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Neutrinoless Double Beta Decay With Massless Neutrinos

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Abstract

We consider a gauge model based on a $SU(3)\otimes U(1)$ symmetry with an extended Higgs sector which allows neutrinoless double beta decay even with massless neutrinos. The lepton number is violated explicitly by charged gauge and scalar bosons, including the vector field with double electric charge.

It is very well known that the observation of neutrinoless double beta decay, $(\beta\beta)_{0\nu}$, will imply a new physics beyond the standard model. Usually, two kinds of mechanisms for this decay were assumed to be independent: massive Majorana neutrinos and right-handed currents [1].

In the latter case, neutrino mass is not required but, if the right-handed currents are part of a gauge theory, it has been argued that at least some neutrinos must have non-zero mass. If this is the case, the observation of $(\beta\beta)_{0\nu}$ would imply the existence of massive neutrinos, whether or not right-handed currents exist [2].

Recently we have considered a $SU(3)\otimes U(1)$ model for the electroweak interactions [3] and in Ref. [4] it was claimed that $(\beta\beta)_{0\nu}$ occurs in this model even for massless neutrinos. Notwithstanding, this is not true at least in the minimal version of the model. This paper substitute Ref. [4] as it will be clear below.

The representation content of the minimal $SU(3)\otimes U(1)$ model is: triplets, $\psi_{lL}=(\nu_l,l,l^c)^T_L,(\underline{3},0)$ with $l=e,\mu,\tau$ and $Q_{1L}=(u,d,J_1)^T_L,(\underline{3},+\frac{2}{3})$ for the left-handed fields, and singlets $u_R,(\underline{1},+\frac{2}{3})$; $d_R,(\underline{1},-\frac{1}{3})$; $J_{1R},(\underline{1},+\frac{5}{3})$, for the respective right-handed fields, and we have not introduced right-handed neutrinos. The second entries in the parentheses are the $U(1)_N$ charges. The electric charge operator has been defined as $2eQ=\lambda_3-\sqrt{3}\lambda_8+2N$, where λ_3 and λ_8 are the usual Gell-Mann matrices; N is proportional to the unit matrix. Then, the exotic quark has electric charge $+\frac{5}{3}$. The charge conjugated field, ψ^c, which appears in the leptonic triplets is defined as $\psi^c=\gamma^5C\bar{\psi}^T$.

The model is anomaly free if we have equal number of triplets and antitriplets, counting the color of $SU(3)_c$, and furthermore requiring the sum of all fermion charges to vanish. As in the model of Ref. [5], the anomaly cancellation occurs for the three generations together and not generation by generation.

Then, we must introduce the antitriplets: $Q_{2L}=(J_2,c,s)^T_L,(\mathbf{3}^*,-\frac{1}{3})$ and $Q_{3L}=(J_3,t,b)^T{}_L,(\mathbf{3}^*,-\frac{1}{3})$ also with the respective right-handed fields in singlets. The quarks J_2 and J_3 have both charge $-\frac{4}{3}$.

In order to generate fermion masses, we introduce the following Higgs scalars, $\eta=(\eta^0,\eta_1^-,\eta_2^+)^T$, $\rho=(\rho^+,\rho^0,\rho^{++})^T$, and $\chi=(\chi^-,\chi^{--},\chi^0)^T$, transforming as $(\mathbf{3},0),(\mathbf{3},1)$ and $(\mathbf{3},-1)$, respectively, under $SU(3)\otimes U(1)$. They produce the following hierarchical symmetry breaking:

$$SU_L(3)\otimes U_N(1)\xrightarrow{<\chi>}SU_L(2)\otimes U_Y(1)\xrightarrow{<\rho,\eta>}U_{e.m}(1). \tag{1}$$

The Yukawa interactions, for leptons and the first generation of quarks, are

$$-\mathcal{L}_Y=\frac{1}{2}\sum_l G_l\epsilon^{ijk}\bar{\psi}^c_{li}\psi_{lj}\eta_k+\bar{Q}_{1L}(G_u u_R\eta+G_d d_R\rho+G_{J1}J_{1R}\chi)+h.c., \tag{2}$$

