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Radiative left-right Dirac neutrino mass

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ABSTRACT

We consider the conventional left-right gauge extension of the standard model of quarks and leptons without a scalar bidoublet. We study systematically how one-loop radiative Dirac neutrino masses may be obtained. In addition to two well-known cases from almost 30 years ago, we find two new scenarios with verifiable predictions.

1. Introduction

To explain why neutrino masses are so small, one approach is to consider the case where they are forbidden at tree level and only arise radiatively. In the standard model (SM) without a singlet right-handed neutrino, the left-handed neutrino may only acquire a mass through a dimension-five operator [1], i.e.

$$\mathcal{L}_M = -\frac{\kappa_{ij}}{\Lambda}(\nu_i\phi^0 - l_i\phi^+)(\nu_j\phi^0 - l_j\phi^+) + H.c. \qquad (1)$$

This means that neutrino masses are Majorana and suppressed by the large scale Λ. In 1998, it was shown [2] how this operator may be realized in three and only three ways at tree level (establishing thus the nomenclature of Types I, II, and III seesaw), as well as in one loop, assuming only fermions and scalars in the loop. Whereas Majorana neutrino masses are theoretically desirable in this context, there is at present still no supporting experimental evidence from neutrinoless double beta decay. Perhaps neutrinos are Dirac particles after all, and lepton number is actually conserved, in which case the question remains as to why they are so small. A general study in the context of the SM has recently appeared [3].

In this paper we focus on the conventional left-right gauge model, which contains the right-handed neutrino in an $SU(2)_R$ doublet and is thus a natural framework for considering Dirac neutrinos. To connect the $SU(2)_L$ fermion doublet with the $SU(2)_R$ fermion doublet, a scalar bidoublet is required. Suppose a bidoublet is absent, then there are no fermion masses in the minimal model. However, they may be generated by dimension-five operators, in analogy with Eq. (1). Specifically, Dirac neutrino masses come from the operator [4]

$$\mathcal{L}_D = -\frac{\kappa_{ij}}{\Lambda}(\bar{\nu}_{iL}\bar{\phi}^0_L - \bar{l}_{iL}\phi^-_L)(\nu_{jR}\phi^0_R - l_{jR}\phi^+_R) + H.c. \qquad (2)$$

These operators may be realized at tree level using heavy singlet quarks and leptons [5,6], i.e. the mechanism of Dirac seesaw [7]. Suppose only quark and charged-lepton masses are obtained in this fashion. Neutrinos would then appear to be massless. However Eq. (2) may still be realized in one loop and neutrinos acquire small Dirac masses, as detailed below.

2. Four generic structures

There are four and only four generic structures which realize Eq. (2), in exact analogy to how Eq. (1) is realized in Ref. [2]. The idea is very simple. To connect ν_L with ν_R in one loop, we need an internal fermion line and an internal scalar line. There are thus only four ways to do this.

- (A) Attach both ϕ_L and ϕ_R to the fermion line.
- (B) Attach both ϕ_L and ϕ_R to the scalar line.
- (C) Attach ϕ_L to the fermion line and ϕ_R to the scalar line.
- (D) Attach ϕ_L to the scalar line and ϕ_R to the fermion line.

Model (A) A possible implementation of this idea is to add a charged scalar singlet χ^-, as shown in Fig. 1. This was done many years ago [8] and it implies that charged leptons have seesaw masses from three heavy singlet leptons E. It is the left-right analog of the Zee model [9], but without the need for a second scalar doublet. Note that the d quark may be used instead of e, then χ^- should be replaced with a colored scalar singlet with charge $-1/3$.

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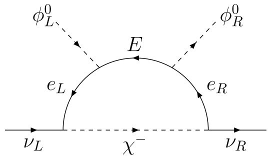

Fig. 1. Dirac neutrino mass in Model (A).

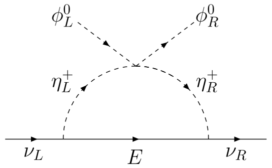

Fig. 2. Dirac neutrino mass in Model (B).

Model (B) To make the connection in this case, the heavy singlet lepton is again used, as shown in Fig. 2. This was also done many years ago [10]. A second scalar $SU(2)_L$ doublet (η^+_L, η^0_L) as well as a second scalar $SU(2)_R$ doublet (η^+_R, η^0_R) are needed, because the invariant quartic scalar coupling is required to be of the form

$$(\phi^+_L \eta^0_L - \phi^0_L \eta^+_L)^* (\phi^+_R \eta^0_R - \phi^0_R \eta^+_R). \tag{3}$$

It is thus also a left-right analog of the Zee model, but without the charged scalar singlet. Without loss of generality, we have chosen in Fig. 2 $\langle \eta^0_{L,R} \rangle = 0$, so that $\eta^\pm_{L,R}$ are the physical charged scalars, whereas $\phi^\pm_{L,R}$ have become the longitudinal components of $W^\pm_{L,R}$.

If the heavy E lepton is replaced by the heavy D quark, then η_L and η_R are replaced by the corresponding scalar leptoquark doublets. In this case, charged leptons also obtain radiative masses from these same leptoquark doublets through the heavy U quarks.

If we impose a discrete Z_2 symmetry such that $\eta_{L,R}$ and E are odd, then this is a left-right analog of the well-known scotogenic model [11] of radiative seesaw neutrino mass through dark matter, as discussed recently [12].

