NEUTRINOLESS DOUBLE BETA DECAY IN THE CASE OF DIRAC NEUTRINOS

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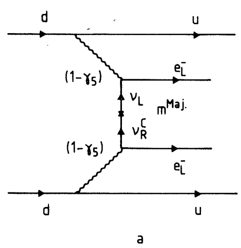
The possibility of generating neutrinoless double beta decay with Dirac neutrinos is discussed. Two scenarios with very different signatures are presented, one with a left-handed and the other with a right-handed lepton number violating electron–neutrino interactions. An example of a gauge model with the latter kind of coupling is given.

The neutrinoless double beta decay $(\beta\beta)_{0\nu}$ provides an important test of the basic properties of neutrinos [1]. According to the standard picture, if such processes are observed, it would indicate that neutrinos (or at least the electron neutrino) are not described by four component Dirac fields as other fermions, but are self-conjugate Majorana particles. If a Majorana neutrino couples to the electron via a pure V – A vertex, the $(\beta\beta)_{0\nu}$ rate is proportional to the mass of the virtual neutrino [2]. The mass determines the intensity of chirality flip necessary for the process to continue (see fig. 1a). Hence a vanishing rate would imply that the neutrino is massless.

On the other hand, going beyond the standard model, a massless Majorana neutrino can generate $(\beta\beta)_{0\nu}$ provided its weak coupling to the electron is not purely V – A, but contains a non-vanishing right-handed part η(V + A) [3] (see fig. 1b). This possibil-



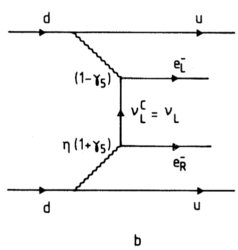


Fig. 1. Neutrinoless double beta decay mediated by a Majorana neutrino with (a) non-zero mass, (b) a right-handed coupling to an electron.

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ity comes about, for example, in left–right symmetric models.

In this note, we wish to point out the possibility that a neutrino need not be a Majorana particle to be able to mediate $(\beta\beta)_{0\nu}$. In the following, we present two feasible scenarios where this process is generated by a Dirac neutrino. Of course, such scenarios require considerable modifications on the standard models, but are nevertheless accessible in the framework of chiral gauge theories.

In $(\beta\beta)_{0\nu}$ the lepton number (L) is violated by two units. When the virtual neutrino is a Dirac particle, this violation must take place in the $e\nu$ interaction vertex, since Dirac particles are eigenstates of L. There are two forms of electron–neutrino couplings which allow for $|\Delta L| = 2$ interactions:

$$J_\lambda^{\mathrm{I}} = \bar{e}\gamma_\lambda(\cos\delta\ \nu_{\mathrm{L}} + \sin\delta\ \nu_{\mathrm{L}}^{\mathrm{c}}) , \quad (1)$$

$$J_\lambda^{\mathrm{II}} = \bar{e}\gamma_\lambda(\cos\epsilon\ \nu_{\mathrm{L}} + \sin\epsilon\ \nu_{\mathrm{R}}^{\mathrm{c}}) , \quad (2)$$

where e and ν are Dirac mass eigenstates and $\nu_{\mathrm{L(R)}}^{\mathrm{c}} = (C\bar{\nu}^{\mathrm{T}})_{\mathrm{L(R)}}$. We will call eqs. (1) and (2) Model I and Model II respectively. We have defined the angles δ and ϵ which measure the magnitude of the lepton number violation. As will be discussed below, there are essential differences between the two models as far as $(\beta\beta)_{0\nu}$ is concerned.

It has been shown by Petcov [4] that the effective coupling (1) may arise in the framework of the $\mathrm{SU(2)_L} \times \mathrm{U(1)}_Y$ gauge theory if one adopts the Zeldovich–Konopinsky–Mahmoud model as the starting point. In this picture, there is a common lepton number for electron and muon type leptons, and the $|\Delta L| = 2$ interaction follows essentially from the assumption that there is only one four-component neutrino, ν, devoted commonly to electron and muon and identified via the assignments $\nu_{\mathrm{L}} = \nu_{\mathrm{eL}}$ and $\nu_{\mathrm{L}}^{\mathrm{c}} = \nu_{\mu\mathrm{L}}$. Mixing of ν_{e} with ν_μ will lead to the current (1). In a recent paper, Valle [5] also has considered the type (1) coupling in connection with $(\beta\beta)_{0\nu}$. Later in this note we will present an example of a gauge model where the explicit breaking of L of the type (2) may occur.