Explicitly, we have for the leptons,

$$2\mathcal{L}_{lY}=\sum_l G_l\left[(\bar{l}^c_R l^c_L-\bar{l}_R l_L)\eta^0-(\bar{\nu}^c_{lR}l^c_L-\bar{l}_R\nu_{lL})\eta_1^-+(\bar{\nu}^c_{lR}l_L-\bar{l}^c_R\nu_{lL})\eta_2^+\right]+h.c., \tag{3}$$

and using the definition of ψ^c given above, we can write Eq. (3) as

$$\mathcal{L}_{lY}=\sum_l G_l(-\bar{l}_R l_L\eta^0+\bar{l}_R\nu_L\eta_1^-+\bar{\nu}^c_R l_L\eta_2^++h.c.). \tag{4}$$

From Eq. (2) we have that the quark Yukawa Lagrangian is

$$-\mathcal{L}_{Q_1Y}=G_u(\bar{u}_L u_R\eta^0+\bar{d}_L u_R\eta_1^-+\bar{J}_{1L}u_R\eta_2^++h.c.). \tag{5}$$

On the other hand, the charged-current-lepton interactions are:

$$\mathcal{L}_l^{CC}=-\frac{g}{\sqrt{2}}\sum_l\left(\bar{\nu}_{lL}\gamma^\mu l_L W^+_\mu+\bar{l}^c_L\gamma^\mu\nu_{lL}V^+_\mu+\bar{l}^c_L\gamma^\mu l_L U^{++}_\mu+h.c.\right), \tag{6}$$

and as we have not assigned a lepton number to the scalar and gauge bosons, we have explicit breakdown of this quantum number induced by the scalar η_2^+ in Eq. (4) and also by the heaviest gauge bosons, V^+ and U^{++} in Eq. (6).

For quarks we have the charged-current interactions,

$$\mathcal{L}^{CC}_{Q_1}=-\frac{g}{\sqrt{2}}\left(\bar{u}_L\gamma^\mu d_L W^+_\mu+\bar{J}_{1L}\gamma^\mu u_L V^+_\mu+\bar{d}_L\gamma^\mu J_{1L}U^{--}+h.c.\right). \tag{7}$$

The neutral currents are consistent with low energy phenomenology. There are flavor changing neutral currents coupled to the heavy neutral boson Z'^0, but the currents coupled to the lightest Z^0, which is identified with the neutral boson of the standard model, are diagonal in the flavor space [3].

The charged currents in Eqs. (6) and (7) do not produce $(\beta\beta)_{0\nu}$. In order to analyse the violation of the lepton number in Eq. (4) it is necessary to determine the physical scalar degrees of freedom. Let us consider the most general Higgs potential involving the three triplets η,ρ and χ

$$\begin{aligned}V(\eta,\rho,\chi) &= \mu_1^2\eta^\dagger\eta+\mu_2^2\rho^\dagger\rho+\mu_3^2\chi^\dagger\chi+\lambda_1(\eta^\dagger\eta)^2+\lambda_2(\rho^\dagger\rho)^2+\lambda_3(\chi^\dagger\chi)^2\\ &\quad+(\eta^\dagger\eta)[\lambda_4\rho^\dagger\rho+\lambda_5\chi^\dagger\chi]+\lambda_6(\rho^\dagger\rho)(\chi^\dagger\chi)\\ &\quad+\sum_{ijk}\epsilon^{ijk}(f\eta_i\rho_j\chi_k+h.c.).\end{aligned} \tag{8}$$

The potential above has been analysed and we have found that after the spontaneous symmetry breaking there are, as expected, three charged Goldstone bosons, one of them with double charge, and three massive charged scalars: a linear combination of η_1^- and χ^-, the other one a combination of η_2^- and ρ^-, and a doubly charged scalar. Then, the interaction we have so far are not enough to produce $(\beta\beta)_{0\nu}$ because there is not mixing neither

between η_1^- and η_2^- in the scalar sector nor between the vectors V^- and W^- and the diagrams in Ref. [4] vanish.

But, if we introduce two new $SU(3)$ triplets, σ and ω, with the same quantum numbers of η, $(\underline{3},0)$, the potential will have terms like those appearing in Eq. (8), with $\eta \to \sigma,\omega$ and also interactions among the three $(\underline{3},0)$ triplets:

