Multiple mechanisms in $(\beta\beta)_{0\nu}$decay

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The $(\beta\beta)_{0\nu}$-decay can be induced by more than one lepton charge nonconserving mechanism. We analyze some mechanisms contributing to the $(\beta\beta)_{0\nu}$ decay amplitude in the general case of CP nonconservation: light Majorana neutrino exchange, heavy left-handed (LH) and right-handed (RH) Majorana neutrino exchanges, lepton charge non-conserving coupling in SUSY theories with R_p breaking. We show the analysis for the cases of two "non-interfering" and two "interfering" mechanisms. This method can be generalized to the case of more than two $(\beta\beta)_{0\nu}$ decay mechanisms and allows to treat the cases of CP conserving and CP nonconserving couplings generating the $(\beta\beta)_{0\nu}$ decay in a unique way.

1 Introduction

Whether the massive neutrinos are Dirac or Majorana particles is one of the fundamental open questions in neutrino (and particle) physics today. The Majorana nature of neutrinos can manifest itself in the existence of processes in which the total lepton charge is not conserved. At present the only feasible experiments that can unveil the Majorana nature of massive neutrinos are the experiments searching for neutrinoless double beta decay ($(\beta\beta)_{0\nu}$): $(A,Z) \rightarrow (A,Z+2)+e^- + e^-$. In this processes the total lepton charge changes by two units, $\Delta L = 2$. If neutrinos are Majorana particles, at some probability level their exchange should trigger the $(\beta\beta)_{0\nu}$ decay. One can consider the light Majorana neutrino exchange as the "standard" mechanism that induces the decay. In this case the fundamental lepton number violating parameter describing this mechanism is the effective Majorana mass $|<m>|$:

$$|<m>| = \left| \sum_j^{light} (U_{ej}^{PMNS})^2 m_j \right|, \tag{1}$$

m_j, $j = 1, 2, 3$, being the three light neutrino masses, $m_j \lesssim 1$eV and U^{PMNS} is the Pontecorvo-Maki-Nakagawa-Sakata neutrino mixing matrix which contains a Dirac and two Majorana CP-violating phases. The observation of $(\beta\beta)_{0\nu}$decay and the measurement of $|<m>|$ would prove not only the Majorana nature of massive neutrinos, but it could give information on the type of neutrino mass spectrum, on the absolute neutrino mass scale, and with additional information from other sources (^3H decay experiments or cosmological and astrophysical data considerations) one might extract unique information on the Majorana CP-violation phases. Experimentally the isotopes used in the searches for $(\beta\beta)_{0\nu}$ decay are those for which the single β-decay is forbidden: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{118}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd. A large number of projects, aiming at a sensitivity of $|<m>| \sim (0.01-0.05)$ eV, will test the results claimed in [?] (with $T_{1/2}^{0\nu}(^{76}Ge) = 2.23^{+0.44}_{-0.31} \times 10^{25}$yr, corresponding to $|<m>| = 0.32 \pm 0.03$ eV) such as CUORE (^{130}Te), GERDA (^{76}Ge), EXO (^{136}Xe), KamLAND-Zen (^{136}Xe).

The $(\beta\beta)_{0\nu}$-decay can be triggered, in principle, not only by the light Majorana neutrino exchange, but by more than one lepton charge nonconserving mechanism. These mechanisms are, in general, CP-nonconserving.

2 CP-violating mechanisms

If the $(\beta\beta)_{0\nu}$-decay will be observed, the question of which lepton charge nonconserving mechanisms induce the decay will inevitably arise. Each of the various $(\beta\beta)_{0\nu}$-decay mechanisms considered in the literature is characterised by its own lepton number violating (LNV) parameter, η_κ^{LNV}, where the idex κ lables the mechanism. The mechanisms we will consider in what follows are, in general, CP-nonconserving. As a consequence, the corresponding LNV parameters are complex.

If several mechanisms are involved in $(\beta\beta)_{0\nu}$-decay, the inverse value of the $(\beta\beta)_{0\nu}$-decay half-life for a given isotope (A, Z) can be written as:

$$\frac{1}{G^{0\nu}(E_0, Z)T_{1/2}^{0\nu}} = |\sum_\kappa \eta_\kappa^{LNV} {M'}_\kappa^{0\nu}|^2 \,, \tag{2}$$

where $G^{0\nu}(E_0, Z)$ and ${M'}_\kappa^{0\nu}$ are, respectively, the known phase-space factor (E_0 is the energy release) and the nuclear matrix element of the decay (we list in Table **??** the values for the isotopes we will consider her). The latter depends on the mechanism generating the decay and on the nuclear structure of the specific isotopes (A, Z), $(A, Z + 1)$ and $(A, Z + 2)$ under study.