It is obvious that in Model I, the neutrino should have non-zero mass in order to yield a non-vanishing $(\beta\beta)_{0\nu}$ rate (fig. 2a). Helicity flip in the virtual state is needed because the $e\nu$ vertices are purely left-handed. The $(\beta\beta)_{0\nu}$ amplitude $A\,(\beta\beta)_{0\nu}$ is therefore proportional to the product of the mass m_ν and the L violation factor sin 2δ:

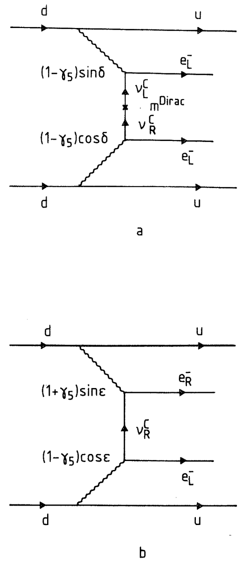

Fig. 2. Neutrinoless double beta decay mediated by a Dirac neutrino with (a) left-handed, (b) right-handed $|\Delta L| = 2$ coupling to an electron.

$$A^{\mathrm{I}}_{(\beta\beta)_{0\nu}} \propto m_\nu \sin 2\delta\ . \quad (3)$$

The small value of the $(\beta\beta)_{0\nu}$ rate does not in this case necessarily mean a small value for the neutrino mass. On the other hand, the L violation angle δ need not be extremely small if m_ν is very light. In fact, if we take $\delta = \pi/4$, i.e. the maximal L violation, we obtain an $e\nu$ coupling that is effectively the same as in the case where the neutrino is a Majorana particle.

The $(\beta\beta)_{0\nu}$ process in Model II is depicted in fig. 2b. The virtual neutrino may now, in contrast with Model I, be massless, since the electron also has right-handed coupling to it. The $(\beta\beta)_{0\nu}$ amplitude depends only on the L violation factor:

$$A^{\mathrm{II}}_{(\beta\beta)_{0\nu}} \propto \sin 2\epsilon\ . \quad (4)$$

The small value of the $(\beta\beta)_{0\nu}$ rate then puts stringent constraints directly on the magnitude of L non-conservation. We find, using the recent experimental results from $^{82}\mathrm{Se} \to {}^{82}\mathrm{Kr}$ [6] as a typical example, the bound

$$|\sin 2\epsilon| \lesssim 1.8 \times 10^{-5}\ . \quad (5)$$

One possible way to distinguish between the two models is to consider the helicity of, or angular correlation between, the emitted electrons. In the first model the electrons have the same helicity, and in the second, opposite helicity. This leads to different angular distributions in these two cases [1,7]. Another important difference is that in Model II, the $0^+ \to 2^+$ (J^P) transitions are allowed, thanks to the right-handed coupling [7,8]. In Model I, only the ordinary $0^+ \to 0^+$ transitions may occur.

These two tests do not, however, answer the question whether the neutrino which mediates the $(\beta\beta)_{0\nu}$ process is a Dirac particle or a Majorana particle. A Dirac neutrino of Model I is indistinguishable from a Majorana neutrino with a mass and with a pure left-handed coupling, and a Dirac neutrino of Model II is indistinguishable from a Majorana neutrino with a non-vanishing right-handed coupling, if these two aspects only are considered.

To solve this ambiguity, one has to study other neutrino processes. Phenomena that could distinguish between Dirac and Majorana neutrinos are the second class neutrino oscillations (ν–ν^c oscillations). These are possible in the case of Majorana neutrinos, but do not occur for Dirac neutrinos. A possible test based on this fact is proposed by Valle [5].

In the above considerations we have limited ourselves to the tree-level only. It should, however, be emphasized that neutrinos which have L violating interactions, such as those in eqs. (1) and (2), though Dirac particles at tree-level, will generally obtain small Majorana mass contributions from higher order effects [9], and will thus split into two almost degenerate Majorana particles. These kinds of particles are called pseudo- (or quasi-) Dirac neutrinos. An exception to this general rule is, however, afforded by the sample model which we shall introduce presently. There the condition which prevents neutrinos acquiring a Majorana mass at tree-level ensures at the same time that no Majorana terms are generated radiatively in any order of perturbation expansion.