$$\begin{aligned} V(\eta,\sigma,\omega) &= \alpha_1^2\eta^\dagger\eta + \alpha_2^2\sigma^\dagger\sigma + \alpha_3^2\omega^\dagger\omega + \delta_1(\eta^\dagger\eta)^2 + \delta_2(\sigma^\dagger\sigma)^2 \\ &+ \delta_3(\omega^\dagger\omega)^2 + (\eta^\dagger\eta)^2[\delta_4(\sigma^\dagger\sigma) + \delta_5(\omega^\dagger\omega)] \\ &+ \delta_6(\sigma^\dagger\sigma)(\omega^\dagger\omega) + f_1(\eta^\dagger\sigma)(\sigma^\dagger\eta) + f_2(\eta^\dagger\omega)(\omega^\dagger\eta) \\ &+ f_3(\sigma^\dagger\omega)(\omega^\dagger\sigma) + [g_1(\eta^\dagger\sigma)^2 + h.c.] + [g_2(\eta^\dagger\omega)^2 + h.c.] \\ &+ [g_3(\sigma^\dagger\omega)^2 + h.c.] + \sum_{ijk}\epsilon^{ijk}(f'\eta_i\sigma_j\omega_k + h.c), \end{aligned} \tag{9}$$

in particular the trilinear term in Eq. (9) allows the mixing between $\eta_1^-, \sigma_1^-, \omega_1^-$ and $\eta_2^-, \sigma_2^-, \omega_2^-$.

For example, considering for simplicity only Eq (9), and with $f_i = g_i = 0$ for all $i = 1,2,3$, it is possible to show that the mixing between lepton-number-conserving and lepton-number-violating scalars occurs. We also assume, for the sake of simplicity, that from the three triplets $(\underline{3},0)$, only η^0 obtain a nonzero expectation value, v. Defining $\eta^0 = v + H_1 + ih_1$, and $\sigma^0 = H_2 + ih_2$, $\omega^0 = H_3 + ih_3$ and requiring that the shifted potential has no linear terms in any of the H_i and h_i fields, $i = 1,2,3$, we obtain in the tree approximation the constraint $\alpha_1^2 + 2\delta_1 v^2 = 0$, $Im\, f' = 0$. In this limit, $\eta_{1,2}^-$ are Goldstone bosons. There are four massive scalars: $\phi_1^- = a_1\sigma_1^- + a_2\omega_2^-$ and $\varphi_1^- = a_1\sigma_2^- - a_2\omega_1^-$ both with the same mass $2m_1^2 = a+b+[(a-b)^2+4c^2]^{\frac{1}{2}}$;

$\phi_2^- = b_1\sigma_1^- + b_2\omega_2^-$, and $\varphi_2^- = b_1\sigma_2^- - b_2\omega_1^-$ with mass $2m_2 = a + b - [(a-b)^2 + 4c^2]^{\frac{1}{2}}$. We have used the notation $a_1 = c/\sqrt{d_1}, a_2 = (m_1^2 - a)/\sqrt{d_1}$, $b_1 = c/\sqrt{d_2}, b_2 = (m_2^2 - a)/\sqrt{d_2}$, with $a = \alpha_2^2 + \delta_4 v_1^2$, $b = \alpha_3^2 + \delta_5 v_1^2$, $c = fv$ and $d_i = (m_i^2 - a)^2 + c^2$, $i = 1,2$. If we consider the general potential with the five triplets $\eta, \sigma, \omega, \rho$ and χ, it will only produce mixing among all the singly charged scalars.

Then, the Yukawa interactions with the scalars $\eta_{1,2}^-, \sigma_{1,2}^-$ and $\omega_{1,2}^-$, will produce $(\beta\beta)_{0\nu}$ since they are linear combinations of the physical scalars, for example, ϕ_1^- in Fig. 1. We can estimate a lower bound on the mass of ϕ_1, by assuming that its contribution to $(\beta\beta)_{0\nu}$ is less than the amplitude due to massive Majorana neutrinos and vector bosons W^- exchange. The latter amplitude is characterized by a strength which is proportional to

$$\frac{g^4 < m_\nu >}{m_W^4 < p^2 >} \tag{10}$$

where $<m_\nu> = |\sum_j U_{ij}^2 m_j|$ is the "effective neutrino mass". The experimental limit on $(\beta\beta)_{0\nu}$ decay rate imply that $<m_\nu> < <M_\nu> = 1-2\,eV$ [2]; $<p^2>$ is an average square 4-momentum carried by the virtual neutrino, its value is usually $(10MeV)^2$ [6]. On the other hand, the amplitude of the process in Fig. 1 is proportional to

$$\frac{a_1^3 a_2 G_u^2 G_e^2}{m_\phi^4 < p^2 >^{\frac{1}{2}}}, \tag{11}$$

Then, assuming that Eq. (11) is less than Eq. (11) when $<m_\nu> = <M_\nu>$ we have,

$$m_{\phi_1}^4 > \frac{a_1^3 a_2 G_u^2 G_e^2 \sqrt{2} < p^2 >^{\frac{1}{2}}}{32 G_F^2 < M_\nu >} \simeq (6,9\,TeV)^4 a_1^3 a_2 G_u^2 G_e^2, \tag{12}$$

Then, using in Eq. (12) $a_{1,2} \approx 1$, $G_u = m_u/v < \sqrt{2}m_u/v_{SM} = 2 \times 10^{-2}$, $G_e = m_e/v < \sqrt{2}m_e/v_{SM} = 2 \times 10^{-6}$ with m_u, m_e the u-quark and electron mass respectively and $v_{SM}^2/2 = \sqrt{2}/G_F$, we obtain that $m_\phi > 3\,GeV$.

