Radiative Generation of Neutrino Masses and its Experimental Signals

K.S. Babu
Department of Physics, Oklahoma State University, Stillwater, OK 74078, USA
E-mail: babu@okstate.edu

Tiny neutrino masses can arise naturally via loop diagrams. After a brief review of the radiative mass generation mechanism, I present a new model wherein TeV scale leptoquark scalars induce neutrino masses via two–loop diagrams. This model predicts the neutrino oscillation parameter $\sin^2\theta_{13}$ to be close to the current experimental limit. The leptoquarks are accessible to experiments at the LHC since their masses must lie below 1.5 TeV, and their decay branching ratios probe neutrino oscillation parameters. Rare lepton flavor violating processes mediated by leptoquarks have an interesting pattern: $\mu \rightarrow e\gamma$ may be suppressed, while $\mu \rightarrow 3e$ and $\mu \rightarrow e$ conversion in nuclei are within reach of the next generation experiments. Muon $g-2$ receives new positive contributions, which can resolve the discrepancy between theory and experiment. New CP violating contributions to $B_s - \bar{B}_s$ mixing via leptoquark box diagrams are in a range that can explain the recently reported dimuon anomaly by the DØ collaboration.
The standard paradigm for explaining tiny neutrino masses is the seesaw mechanism, which generates an effective dimension–5 operator $\mathcal{O}_1 = (LLHH)/M$, suppressed by the mass scale $M$ of the heavy right–handed neutrino. ($L$ here denotes lepton doublets, while $H$ is the Higgs doublet.) Oscillation data suggests that in this scenario $M \sim 10^{14}$ GeV, which is well beyond the reach of foreseeable experiments for direct scrutiny. An interesting alternative to the high scale seesaw mechanism is radiative mass generation. The smallness of neutrino masses can be understood as originating from loop and chirality suppression factors. The scale of new physics can naturally be around a TeV in this scenario. The simplest among this class of models is the Zee model [1] where neutrino masses are induced as one–loop radiative corrections arising from the exchange of charged scalar bosons. The effective lepton number violating operator in this model is $\mathcal{O}_2 = LLLL\bar{e}H/M$.

To convert this operator to neutrino mass, a loop diagram is necessary, as shown in the first diagram of Fig. 1. Here $\Phi_1$ is a charged scalar singlet transforming as $(1,1,1)$ of $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge symmetry and coupling to lepton doublets as $f_{ij}L_i L_j \Phi^+_{1i}$ with $f^T = -f$. $\Phi_2(1,2,−1/2)$ is a second Higgs doublet that generates charged lepton masses. The cubic scalar coupling $\mathcal{O}_1 \Phi_1^2 \Phi_2$ in the scalar potential, along with the term $(\Phi_2 H)^2$, ensures that lepton number is explicitly broken. The neutrino mass in this model is given by $m_\nu \sim (f m_{\nu}^2 + m_{\nu}^2 f^T)/(16\pi^2 M_\Phi)$, which for $M_\Phi = 1$ TeV and $f = 10^{-3}$ yields $m_\nu \sim 0.05$ eV, of the right order to explain atmospheric neutrino oscillations. The simplest version of the Zee model is however excluded by neutrino oscillation data, since it predicts all the diagonal entries of the neutrino mass matrix to be zero, which is inconsistent.

In a second class of models, neutrino masses arise as two–loop radiative corrections [2] via the exchange of a singly charged scalar $\Phi_1(1,1,1)$ and a doubly charged scalar $\Phi_2(1,1,−2)$, as shown in the second diagram of Fig. 1. The Yukawa couplings $f_{ij}L_i L_j \Phi^+_{1i} + g_{ij}c_i \Phi^+_{1j} \Phi_2^−$, with $f^T = -f$, $g^T = g$, along with the cubic scalar coupling $\Phi_1^+ \Phi_1^− \Phi_2^−$ ensure lepton number violation. The effective operator of this model is $\mathcal{O}_3 = LLLL\bar{e}^c H^c / M^2$, which requires two–loop dressing to convert to neutrino mass. Since $m_\nu \sim (f m_{\nu} g m_f f^T)/(16\pi^2 M_\Phi)$ in this model, for $f \sim g \sim 0.1$, and $M_\Phi \sim 1$ TeV, $m_\nu \sim 0.05$ eV is generated. This model is consistent with neutrino oscillation data, and predicts the lightest neutrino to be nearly massless. Phenomenology of this model has been studied in Ref. [3]. The cross section for the production of a 1 TeV $\Phi_2^−$ at the LHC ($\sqrt{s} = 14$ TeV) is about 20 $fb$, which should be observable with its decay into same sign dileptons.