Let us now describe a gauge model where the coupling of eq. (2) may arise. The model is based on a "left–right symmetric" gauge group which we denote as $SU(2)_L \times SU(2)_{R'} \times U(1)_{Y'}$. It differs from the ordinary left–right symmetric $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model (LR model) by its unconventional assignment for leptons:

$$\begin{pmatrix}\nu_1\\ e^-\end{pmatrix}_L \sim (2,1,-1)\,, \qquad \begin{pmatrix}\nu_2^c\\ e^-\end{pmatrix}_R \sim (1,2,-1)\,, \tag{6}$$

$$\nu_{1R} \sim \nu_{2R} \sim (1,1,0)\,.$$

Two four-component neutrinos are required in order for the picture to work. For quarks, the assignment is the same as in the standard version of the LR model. The lepton number is +1 for ν_1, ν_2, and e^- and -1 for the corresponding antiparticles. It is seen from (6) that the charged gauge bosons $W^{\pm}_{R'}$ of $SU(2)_{R'}$ mediate $|\Delta L| = 2$ interactions. If ν_1 and ν_2 are mixed through Dirac mass terms with each other, the desired form of $e\nu$ interaction follows. In passing, it is obvious that the generator Y' of the U(1) factor cannot in this model be identified with $B-L$, the baryon minus lepton number, since $B-L$ does not commute with $SU(2)_{R'}$.

Dirac masses for neutrinos are generated by two Higgs doublets H_L and H_R, transforming as $H_L \sim (2,1,-1)$ and $H_R \sim (1,2,1)$, and acquiring non-vanishing VEVs $\langle H_L\rangle = v_L$ and $\langle H_R\rangle = v_R$. Since ν_{1R} and ν_{2R} transform equivalently, mixing between two neutrinos may happen. The following mass lagrangian is allowed:

$$\mathcal{L}_m = \sum_{i=1}^{2} (h_{Li}\bar{\nu}_{iR} v_L \nu_{1L} + h_{Ri}\bar{\nu}_{iR} v_R \nu_{2L}) + \text{h.c.} \tag{7}$$

As a result of diagonalization we obtain two Dirac neutrinos, $\nu = \cos\theta\, \nu_1 - \sin\theta\, \nu_2$ and $N = \sin\theta\, \nu_1 + \cos\theta\, \nu_2$, with masses

$$m_\nu \simeq h_{1L} v_L + \theta\, h_{2L} v_L\,, \qquad m_N \simeq h_{2R} v_R - \theta\, h_{2L} v_L\,, \tag{8}$$

where the ν_1–ν_2 mixing angle θ is approximately

$$\theta \simeq h_{2L} v_L / (h_{2R} v_R - h_{1L} v_L)\,. \tag{9}$$

We have assumed that $h_{2L} v_L = h_{1R} v_R$ in order to make the mass lagrangian (7) symmetric and $|\theta| \ll 1$.

Since the doublet H_R may give the main contribution to the mass of $W_{R'}$, and therefore $v_R \gg v_L$, it is reasonable to assume that m_N is quite large. We assume for simplicity that it is so large ($\gtrsim$1 GeV) that the contribution of N to $(\beta\beta)_{0\nu}$ can be neglected on account of propagator suppression. Assuming further that m_ν is in the eV range or less, i.e., small compared to the average momentum $\langle p_\nu \rangle \simeq 30-100$ MeV of the intermediate state, we obtain from eq. (5) a rough lower bound for the mass of $W_{R'}$:

$$M_{W_{R'}} \gtrsim 2 \times 10^2 \sin^{1/2} 2\theta \, M_{W_L} . \tag{10}$$

If $M_{W_{R'}}/M_{W_L} \simeq 10$, for example, this leads to the following upper limit for the $\nu_1-\nu_2$ mixing angle:

$$|\theta| \lesssim 10^{-3} . \tag{11}$$

In order to arrange a mass for the electron, we must introduce a Higgs multiplet $\phi \sim (2, 2, 0)$, which can develop a VEV as follows