Model (C) This is a new proposal and requires the existence of an exotic $SU(2)_R$ scalar doublet $(\zeta^{++}_R, \zeta^+_R)$. Again, if d and D are used instead of e and E, χ and ζ are replaced with the corresponding singlet and doublet scalar leptoquarks respectively.

Model (D) This is the companion to (C) and requires the existence of an exotic $SU(2)_L$ scalar doublet $(\zeta^{++}_L, \zeta^+_L)$. Note that if we have both ζ_L and ζ_R, then Model (B) may be realized in Fig. 2 by reversing the arrows of the internal lines and replacing $\eta_{L,R}$ with $\zeta_{L,R}$. (See Fig. 4.)

3. Discussion

To discover which of the above mechanisms is truly responsible for the radiative generation of Dirac neutrino masses, the corresponding new particles in the loop would have to be observed experimentally. Of particular interest are the doubly charged scalars $\zeta^{++}_{L,R}$. It is of course well-known that a scalar triplet (ξ^{++}, ξ^+, ξ^0) may couple to the doublet neutrinos directly and provide them with Majorana masses with a small $\langle \xi^0 \rangle$. In that case [13], the decays of ξ^{++} would map out [14] the elements of the 3×3 neutrino mass matrix. These decays have been searched for at the Large Hadron Collider (LHC). Assuming 100% (50%) branching fraction to $e^-_L e^-_L$, the ATLAS Collaboration has the preliminary [15] lower bound of 570 (530) GeV on its mass, based on an integrated luminosity of 13.9 fb^{-1} at 13 TeV. However, if ξ is indeed responsible for the neutrino mass matrix, its branching fraction to $e^-_L e^-_L$ is proportional to the ee entry of the 3×3 Majorana neutrino mass matrix and if that is zero, there will be no bound from the LHC in this mode. Note also that if the decay is to $e^-_R e^-_R$ instead, the ATLAS bound becomes 420 (380) GeV. Recently, it was shown [16] that the pair production of doubly charged scalars may be enhanced by photon–photon fusion, resulting in an improvement of the above limits.

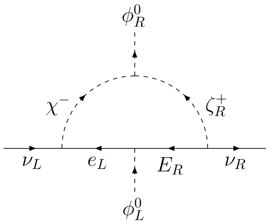

Fig. 3. Dirac neutrino mass in Model (C).

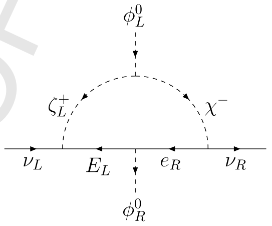

Fig. 4. Dirac neutrino mass in Model (D).

In the models we are concerned with, the doubly charged scalar ζ^{++}_L is part of an $SU(2)_L$ doublet, whereas ζ^{++}_R is part of an $SU(2)_R$ doublet, so it is an $SU(2)_L$ singlet. This is important because any $SU(2)_L$ doublet or triplet will contribute to the S, T, U oblique parameters in precision electroweak measurements, but not a singlet. In the triplet Higgs model, these are important constraints [17]. In this context, we note that the new particles of Model (C) are all SM singlets, i.e. χ^-, $(\zeta^{++}_R, \zeta^+_R)$, $E_{L,R}$, and (ϕ^+_R, ϕ^0_R), so they will not affect the oblique parameters.

Details of Model (C) The charged leptons e, μ, τ obtain masses through the heavy singlets $E_{1,2,3}$ in the 6×6 Dirac mass matrix linking $(\bar e_L, \bar\mu_L, \bar\tau_L; \bar E_{1L}, \bar E_{2L}, \bar E_{3L})$ to $(e_R, \mu_R, \tau_R; E_{1R}, E_{2R}, E_{3R})$:

$$\mathcal{M}_{eE} = \begin{pmatrix} 0 & \mathcal{M}_L \\ \mathcal{M}_R & \mathcal{M}_E \end{pmatrix}, \tag{4}$$

where $\mathcal{M}_{L,R}$ are 3×3 mass matrices proportional to $\langle \phi^0_{L,R} \rangle$ respectively. Hence

$$\mathcal{M}_e = \mathcal{M}_L \mathcal{M}_E^{-1} \mathcal{M}_R. \tag{5}$$

The terms in the Lagrangian responsible for the above are

$$\mathcal{L}_1 = f^L_{ij}(\bar\nu_{iL}\phi^+_L + \bar l_{iL}\phi^0_L)E_{jR} + f^R_{ij}(\bar\nu_{iR}\phi^+_R + \bar l_{iR}\phi^0_R)E_{jL} + H.c. \tag{6}$$

For simplicity, we choose $f^{L,R}_{ij}$ to be diagonal in the basis where $\mathcal{M}_E$ is diagonal. To obtain Fig. 3, we need also the following Yukawa terms:

$$\mathcal{L}_2 = f^\chi_{ij}\chi^+(\nu_{iL} l_{jL} - l_{iL}\nu_{jL}) + f^E_{ij}(\zeta^{++}_R l_{iR} - \zeta^+_R \nu_{iR})E_{jR} + H.c. \tag{7}$$

To avoid flavor changing processes such as $\mu \to e\gamma$ or $\mu \to eee$ from ζ^{++}_R exchange, we also assume f^E_{ij} to be diagonal. As for f^χ_{ij}, it has to be antisymmetric, so that the radiative Dirac neutrino mass matrix (in the basis where the charged-lepton mass matrix

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