NEUTRINO-LESS DOUBLE BETA DECAY: NEUTRINO PHYSICS*

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Some neutrino physics aspects of neutrino-less double beta decay are discussed: this includes the possibility to test or rule out the inverted neutrino mass ordering, distinguishing neutrino mass models, or the effects of light sterile neutrinos.

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1. Introduction

Neutrino-less double beta decay ($0\nu\beta\beta$) is a process of fundamental importance for particle physics. It is defined as the transition of a nucleus into a nucleus with proton number larger by two units, and the emission of two electrons

$$(A,Z) \to (A,Z+2) + 2\,e^- \qquad (0\nu\beta\beta)\,. \tag{1}$$

There are no leptons in the initial state, but two in the final state. Observation of $0\nu\beta\beta$ would, therefore, show that lepton number, an accidental and classical symmetry of the Standard Model of particle physics, is violated by Nature. The process, therefore, stands on equal footing with baryon number violation, *i.e.* proton decay. For this reason a huge amount of experimental and theoretical activity is pursued in order to detect and predict the process (see *e.g.* [1, 2, 3, 4] for recent reviews).

In order to extract more specific physics from a signal or an improved signal, one has to assume something about the underlying physics. Here one has basically two choices:

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1. Standard interpretation:

   neutrino-less double beta decay is mediated by light 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:

   neutrino-less double beta decay is mediated by some other lepton number violating physics, and light massive Majorana neutrinos (the ones which oscillate) potentially leading to $0\nu\beta\beta$ give negligible or no contribution.

Here we will focus on the standard interpretation, which is presumably the best motivated one. However, one always has to keep in mind that particles other than light Majorana neutrinos can mediate the decay, such as particles associated with R-parity violating SUSY, left–right symmetric theories, Higgs triplets, heavy neutrinos, leptoquarks, *etc.* A recent review on all possibilities including methods to distinguish them from each other, with a complete list of references, can be found in [3].

Experimentally, the life-time reach depends strongly on whether the experiment is background-dominated, or background-free

$$\left(T_{1/2}^{0\nu}\right)^{-1} \propto \left\{ \begin{array}{cc} a\,M\,\varepsilon\,t & \text{without background} \\ a\,\varepsilon\,\sqrt{\dfrac{M\,t}{B\,\Delta E}} & \text{with background} \end{array} \right. , \tag{2}$$

with B background index in counts/(keV kg yr), ΔE is the energy resolution, ε the efficiency, a the abundance of the isotope, M the mass and t the measurement time. The "master formula" for $0\nu\beta\beta$ mediated by a mechanism x is

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_x(Q,Z)\,|\mathcal{M}_x(A,Z)\,\eta_x|^2\,, \tag{3}$$

with $G_x(Q,Z)$ the (calculable) phase space factor, $\mathcal{M}_x(A,Z)$ the (problematic) nuclear physics matrix element and η_x the (interesting) particle physics parameter. Therefore, an improvement of a factor 2 of the particle physics parameter implies a total factor of 16 improvement of background index, energy resolution, mass and time. Given that upcoming next generation experiments are at the very end of what is currently technologically feasible, this factor is far from trivial.

2. Neutrino physics and $0\nu\beta\beta$

2.1. General aspects

The quark level Feynman diagram for $0\nu\beta\beta$ is shown in Fig. 1. Neutrinos have to be massive and Majorana particles for the process to occur. The amplitude is proportional to the "effective mass"

$$\langle m_{ee}\rangle = \left|\sum U_{ei}^2\, m_i\right| = \left|\left|m_{ee}^{(1)}\right| + \left|m_{ee}^{(2)}\right|\, e^{2i\alpha} + \left|m_{ee}^{(3)}\right|\, e^{2i\beta}\right| , \tag{4}$$

and is a function of the 3 neutrino masses m_i, the lepton mixing matrix elements from the first row (or θ_{12} and θ_{13}) and the two Majorana phases. All in all, it depends on 7 out of the 9 parameters of neutrino physics (only δ and θ_{23} do not appear) and therefore contains a lot of information. A typical plot of $\langle m_{ee}\rangle$ as a function of the smallest mass can be seen in Fig. 1. The dark gray/blue (light gray/yellow) areas are for the normal (inverted) ordering, while the darker areas inside the lighter ones are for the best-fit values of the oscillation parameters (the range is induced by the unknown Majorana phases).