![Figure 1: Loop diagrams generating small neutrino masses in the Zee model (left) and in the model of Ref. [2] (right).](image)

A classification of low-dimensional effective $\Delta L = 2$ lepton number violating operators that can lead to neutrino masses has been given in Ref. [4]. The list of operators includes $\mathcal{O}_3 = L^c L^c H \bar{e}_\beta \bar{e}_\beta$, which appears in the context of R–parity violating supersymmetry. The operator $\mathcal{O}_8 = L^c \bar{e}_\beta \bar{e}_\beta \bar{d} \bar{d} H_1 e^\beta$ is the subject for the remainder of this paper, which leads to an interesting neutrino mass model. $\mathcal{O}_8$ is most directly induced by the exchange of scalar leptoquarks (LQ).
The order of magnitude of $m_{\nu}$ arising from $\mathcal{O}_8$ is $m_{\nu} \sim (m_{\nu} m_{\tau} \mu_{\nu})/[(16\pi^2)^2 M_{\text{LQ}}^4]$, where $\mu$ is the coefficient of a cubic scalar coupling, and $\nu = 174$ GeV is the electroweak VEV. In order to generate $m_{\nu} \sim 0.05$ eV, it is clear that $M_{\text{LQ}}$ must be of order TeV, which would be within reach of the LHC. The scalar sector consists of the leptoquark multiplets $\Omega(3, 2, 1/3) \equiv (\omega^{2/3}, \omega^{-1/3})$ and $\chi^{-1/3}(3, 1, -2/3)$. Assuming global baryon number conservation, the Lagrangian relevant for neutrino mass is

$$\mathcal{L}_{\nu} = Y_{ij}(\nu_{i} d_{j} \omega^{-1/3} - \ell_{i} d_{j} \omega^{-2/3}) + F_{ij} e_{i} d_{j} \chi^{-1/3} - \mu(\omega^{-2/3} H^{+} + \omega^{1/3} H^{0})\chi^{-1/3} + \text{h.c.} \quad (1)$$

The cubic scalar coupling will generate mixing between $\omega^{-1/3}$ and $\chi^{-1/3}$, we denote the mass eigenstates $X^{a}$, their masses $M_{1,2}$, and the mixing angle $\theta$. Neutrino masses are induced via Fig. 2.

Combining constraints from flavor changing processes, we find the neutrino mass matrix to be

$$M_{\nu} \simeq m_{0} \begin{pmatrix} 0 & \frac{1}{2} m_{\mu} x y & \frac{1}{2} y \\ \frac{1}{2} m_{\mu} x y & \frac{1}{2} m_{\tau} x \tau & \frac{1}{2} \tau z + \frac{1}{2} m_{\mu} y \tau \\ \frac{1}{2} y & \frac{1}{2} \tau z + \frac{1}{2} m_{\mu} y \tau & 1 + w \end{pmatrix} \quad (2)$$

Here $x = F_{33}^{*}/F_{32}^{*}$, $y = Y_{13}/Y_{33}$, $z = Y_{23}/Y_{33}$, $w = (F_{32}^{*}/F_{33}^{*})(Y_{32}/Y_{33})(m_{\tau}/m_{\mu})(m_{\mu}/m_{\tau})(I_{j k 3})/[(16\pi^2)^2 M_{1}^2]$. $I_{j k 3}$ denotes the two loop integral function shown in Fig. 3, with the internal up–type quark being the top. Since the $(1,1)$ entry is zero, and $w$ is highly suppressed, the determinant of $M_{\nu}$ is nearly zero. This leads to the predictions $m_{1} \simeq 0$, and $\tan^{2} \theta_{13} \simeq m_{2}/m_{3} \sin^{2} \theta_{12}$ in the standard parametrization of neutrino mixing. This leads to $\sin^{2} \theta_{13} = (0.044 - 0.051)$, which is near the current limit. A consistent fit to global oscillation parameters is obtained. The parameters $x, y, z$ for such a fit are plotted as functions of the unknown CP violating phase $\delta$ in Fig. 3 (middle panel). We see that $|x| \gg 1$ and $|y|, |z| \sim 1$. These values fix the branching ratios of the leptoquarks: $\Gamma(\omega^{2/3} \rightarrow e^{+} b) : \Gamma(\omega^{2/3} \rightarrow \mu^{+} b) : \Gamma(\omega^{2/3} \rightarrow \tau^{+} b) = |y|^2 : |z|^2 : 1$, and $\Gamma(X_{\alpha}^{-1/3} \rightarrow \mu^{-} t) : \Gamma(X_{\alpha}^{-1/3} \rightarrow \tau^{-} t) = |x|^2 : 1$. Measuring these decays will
thus probe CP violation in neutrino oscillations. From the experimental limit on $\mu \to 3e$ and $\mu - e$ conversion in nuclei, we derive the upper limit on $|Y_{13}^3 Y_{23}^3|$ as a function of $\omega^{2/3}$ mass. Since neutrino oscillation data requires $Y_{33}$ to be of the same order for $i = 1 \sim 3$, one can also determine an upper limit on $Y_{33}$. Combining these, we obtain an upper limit of 1.5 TeV on $M_1$, as shown in Fig. 3 as a function of $Y_{33}$. 

The diagram involves exchange of one leptoquark and one $W$ boson. We obtain the constraint for the $Y_{33} - B_i$ mixing, which can be as large as $10^{-6}$. Finally, neutrinoless double beta decay proportional to neutrino mass is suppressed in this model. However, it can proceed via the vector–scalar exchange process [7].

The diagram involves exchange of one leptoquark and one $W$ boson. We obtain the constraint $|Y_{11}^* F_{11}| < 1.7 \times 10^{-6} \left( \frac{M_1}{1 \text{ TeV}} \right)^2 \left( \frac{0.5 \text{ TeV}}{\mu} \right)$ from this process, indicating that neutrinoless double beta decay may be observable, in spite of the mass hierarchy being normal.

References