physics which can induce it. In this proceedings report we present possible other mechanisms of $0\nu\beta\beta$ decay where the lepton number violation (LNV) does not directly originate from Majorana neutrino masses but rather due to LNV masses or couplings of new particles appearing in various possible extensions of the Standard Model. While the same couplings will also induce Majorana neutrino masses, due to the Schechter-Valle black box theorem [1], the $0\nu\beta\beta$ decay half life will not yield direct information about the neutrino mass. We rather consider the $0\nu\beta\beta$ decay rate by expressing the new physics contributions in terms of effective low-energy operators [2, 3].

We here focus on the particle physics aspects. On the nuclear physics side, the uncertainties in nuclear matrix elements are notoriously difficult to estimate and limits derived from $0\nu\beta\beta$ decay are affected. Unfortunately, despite efforts devoted to the improvement of the nuclear calculations, the latest matrix elements in the QRPA approach from the Tübingen group [4] differ from the shell model results in many cases by factors of $\sim (2-3)$. Experimentally, the most stringent bounds on neutrinoless double beta decay are currently from ^{76}Ge [5] and ^{136}Xe [6]. The results presented below are based on [7], using the limits ^{76}Ge

Email address: `f.deppisch@ucl.ac.uk` (Frank F. Deppisch)

Selection and peer review is the responsibility of the Conference lead organizers, Frank Avignone, University of South Carolina, and Wick Haxton, University of California, Berkeley, and Lawrence Berkeley Laboratory
doi:10.1016/j.phpro.2014.12.036

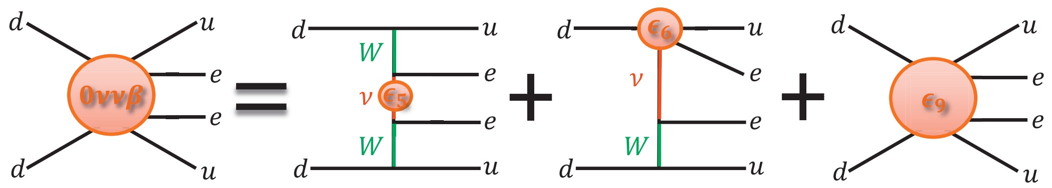

Fig. 1. Schematic overview of different contributions to $0\nu\beta\beta$: Standard mass mechanism, long–range 6-dim operator, short–range 9-dim operator.

of $T_{1/2} \geq 1.9 \times 10^{25}$ y and the recent result $T_{1/2} \geq 1.6 \times 10^{25}$ y for ^{136}Xe. In this report, we provide a brief overview of the possible effective operators (c.f. Figure 1) that can trigger $0\nu\beta\beta$ beta decay and give a summary of the most relevant LNV models. For more details, see the review [7] and references therein.

2. Contributions to Neutrinoless Double Beta Decay

Standard Mass Mechanism. Before discussing other contributions, recall that the mass mechanism of $0\nu\beta\beta$ probes the effective Majorana neutrino mass $\langle m_\nu \rangle = \sum_j U_{ej}^2 m_j \equiv m_{ee}$, where the sum runs over all active light neutrinos. This quantity is equal to the (ee) entry of the Majorana neutrino mass matrix. The $0\nu\beta\beta$ half life in a given isotope is then given by $[T_{1/2}^{0\nu\beta\beta}]^{-1} = |\langle m_\nu \rangle / m_e|^2 G_0 |ME|^2$, where G_0 denotes the nuclear phase space factor and $|ME|$ the nuclear matrix element. The current experimental results lead to a limit $\langle m_\nu \rangle \lesssim 0.5 - 1.0$ eV.

Long–Range Contributions. Long–range contributions to $0\nu\beta\beta$ decay involve two vertices, point-like at the Fermi scale, with the exchange of a light neutrino in between. The general Lagrangian can be written in terms of effective couplings ϵ_β^α [2],

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \left(j_{V-A}^\mu J_{V-A,\mu}^\dagger + \sum_{\alpha,\beta} \epsilon_\alpha^\beta j_\beta J_\alpha^\dagger \right), \tag{1}$$

with the hadronic and leptonic currents $J_\alpha^\dagger = \bar{u} O_\alpha d$ and $j_\beta = \bar{e} O_\beta \nu$, respectively. The sum runs over all combinations allowed by Lorentz invariance, except for the standard case $\alpha = \beta = (V - A)$, and all currents have been scaled relative to the strength of the ordinary $(V - A)$ interaction. The operators O_α are defined as

$$O_{V\pm A} = \gamma^\mu (1 \pm \gamma_5), \qquad O_{S\pm P} = (1 \pm \gamma_5), \qquad O_{T_\pm} = \frac{i}{2}[\gamma_\mu, \gamma_\nu](1 \pm \gamma_5). \tag{2}$$