We can see that $(\beta\beta)_{0\nu}$ proceeds in this model only as a Higgs bosons effect, with massless neutrinos at tree level. There are not contributions to $(\beta\beta)_{0\nu}$ from trilinear Higgs interactions because the charged leptons couple only to the η-like triplets, and those triplets do not contain doubly charged scalars. In models in which these contributions exist, they are negligible [6] unless a neighboring mass scale ($\sim 10^4 GeV$) exist [7].

Vertices like the following, appear in the scalar-vector sector:

$$\frac{ig}{\sqrt{2}}\left[W_\mu^+\left(\eta_1^-\partial^\mu\eta^0 - \partial^\mu\eta_1^-\eta^0\right) + V_\mu^-\left(\eta_2^+\partial^\mu\eta^0 - \partial^\mu\eta_2^+\eta^0\right)\right], \qquad (13)$$

and also for the scalars σ and ω. Then, because of the mixing between $\eta_1^-, \sigma_1^-, \omega_1^-$ and $\eta_2^-, \sigma_2^-, \omega_2^-$ the loop diagrams contributing to $(\beta\beta)_{0\nu}$ in Ref. [4] are no longer vanish but they are not the main contributions to the decay.

Finally, we would like to comment the following: (a) If we admit lepton number violation, $SU(3)$ could be a good symmetry at high energies, at least for the lightest leptons (ν, e^-, e^+). Assuming that this is a local gauge symmetry, the rest of the model follows naturally, including the exotic quarks, J's. To the best of our knowledge, there is not laboratory or cosmological/astrophysical constraints to the masses of the exotic quarks– J_1 and $J_{2,3}$ with charge $+\frac{5}{3}$ and $-\frac{4}{3}$ respectively but, they must be too massive to be detected by present accelerators. (b) The vacuum expectation value v_χ is, in principle, arbitrary but phenomenological constraints imply that $v_\chi > 8\,TeV$. With this value we have $m_{Z'} > 40\,TeV$ and $m_{V,U} > 4\,TeV$ [3]. (c) It has been usually considered that whatever mechanism generates the neutrinoless double beta decay, it also generates a finite Majorana mass [6,8]. However, an important point is to find what mechanism triggers $(\beta\beta)_{0\nu}$. The mass induced by it could be quite small to be detected. (d) The Higgs sector is rich enough to produced CP violation. Here, we have assumed there are not any non-trivial phases in the vacuum expectation values of the Higgs fields.

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FIGURE CAPTIONS

Fig. 1 Scalar contribution to the $(\beta\beta)_{0\nu}$, $G_{u,e}$ are Yukawa couplings and $a_{1,2}$ mixing parameters.

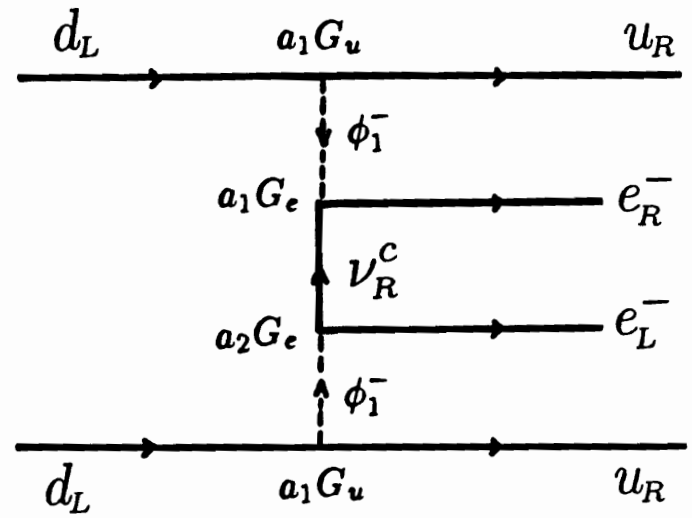

Fig. 1