Depending on the Lorenz structure of, e.g., the currents describing the two electrons in the final state of $(\beta\beta)_{0\nu}$-decay, two mechanisms generating the $(\beta\beta)_{0\nu}$-decay can be either "interfering" or "non-interfering". In the first case the interference term in the $(\beta\beta)_{0\nu}$-decay rate, originating from the product of the contributions of each of the two mechanisms to the $(\beta\beta)_{0\nu}$-decay amplitude, is not supptressed, while in the second case - it is suppressed and often can be neglected. Such a suppression can occure if, e.g., the electron currents predicted by the two mechanisms have different chiral structure and the level of suppression depends on the decaying nucleus [?].

The $(\beta\beta)_{0\nu}$decay is allowed in a wide range of models. We will consider in this analysis in addition to the standard case in which $(\beta\beta)_{0\nu}$decay is triggered by the exchange of light Majorana neutrino, a finite number of models such as the Left-Right Symmetry model, in which $(\beta\beta)_{0\nu}$decay is induced by heavy right handed Majorana neutrinos, and for example R_p-parity nonconserving Supersymmetry (SUSY) theories where Majorana fermions such as gluinos and neutralinos can induce the decay. The complete analysis in the general case of CP nonconserving couplings can be found in [?]. Here we briefly discuss the two main cases: $(\beta\beta)_{0\nu}$decay induced by i) two "non-interfering" mechanisms, e.g. LH light and RH heavy ($M_k > 10$ GeV) Majorana neutrino exchange whose LNV parameters are denoted respectively by $|\eta_\nu|$ and $|\eta_N^R|$ and ii) two interfering mechanisms, e.g, light Majorana neutrino, $|\eta_\nu|$, and supersymmetric gluino exchange, $|\eta_{\lambda'}|$.

One can determine and/or sufficiently constrain the fundamental parameters $|\eta_\nu|$, $|\eta_N^R|$, etc. associated with the lepton charge nonconserving couplings exploiting the dependence of the nuclear matrix elements on the decaying nucleus, and using as input hypothetical values of the $(\beta\beta)_{0\nu}$-decay half-life of ^{76}Ge satisfying the existing lower limits and the value claimed in ref. [?] [?] as well as the following hypothetical ranges for $T_{1/2}^{0\nu}(^{100}\text{Mo})$ and $\text{T}_{1/2}^{0\nu}(^{130}\text{Te})$:

$$\begin{array}{c} T_{1/2}^{0\nu}(^{76}Ge) \geq 1.9 \times 10^{25} y, \quad T_{1/2}^{0\nu}(^{76}Ge) = 2.23^{+0.44}_{-0.31} \times 10^{25} y \\ 5.8 \times 10^{23} y \leq T_{1/2}^{0\nu}(^{100}Mo) \leq 5.8 \times 10^{24} y, \quad 3.0 \times 10^{24} y \leq T_{1/2}^{0\nu}(^{130}Te) \leq 3.0 \times 10^{25} y \end{array} \tag{3}$$

Let us note that 5.8×10^{23} y and 3.0×10^{24} y are the existing lower bounds on the half-lives of ^{100}Mo and ^{130}Te [?,?].

As we will see, in certain cases of at least one more mechanism being operative in $(\beta\beta)_{0\nu}$-decay beyond the light neutrino exchange, one has to take into account the upper limit on the absolute scale of neutrino masses set by the ^3H β-decay experiments [?,?]: $m(\bar{\nu}_e) < 2.3$ eV. In

Table 1: Phase space factors and values of NMEs.

Transition	$G_i^{0\nu}(E,Z)[y^{-1}]$	$\lvert M'^{0\nu}_{\nu}\rvert$	$\lvert M'^{0\nu}_{N}\rvert$	$\lvert M'^{0\nu}_{\lambda'}\rvert$
^{76}Ge $\rightarrow$ ^{76}Se	7.98×10^{-15}	5.82	412	596
^{100}Mo $\rightarrow$ ^{100}Ru	5.73×10^{-14}	5.15	404	589
^{130}Te $\rightarrow$ ^{130}Xe	5.54×10^{-14}	4.70	385	540

the case of $(\beta\beta)_{0\nu}$-decay, this limit implies a similar limit on the effective Majorana mass [a] $|{<}m{>}| < 2.3$ eV.