The effective Lagrangian (1) represents the most general low-energy four-fermion charged-current interaction. The interpretation of the effective couplings ϵ_β^α depends on the specific particle physics model. Considering only one ϵ_α^β at a time one can now derive constraints on the effective coupling parameters from a $0\nu\beta\beta$ half life measurement or bound,

$$[T_{1/2}^{0\nu\beta\beta}]^{-1} = |\epsilon_\alpha^\beta|^2 G_{0k} |ME|^2, \tag{3}$$

where G_{0k} denotes the corresponding nuclear phase space factors and $|ME|$ the nuclear matrix elements. For ^{76}Ge and ^{136}Xe, the current limits are shown in Table 1.

Short–Range Contributions. Short–range contributions to $0\nu\beta\beta$ decay involve one vertex, point-like at the Fermi scale. The decay rate results from the following general Lorentz invariant Lagrangian [3]

$$\mathcal{L} \;=\; \frac{G_F^2}{2m_p} \left(\epsilon_1 JJj + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^\mu J_\mu j + \epsilon_4 J^\mu J_{\mu\nu} j^\nu + \epsilon_5 J^\mu J j_\mu \right), \tag{4}$$

Isotope	$\lvert\epsilon_{V-A}^{V+A}\rvert$	$\lvert\epsilon_{V+A}^{V+A}\rvert$	$\lvert\epsilon_{S-P}^{S+P}\rvert$	$\lvert\epsilon_{S+P}^{S+P}\rvert$	$\lvert\epsilon_{TL}^{TR}\rvert$	$\lvert\epsilon_{TR}^{TR}\rvert$
^{76}Ge	$3.5 \cdot 10^{-9}$	$6.2 \cdot 10^{-7}$	$1.1 \cdot 10^{-8}$	$1.1 \cdot 10^{-8}$	$6.7 \cdot 10^{-10}$	$1.1 \cdot 10^{-9}$
^{136}Xe	$2.8 \cdot 10^{-9}$	$5.6 \cdot 10^{-7}$	$6.8 \cdot 10^{-9}$	$6.8 \cdot 10^{-9}$	$4.8 \cdot 10^{-10}$	$8.1 \cdot 10^{-10}$

Table 1. Current limits on effective long-range violating couplings. These limits are derived assuming only one ϵ is different from zero at a time (taken from [7]).

with the hadronic currents $J = \overline{u}(1 \pm \gamma_5)d$, $J^\mu = \overline{u}\gamma^\mu(1 \pm \gamma_5)d$, $J^{\mu\nu} = \overline{u}\frac{i}{2}[\gamma^\mu, \gamma^\nu](1 \pm \gamma_5)d$ and the leptonic currents $j = \overline{e}(1 \pm \gamma_5)e^C$, $j^\mu = \overline{e}\gamma^\mu(1 \pm \gamma_5)e^C$. In some of the cases the decay rate for the effective coupling ϵ_α depends also on the chirality of the currents involved. The $0\nu\beta\beta$ decay rate can be expressed as in (3) with the corresponding phase space and matrix elements. For ^{76}Ge and ^{136}Xe, the resulting limits from current experiments are shown in Table 2.

Isotope	$\lvert\epsilon_1\rvert$	$\lvert\epsilon_2\rvert$	$\lvert\epsilon_3^{LL(RR)}\rvert$	$\lvert\epsilon_3^{LR(RL)}\rvert$	$\lvert\epsilon_4\rvert$	$\lvert\epsilon_5\rvert$
^{76}Ge	$3.2 \cdot 10^{-7}$	$1.8 \cdot 10^{-9}$	$2.2 \cdot 10^{-8}$	$1.4 \cdot 10^{-8}$	$1.5 \cdot 10^{-8}$	$1.5 \cdot 10^{-7}$
^{136}Xe	$2.6 \cdot 10^{-7}$	$1.4 \cdot 10^{-9}$	$1.1 \cdot 10^{-8}$	$1.7 \cdot 10^{-8}$	$1.2 \cdot 10^{-8}$	$1.2 \cdot 10^{-7}$

Table 2. Current limits on effective short-range violating couplings. These limits are derived assuming only one ϵ is different from zero at a time (taken from [7]). For ϵ_3, the result depends on the chirality of the hadronic currents as shown.

