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Neutrinoless double beta decay with small and hierarchical neutrino mass

BISWAJOY BRAHMACHARI[1,2]
[1]Theoretical Physics Group, Saha Institute of Nuclear Physics, 1/AF Bidhan Nagar, Kolkata 700 064, India
[2]Physics Department, Vidyasagar Evening College, 39, Sankar Ghosh Lane, Kolkata 700 006, India

Abstract. We construct a model where neutrino Majorana masses are small and hierarchical but where neutrinoless double beta decay occurs at an observable rate potentially detectable by present day experiments.

Keywords. Double beta decay; neutrino mass; fermion masses.

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1. Introduction

Evidence of atmospheric [1] and solar [2] neutrino oscillations has made the notion of neutrino mass generally acceptable. In the absence of any direct evidence of neutrino mass in plain old beta decay [3], a recent observation [4] of neutrinoless double beta decay [5] has made a second case of a large effective Majorana mass term of electron neutrino. One then has to explore consequences [6] of having neutrino masses constrained by neutrino oscillations as well as neutrinoless double beta decay. We expect it to happen naturally when lepton number is violated by two units. In this case a non-zero Majorana neutrino mass is unavoidable. A study in this direction has recently been performed [7].

2. The model

We construct a model with the following features [8]. (1) Neutrinoless double beta decay amplitude depends on the trilinear coupling between two scalar diquarks and one scalar dilepton. Therefore, the symmetry under consideration allows this coupling. (2) The Majorana neutrino mass generated by the above trilinear coupling at four loops and higher is negligibly small. Other contribution to neutrino mass will come from some mechanism which is not related to that of neutrinoless double beta decay under consideration. (3) Extra scalar diquarks and dileptons, which are

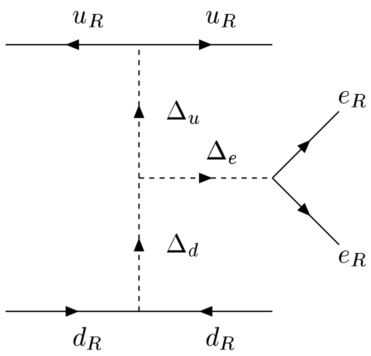

Figure 1. Diagram for neutrinoless double beta decay.

introduced here in this model, interact only with first-generation fermions, namely u, d, and e. In this way one can avoid experimental constraints due to the presence of flavor changing interactions such as $\mu \to eee$ $K^0 - \overline{K^0}$ mixing, and so on. (4) The smallness of m_u, m_d, and m_e can be understood in terms of a simple mechanism which was proposed in [9]. (5) The model makes definite predictions which can be falsified in experiments which have to be performed at the TeV energy scale.

We extend standard-model particle content and include scalar diquarks and dileptons. Their transformation properties under $SU(3)_\mathrm{C} \times SU(2)_\mathrm{L} \times U(1)_\mathrm{Y}$ are, $\Delta_u = (6,1,4/3), \Delta_d = (6,1,-2/3), \Delta_e = (1,1,-2)$. We also include a second Higgs doublet $\Phi_2 \equiv (\phi_2^+, \phi_2^0)$ which gets a VEV. We assume that a discrete Z_3 symmetry exists ($\omega^3 = 1$) such that apart from the following fermionic and bosonic fields, $d_\mathrm{R}, e_\mathrm{R} \to \omega, u_\mathrm{R} \to \omega^2, \Delta_u \to \omega, \Delta_d, \Delta_e, \Phi_2 \to \omega^2$, all other fields are singlets of this Z_3 symmetry. Thus the allowed Yukawa couplings are $\Delta_u^* u_\mathrm{R} u_\mathrm{R}, \Delta_d^* d_\mathrm{R} d_\mathrm{R}, \Delta_e^* e_\mathrm{R} e_\mathrm{R}, \overline{(u,d)}_\mathrm{L} u_\mathrm{R} \tilde{\Phi}_2, \overline{(u,d)}_\mathrm{L} d_\mathrm{R} \Phi_2, \overline{(\nu,e)}_\mathrm{L} e_\mathrm{R} \Phi_2$ where $\tilde{\Phi}_2 \equiv (\bar{\phi}_2^0, -\phi_1^-)$. Baryon number ($B$) and lepton number ($L$) are still conserved because Δ_u and Δ_d may be assigned $B = 2/3$, and Δ_e may be assigned $L = 2$. Now let us include the terms $\Phi_1^\dagger \Phi_2$ and $\Delta_u \Delta_d^* \Delta_e$. This will break the Z_3 symmetry explicitly. We note that B is still conserved but L is broken down to $(-1)^L$, i.e., lepton parity.

Scalar potential of two doublets can be written as [9a]

$$\begin{aligned} V = {} & m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ & + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + [\mu_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}]. \end{aligned} \tag{1}$$

Let $m_1^2 < 0$, $m_2^2 > 0$, and $|\mu_{12}^2| \ll m_2^2$, then the minimization condition becomes

$$v_1^2 \simeq -\frac{m_1^2}{\lambda_1}, \quad v_2^2 \simeq \frac{-\mu_{12}^2 v_1}{m_2^2 + (\lambda_3 + \lambda_4) v_1^2}. \tag{2}$$

Since the μ_{12}^2 term breaks the Z_3 symmetry we expect it to be natural [10] that it is small compared to m_2^2. Thus $v_2 \ll v_1$ is obtained. Since the first-generation quark and lepton masses are proportional to v_2, they will be naturally small in this model.

3. Other experimental tests of this model

The mass matrices with this flavor symmetry can be written as

$$\mathcal{M} = \begin{bmatrix} f_{11}v_2 & f_{12}v_1 & f_{13}v_1 \\ 0 & f_{22}v_1 & f_{23}v_1 \\ 0 & f_{32}v_1 & f_{33}v_1 \end{bmatrix}. \tag{3}$$

This contributes [8] to $D^0 - \overline{D^0}$ mixing, i.e., $(\Delta m_{D^0}/m_{D^0}) \simeq (B_D f_D^2 m_u^3/3m_2^2 v_2^2 m_c)|V_{ud}^* V_{us}|^2$. Using $f_D = 150.0$ MeV, $B_D = 0.8$, $m_u = 4.0$ MeV, $m_c = 1.25$ GeV, $|V_{ud}| \simeq 1.0$, $|V_{us}| \simeq 0.22$, and the experimental upper bound of 2.5×10^{-14} [11], we find $m_2\ v_2 > 24.4$ GeV^2, which may be satisfied for example with $m_2 = 1.0$ TeV and $v_2 = 25.0$ MeV. Another contribution [8] to $D^0 - \overline{D^0}$ mixing is through Δ_u exchange. In this case one gets $(\Delta m_{D^0}/m_{D^0}) \simeq (B_D f_D^2 h_u^2 m_u^2/3m_{\Delta_u}^2 m_c^2)|V_{ud}^* V_{us}|^2 \simeq 3.0 \times 10^{-15}$, for $h_u = 1.0$ and $m_{\Delta_u} = 1.0$ TeV, which is well below the present experimental upper bound.

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