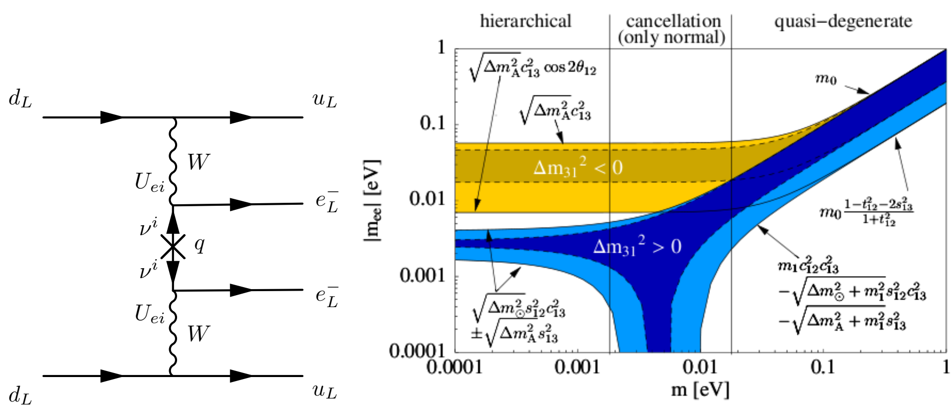

Fig. 1. Left: quark level Feynman diagram for the standard interpretation of neutrino-less double beta decay. Right: effective mass as function of the smallest neutrino mass.

As can be seen from Eq. (3), to go from a life-time measurement or limit to the effective mass, precise knowledge of the nuclear matrix elements is necessary. Unfortunately, a large uncertainty is present here, stemming from different calculational approaches (such as QRPA, NSM, IBM, *etc.*), and uncertainties within each individual approach. The procedure is to interpret the different results for the matrix elements as "theory error". A typical compilation of results, carefully checked for convention issues, is shown in Fig. 2, taken from Ref. [5], where the references and details can be found.

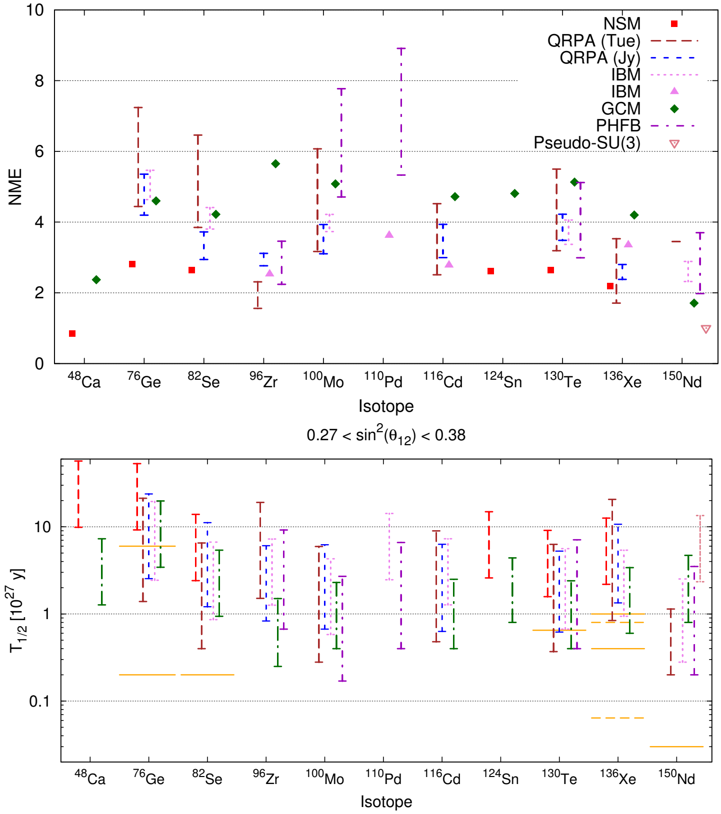

Fig. 2. Top: Compilation of nuclear matrix element results. Bottom: necessary half-life to rule out the inverted ordering. The horizontal (yellow) lines indicate future experimental limits.