3. Models of Lepton Number Violation

Left-Right Symmetry. The minimal Left-Right symmetric model (LRSM) extends the Standard Model gauge symmetry to the group $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ [8]. Right-handed neutrinos are a necessary ingredient to realize this model and the LRSM can accommodate a general seesaw type I+II neutrino mass matrix. The model provides several mechanisms that contribute to $0\nu\beta\beta$ decay: (i) Standard light neutrino exchange with mass helicity flip; (ii) Long-range light neutrino exchange with right-handed currents; (iii) Short-range heavy right-handed neutrino exchange; (iv) Short-range right-handed doubly-charged triplet Higgs exchange. Lepton number violation can also be probed via heavy neutrino production at the LHC [9]. The potential to discover lepton flavour and lepton number violation using this process has recently been analyzed in [10, 11].

R–Parity Violating Supersymmetry. In R_P violating SUSY, the terms $\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \epsilon_iL_iH_u + \lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k$, are added to the MSSM, where indices i, j, k label generations. Since the LNV terms generate Majorana neutrino masses, a small amount of R_P violation could explain the observed neutrino oscillation data. In addition, $0\nu\beta\beta$ decay can occur through Feynman graphs involving the exchange of superpartners. Current experimental limits correspond to $\lambda'_{111} \lesssim 2.6 \cdot 10^{-4} \times (m_{\tilde{q}}/(100\,\text{GeV}))^2(m_{\tilde{g}}/(100\,\text{GeV}))^{1/2}$, for $m_{\tilde{d}_R} = m_{\tilde{u}_L}$. Complementary information can be obtained from the $0\nu\beta\beta$ decay analogue at the LHC, i.e. single selectron production with two like sign electrons in the final state [12].

Leptoquarks. Leptoquarks (LQs) are hypothetical scalar or vector particles coupling to both leptons and quarks. They appear in low-energy Technicolor or Compositeness models. LQs which conserve baryon number can be relatively light, possibly within reach of accelerator experiments. Lepton number violating LQ-Higgs couplings Y_{LQ-H} lead to a contribution to $0\nu\beta\beta$ decay [13] and the current experimental limits roughly correspond to $Y_{LQ-H} \lesssim 10^{-6}$, for LQ masses of the order 200 GeV.

Extra Dimensions. Theories with large extra dimensions of TeV size provide an additional source of LNV. The minimal higher-dimensional framework of LNV considers a 5-dimensional theory compactified on a orbifold, in which one 5-dimensional sterile neutrino is added to the SM [14]. This model generates neutrino masses via a higher-dimensional seesaw mechanism, and the Kaluza-Klein excitations of the sterile neutrino additionally contribute to the $0\nu\beta\beta$ decay rate.

Majorons. Majorons have been originally introduced as Nambu-Goldstone bosons responsible for breaking a global lepton symmetry and generating neutrino Majorana masses [15]. This however requires severe fine-tuning in order to respect the bounds on neutrino masses and at the same time induce observable $0\nu\beta\beta$. Other models have been proposed where the term Majoron simply refers to a light or massless boson that couples to neutrinos. In these modes, one or more Majorons is emitted in $0\nu\beta\beta$ in addition to the two electrons. Recent experimental limits correspond to a bound on the Majoron-neutrino coupling constant of $g \lesssim 10^{-4}$.

4. Summary

Neutrinoless double beta decay is a crucial observable in search for physics beyond the Standard Model as it tests the fundamental symmetry of lepton number. Lepton number violation is predicted in many new physics scenarios. In this context, searches for $0\nu\beta\beta$ are highly complementary to neutrino oscillation experiments, direct neutrino mass determinations in Tritium decay and cosmological observations of the impact of neutrinos on large scale structure formation. The lightness of neutrinos is still be unexplained and $0\nu\beta\beta$ decay is the only realistic probe to distinguish between the Dirac or Majorana nature of light neutrinos.

The observation of $0\nu\beta\beta$ decay at a level corresponding to an effective $0\nu\beta\beta$ mass $m_{ee} \gtrsim 10^{-2}$ eV would be an indication for light neutrino exchange. On the other hand, such a conclusion is not straightforward as there is a large number of models which can trigger $0\nu\beta\beta$ decay. As briefly outlined in this report, there is large number of effective operators and an even larger number of new physics scenarios that can give rise to $0\nu\beta\beta$ decay. Within the context of $0\nu\beta\beta$ decay, relevant techniques include the comparison of $0\nu\beta\beta$ decay rates in different isotopes [16] and the determination of the electron angular and energy distribution [17, 18].

References

[1] J. Schechter, J. Valle, Neutrinoless Double beta Decay in SU(2) x U(1) Theories, Phys.Rev. D25 (1982) 2951. doi:10.1103/PhysRevD.25.2951.