$$\langle \phi \rangle = \mathrm{diag}(k, k') . \tag{12}$$

Since a non-vanishing value of k would give rise to a Majorana mass term $\bar{\nu}_{1L}\nu_{2R}^c$, we choose $k = 0$. One might expect that a Majorana mass is in any case generated radiatively due to the diagram depicted in fig. 3. The contribution from this is

$$m_\nu^{\text{Majorana}} \sim (\alpha/\pi)\, m_e \sin 2\theta \sin 2\zeta , \tag{13}$$

where ζ is the $W_L-W_{R'}$ mixing angle. The angle ζ is, however, proportional to $kk'M_{W_{R'}}^{-2}$, and therefore the choice $k = 0$ that denies the Majorana mass at the tree-level will, at the same time, prevent it being generated by this one-loop correction.

In order to implement the tree-level condition $k=0$ naturally, we should impose a discrete symmetry on the model. Such a symmetry has recently been constructed in the context of the LR model [10]. It was shown in ref. [10] that imposing a discrete phase transformation symmetry $\phi \to \exp(\mathrm{i}\alpha)\,\phi$ ($\alpha \neq n\pi$) has as a consequence that the relation $k = 0$ holds at all orders of perturbation expansion. In our model, this would imply that the Majorana mass is not generated radiatively in any order, and consequently ν and N are true Dirac states.

We have not introduced isotriplet Higgs scalars $\Delta_L(3, 1, 2)$ or $\Delta_R(1, 3, 2)$ to our model, because

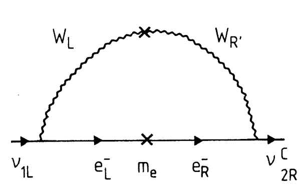

Fig. 3. A one-loop diagram to generate Majorana mass for a neutrino.

these could give rise to the diagonal Majorana mass terms $\langle\Delta_L\rangle \overline{\nu_{1R}^c}\,\nu_{1L}$ and $\langle\Delta_R\rangle \overline{\nu_{2R}^c}\,\nu_{2L}$. Hence contributions to the W_L and W_R masses come only from $\langle H_L \rangle$, $\langle H_R \rangle$ and $\langle \phi \rangle$. If we assume that $k' \ll v_L, v_R$, the ratio of the masses becomes

$$M_{W_L}/M_{W_{R'}} \simeq v_L/v_R . \tag{14}$$

In this case, we can connect the magnitude of L breaking and $(\beta\beta)_{0\nu}$ rate directly to the two mass scales. Making a reasonable assumption $h_{1L} \simeq h_{2L} \simeq h_{2R}$ for the Yukawa coupling constants, we obtain from (9)

$$\theta \simeq M_{W_L}/M_{W_{R'}} , \tag{15}$$

and from (10) follows a lower limit for the gauge boson mass $M_{W_{R'}}$:

$$M_{W_{R'}} \gtrsim 0.4 \times 10^2 \, M_{W_L} . \tag{16}$$

It must be stressed that the model we have described is by no means seriously explored from all sides, and it might well turn out to be unrealistic for some reason or other. In the limit of superheavy $W_{R'}$ it will, however, become equivalent to the standard $SU(2)_L \times U(1)_Y$ model. What we have demonstrated by this example is that in principle it is possible to have right-handed $|\Delta L| = 2$ interactions between electrons and neutrinos [allowing $(\beta\beta)_{0\nu}$ to be generated with a Dirac neutrino] within the framework of a gauge theory.

In conclusion, we have discussed the possibility of generating neutrinoless double beta decay with Dirac neutrinos. There are two scenarios that can allow for this: (i) the L violating coupling is left-handed and the neutrinos are massive Dirac particles; and (ii) the L violating coupling is right-handed and the neutrinos are either massive or massless Dirac particles. These two cases were found to have essential differences which will make it possible to distinguish between them experimentally. On the other hand, (i) and (ii) simulate the two Majorana neutrino mechanisms for the process, Majorana neutrinos with mass and Majorana neutrinos with a right-handed coupling respectively, and therefore one cannot decide whether neutrinos are Dirac or Majorana particles by using the neutrinoless double beta decay data alone.

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