2.1 Example of two "non-interfering" mechanism

In the case of two "non-interfering" mechanisms, the light Majorana neutrino (denoted by η_ν) and the right-handed heavy Majorana neutrino exchange (denoted by η_N^R), the inverse of the half-life of an isotope i undergoing $(\beta\beta)_{0\nu}$decay is given by:

$$(T^{0\nu}_{1/2})_i^{-1} = G_i^{0\nu}(|\eta_\nu|^2|M'^{0\nu}_{i,\nu}|^2 + |\eta_N^R|^2|M'^{0\nu}_{i,N}|^2), \quad \text{with}$$
$$\eta_\nu = \frac{|{<}m{>}|}{m_e}, \quad \eta_N^R = \left(\frac{M_W}{M_{W_R}}\right)^4 \sum_k^{heavy} V_{ek}^2 \frac{m_p}{M_k}. \tag{4}$$

where $G_i^{0\nu}$ and $M'^{0\nu}_{i,\kappa}$, $\kappa = \nu, N$ are respectively the phase space factor and the nuclear matrix element (NMEs), m_e and m_p are the electron and the proton masses, V_{ek} is the element of the ν- mixing matrix through which the heavy neutrino N_k couples to the electron in the hypothetical $V+A$ charged lepton current, and $M_W \cong 80$ GeV ($M_{W_R} > 2.5$ TeV) is the LH (RH) weak charged boson mass.

In this "non-interfering" case one can see that, in order to determine the LNV parameters (the unknowns) we can set a system of two linear equations using as input hypothetical half-lives of two isotopes (T_1 and T_2), and reference values for the NMEs $M'^{0\nu}_{i,k}$, and the kinematical factor (see Table ??). One finds that the LNV parameters, solutions of the system of equations, are given by:

$$|\eta_\nu|^2 = \frac{|M'^{0\nu}_{2,N}|^2/T_1G_1 - |M'^{0\nu}_{1,N}|^2/T_2G_2}{|M'^{0\nu}_{1,\nu}|^2|M'^{0\nu}_{2,N}|^2 - |M'^{0\nu}_{1,N}|^2|M'^{0\nu}_{2,\nu}|^2}, \quad |\eta_N^R|^2 = \frac{|M'^{0\nu}_{1,\nu}|^2/T_2G_2 - |M'^{0\nu}_{2,\nu}|^2/T_1G_1}{|M'^{0\nu}_{1,\nu}|^2|M'^{0\nu}_{2,N}|^2 - |M'^{0\nu}_{1,N}|^2|M'^{0\nu}_{2,\nu}|^2}. \tag{5}$$

Negative solutions are not physical, so requiring $|\eta_\nu|^2 > 0$ $|\eta_N^R|^2 > 0$ and fixing one of the two half-lives, e.g. T_1, we can find a range for T_2 of physical solutions [b]:

$$\frac{T_1G_1|M'^{0\nu}_{1,N}|^2}{G_2|M'^{0\nu}_{2,N}|^2} \le T_2 \le \frac{T_1G_1|M'^{0\nu}_{1,\nu}|^2}{G_2|M'^{0\nu}_{2,\nu}|^2}\,, \tag{6}$$

where we have used the fact that $|M'^{0\nu}_{1,\nu}|^2/|M'^{0\nu}_{2,\nu}|^2 > |M'^{0\nu}_{1,N}|^2/|M'^{0\nu}_{2,N}|^2$ (see table ??). Using as two isotopes ^{76}Ge and ^{100}Mo and fixing $T_1 \equiv T^{0\nu}_{1/2}(^{76}Ge) = 2.23\times10^{25}$ y [?], one obtains the results shown in the left panel in Fig. ??.

[a] We remind the reader that for $m_{1,2,3} \gtrsim 0.1$ eV the neutrino mass spectrum is quasi-degenerate (QD), $m_1 \cong m_2 \cong m_3 \equiv m$, $m_j^2 >> \Delta m^2_{21}, |\Delta m^2_{31}|$. In this case we have $m(\bar\nu_e) \cong m$ and $|{<}m{>}| \lesssim m$.

[b] This results are valid for $A_1 < A_2$ where A is the atomic number of a given isotope, chosen among the set ^{76}Ge, ^{100}Mo and ^{130}Te.