2.2. The inverted hierarchy

As can be seen from Fig. 1, the effective mass in the case of the inverted mass ordering cannot vanish. Hence, nature provides us two important scales, namely the minimal and maximal effective mass for $m_3 = 0$

$$\langle m_{ee}\rangle^{\rm IH}_{\rm max} \simeq \cos^2\theta_{13}\sqrt{\Delta m^2_{\rm A}} \quad \text{and} \quad \langle m_{ee}\rangle^{\rm IH}_{\rm min} \simeq \cos^2\theta_{13}\sqrt{\Delta m^2_{\rm A}}\,\cos 2\theta_{12}\,. \quad (5)$$

If we knew that the mass ordering is inverted, then going below $\langle m_{ee}\rangle^{\rm IH}_{\rm min}$ would rule out the Majorana nature of neutrinos. Alternatively, going below $\langle m_{ee}\rangle^{\rm IH}_{\rm min}$ would rule out the inverted ordering under the assumptions that neutrinos are Majorana particles. Though θ_{12} is the best-known neutrino parameter, its current 3σ range implies a factor of 2 range for $\langle m_{ee}\rangle^{\rm IH}_{\rm min}$. Recall from above that this factor 2 implies a total factor 16 in background index, energy resolution, mass and time. Hence, a better knowledge of this angle would be of crucial importance to evaluate the physics potential of neutrino-less double beta decay experiments. Fig. 2, taken from [5], shows the necessary half-life to rule out the inverted ordering. The uncertainty from the nuclear matrix elements *and* θ_{12} is taken into account. Though the inverted ordering cannot be fully covered with upcoming next generation experiments, we will surely enter its regime [5].

2.3. Ruling out flavor symmetry models

The peculiar mixing scheme that leptons display forces one to introduce flavor symmetries [6]. Ref. [7] lists about 70 different models which all give tri-bimaximal mixing. The natural question on how to distinguish them from each other could be answered by neutrino mass experiments such as neutrino-less double beta decay (in the standard interpretation). The reason is that very often "sum-rules" between the neutrino masses are induced within the models. While masses cannot be predicted by flavor symmetries, relations between them can very well be predicted. Examples are $m_1 + m_2 = m_3$, or $2/m_2 + 1/m_3 = 1/m_1$. Here the masses are understood to be complex, *i.e.* the absolute values and the Majorana phases are constrained by these sum-rules. Consequently, the effective mass will only take specific values in its general parameter space, which can be used to rule out some of the models. Fig. 3 shows the results of such an analysis, taken from Ref. [8].

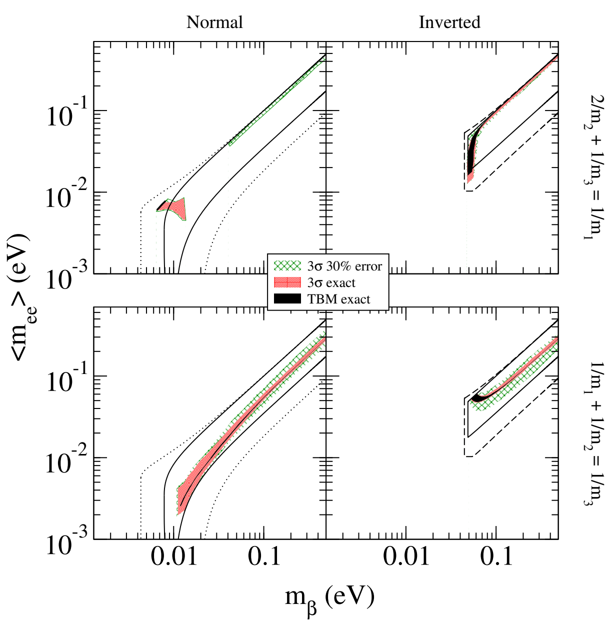

Fig. 3. Direct neutrino parameter m_β as measurable in KATRIN *versus* the effective mass for two specific neutrino mass sum-rules, $2/m_2 + 1/m_3 = 1/m_1$ and $1/m_1 + 1/m_2 = 1/m_3$.

2.4. Sterile neutrinos

More and more evidence accumulates which hints to the existence of sterile neutrinos with mass at the eV-scale. The most recent one is the "reactor anomaly" [9], which denotes the outcome of a re-evaluation of neutrino spectra from nuclear reactors. A systematic upward shift of about 3% was found, and the results of past very short baseline reactor experiments, interpreted back then as negative, were in fact observing a deficit. This is in agreement with effects of sterile neutrinos with $\Delta m^2_{\rm st} \simeq 1\,{\rm eV}^2$, and mixing of the order of 0.15 with electron neutrinos [9]. What is the effect for neutrino-less double beta decay?