[2] H. Päs, M. Hirsch, H. Klapdor-Kleingrothaus, S. Kovalenko, Towards a superformula for neutrinoless double beta decay, Phys.Lett. B453 (1999) 194–198. doi:10.1016/S0370-2693(99)00330-5.

[3] H. Päs, M. Hirsch, H. Klapdor-Kleingrothaus, S. Kovalenko, A Superformula for neutrinoless double beta decay. 2. The Short range part, Phys.Lett. B498 (2001) 35–39. arXiv:hep-ph/0008182, doi:10.1016/S0370-2693(00)01359-9.

[4] A. Faessler, G. Fogli, E. Lisi, A. Rotunno, F. Simkovic, Multi-Isotope Degeneracy of Neutrinoless Double Beta Decay Mechanisms in the Quasi-Particle Random Phase Approximation, Phys.Rev. D83 (2011) 113015. arXiv:1103.2504, doi:10.1103/PhysRevD.83.113015.

[5] C. Macolino, Results on neutrinoless double beta decay from GERDA Phase I, Mod.Phys.Lett. A29 (1) (2014) 1430001. arXiv:1312.0562, doi:10.1142/S0217732314300018.

[6] M. Auger, et al., Search for Neutrinoless Double-Beta Decay in ^{136}Xe with EXO-200arXiv:1205.5608.

[7] F. F. Deppisch, M. Hirsch, H. Pas, Neutrinoless Double Beta Decay and Physics Beyond the Standard Model, J.Phys. G39 (2012) 124007. arXiv:1208.0727, doi:10.1088/0954-3899/39/12/124007.

[8] J. C. Pati, A. Salam, Lepton Number as the Fourth Color, Phys.Rev. D10 (1974) 275–289. doi:10.1103/PhysRevD.11.703, 10.1103/PhysRevD.10.275.

[9] W.-Y. Keung, G. Senjanovic, MAJORANA NEUTRINOS AND THE PRODUCTION OF THE RIGHT-HANDED CHARGED GAUGE BOSON, Phys.Rev.Lett. 50 (1983) 1427. doi:10.1103/PhysRevLett.50.1427.

[10] J. Aguilar-Saavedra, F. Deppisch, O. Kittel, J. Valle, Flavour in heavy neutrino searches at the LHC, Phys.Rev. D85 (2012) 091301. arXiv:1203.5998, doi:10.1103/PhysRevD.85.091301.

[11] S. Das, F. Deppisch, O. Kittel, J. Valle, Heavy Neutrinos and Lepton Flavour Violation in Left-Right Symmetric Models at the LHC, Phys.Rev. D86 (2012) 055006. arXiv:1206.0256, doi:10.1103/PhysRevD.86.055006.

[12] B. Allanach, C. Kom, H. Päs, Large Hadron Collider probe of supersymmetric neutrinoless double beta decay mechanism, Phys.Rev.Lett. 103 (2009) 091801. arXiv:0902.4697, doi:10.1103/PhysRevLett.103.091801.

[13] M. Hirsch, H. Klapdor-Kleingrothaus, S. Kovalenko, New leptoquark mechanism of neutrinoless double beta decay, Phys.Rev. D54 (1996) 4207–4210. arXiv:hep-ph/9603213, doi:10.1103/PhysRevD.54.R4207.

[14] G. Bhattacharyya, H. Klapdor-Kleingrothaus, H. Päs, A. Pilaftsis, Neutrinoless double beta decay from singlet neutrinos in extra dimensions, Phys.Rev. D67 (2003) 113001. arXiv:hep-ph/0212169, doi:10.1103/PhysRevD.67.113001.

[15] Y. Chikashige, R. N. Mohapatra, R. Peccei, Are There Real Goldstone Bosons Associated with Broken Lepton Number?, Phys.Lett. B98 (1981) 265. doi:10.1016/0370-2693(81)90011-3.

[16] F. Deppisch, H. Päs, Pinning down the mechanism of neutrinoless double beta decay with measurements in different nuclei, Phys.Rev.Lett. 98 (2007) 232501. arXiv:hep-ph/0612165, doi:10.1103/PhysRevLett.98.232501.

[17] M. Doi, T. Kotani, H. Nishiura, E. Takasugi, DOUBLE BETA DECAY, Prog.Theor.Phys. 69 (1983) 602. doi:10.1143/PTP.69.602.

[18] F. Deppisch, C. Jackson, I. Nasteva, S. Soldner-Rembold, Probing the mechanism of neutrinoless double beta decay with SuperNEMO, Prog.Part.Nucl.Phys. 64 (2010) 278–280. doi:10.1016/j.ppnp.2009.12.028.