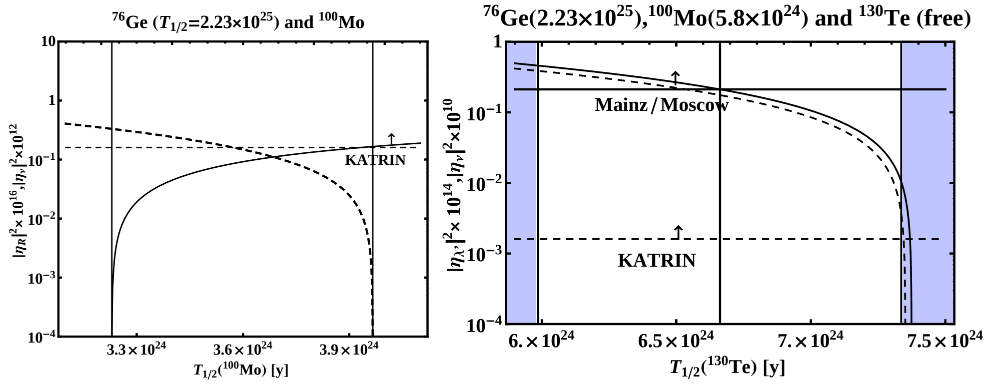

Figure 1: Rescaled values of i) $|\eta_\nu|^2$ (solid line) and $|\eta_N^R|^2$ (dashed line) for $T_{1/2}^{0\nu}(^{76}Ge) = 2.23\times10^{25}$y [?] (left panel), and of ii) $|\eta_\nu|^2$ (solid line) and $|\eta_{\lambda'}|^2$ (dashed lined) for the same value of $T_{1/2}^{0\nu}(^{76}Ge)$ and $T_{1/2}^{0\nu}(^{100}Mo) = 5.8\times10^{24}$y (right panel). The experimental lower bound [?] $T_{1/2}^{0\nu}(^{130}Te) > 3\times10^{24}$y is taken into account. The physical allowed regions correspond to the areas shown in white; the areas shown in gray are excluded. The horizontal solid (dashed) line corresponds to the upper limit [?,?] $|\langle m \rangle| < 2.3$eV (prospective upper limit [?] $|\langle m \rangle| \leq 0.2$eV).

2.2 Example of two "interfering" mechanism

In this second case, considering as interfering mechanisms the light Majorana neutrino and the supersymmetric gluino exchange, (denoted by $\eta_{\lambda'}$), the $(\beta\beta)_{0\nu}$decay inverse half-life of a given nucleus reads:

$$(T_{1/2,i}^{0\nu})^{-1} = G_i^{0\nu}(|\eta_\nu|^2(M'^{0\nu}_{i,\nu})^2 + |\eta_{\lambda'}|^2(M'^{0\nu}_{i,\lambda'})^2 + 2\cos\alpha M'^{0\nu}_{i,\lambda'} M'^{0\nu}_{i,\nu}|\eta_\nu||\eta_{\lambda'}|)\,, \qquad (7)$$

where the LNV parameters are given in [?]. From Eq. (**??**) it is possible to extract the values of $|\eta_\nu|^2$, $|\eta_{\lambda'}|^2$ and $\cos\alpha$ setting up a system of three equation with these three unknowns using as input the "data" on the half-lives of three different nuclei. The solutions are given using the Cramer's rule. As well, we must require that $|\eta_\nu|^2$ and $|\eta_{\lambda'}|^2$ be non-negative and that the factor $2\cos\alpha|\eta_\nu||\eta_{\lambda'}|$ in the interference term satisfies:

$$-2|\eta_\nu||\eta_{\lambda'}| \leq 2\cos\alpha|\eta_\nu||\eta_{\lambda'}| \leq 2|\eta_\nu||\eta_{\lambda'}|. \qquad (8)$$

If we fix (i.e. have data on) the half-lives of two of the nuclei and combine these with the condition in Eq. (**??**), we can obtain the interval of values of the half-life of the third nucleus, which is compatible with the data on the half-lives of the two other nuclei and the mechanisms considered. The minimal (maximal) value of this interval of half-lives of the third nucleus is obtained for $\cos\alpha = +1$ ($\cos\alpha = -1$). An example of such an analysis is plotted in Fig. **??** (right panel). One can notice that the positivity conditions in this case allow to constrain the region of positive solutions given by the white area. For a detailed analysis see [?].

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