For one sterile neutrino, the effective mass is now a sum of four terms, the additional term quantifying the sterile contribution

$$\langle m_{ee}\rangle = |\, \underbrace{|U_{e1}|^2 m_1 + |U_{e2}|^2 m_2\, e^{2i\alpha} + \left|U_{e3}^2\right| m_3\, e^{2i\beta}}_{\langle m_{ee}\rangle^{\rm act}} + \underbrace{|U_{e4}|^2 m_4\, e^{2i\Phi_1}}_{\langle m_{ee}\rangle^{\rm st}} \,| \,. \tag{6}$$

Here $|\langle m_{ee}\rangle^{\rm act}|$ is the contribution discussed so far, and $\langle m_{ee}\rangle^{\rm st}$ the sterile one. Suppose the easiest case that there is only one sterile neutrino, and that it is heavier than the 3 active ones (the complete list of possibilities including the case of two sterile neutrinos can be found in Refs. [10,11]). Recall from above that $|\langle m_{ee}\rangle^{\rm act}_{\rm NH}|$ can vanish and that $|\langle m_{ee}\rangle^{\rm act}_{\rm IH}|$ cannot vanish, having a typical value of 0.02 eV. With the typical sterile neutrino parameters given above one has that

$$\left|\langle m_{ee}\rangle^{\rm st}\right| \simeq \sqrt{\Delta m^2_{\rm st}}\, |U_{e4}|^2 \simeq 0.02 \text{ eV} \left\{ \begin{array}{c} \gg \left|\langle m_{ee}\rangle^{\rm act}_{\rm NH}\right| \\ \simeq \left|\langle m_{ee}\rangle^{\rm act}_{\rm IH}\right| \end{array} \right. . \tag{7}$$

Therefore, if the active neutrinos are normally ordered, the effective mass *cannot* vanish anymore, whereas it *can* vanish when they are inversely ordered [11]. Hence, the usual standard phenomenology has been completely turned around. Given that the addition of light sterile neutrinos is presumably the simplest modification of the standard picture, it shows that when discussing the physics potential of $0\nu\beta\beta$ one should carefully list one's assumptions.

3. Final comments

The field of neutrino-less double beta decay is currently entering a very exciting stage. The strongest constraint on the process (half-life larger than 1.9×10^{25} yrs for ^{76}Ge [12]) is the leading limit since 10 years, and will finally be improved in 2012. A variety of experiments with different experimental techniques and different isotopes is upcoming. Multi-isotope and -technique determination will be crucial to increase the credibility of a signal, helpful to test calculations of nuclear matrix elements, and distinguish the mechanism of $0\nu\beta\beta$.

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REFERENCES

[1] F.T. Avignone, S.R. Elliott, J. Engel, *Rev. Mod. Phys.* **80**, 481 (2008) [arXiv:0708.1033 [nucl-ex]].

[2] A. Giuliani, *Acta Phys. Pol. B* **41**, 1447 (2010).

[3] W. Rodejohann, *Int. J. Mod. Phys.* **E20**, 1833 (2011) [arXiv:1106.1334 [hep-ph]].

[4] J.J. Gomez-Cadenas *et al.*, arXiv:1109.5515 [hep-ex].

[5] A. Dueck, W. Rodejohann, K. Zuber, *Phys. Rev.* **D83**, 113010 (2011) [arXiv:1103.4152 [hep-ph]].

[6] For reviews, see G. Altarelli, F. Feruglio, *Rev. Mod. Phys.* **82**, 2701 (2010) [arXiv:1002.0211 [hep-ph]]; H. Ishimori *et al.*, *Prog. Theor. Phys. Suppl.* **183**, 1 (2010) [arXiv:1003.3552 [hep-th]].

[7] J. Barry, W. Rodejohann, *Phys. Rev.* **D81**, 093002 (2010) [arXiv:1003.2385 [hep-ph]].

[8] J. Barry, W. Rodejohann, *Nucl. Phys.* **B842**, 33 (2011) [arXiv:1007.5217 [hep-ph]].

[9] G. Mention *et al.*, *Phys. Rev.* **D83**, 073006 (2011) [arXiv:1101.2755 [hep-ex]].

[10] S. Goswami, W. Rodejohann, *J. High Energy Phys.* **0710**, 073 (2007) [arXiv:0706.1462 [hep-ph]].

[11] J. Barry, W. Rodejohann, H. Zhang, *J. High Energy Phys.* **1107**, 091 (2011) [arXiv:1105.3911 [hep-ph]].

[12] H.V. Klapdor-Kleingrothaus *et al.*, *Eur. Phys. J.* **A12**, 147 (2001) [arXiv:hep-ph/0103062v1].