“Exploring Neutrino Masses and Mixing in the Seesaw Model with $L_e - L_\tau$ Gauged Symmetry”

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Abstract

We investigate neutrino phenomenology in the $U(1)_{L_e-L_\tau}$ gauge extension of the Standard Model with symmetry following the framework of type-(I+II) seesaw mechanism. For this, we have added three right handed neutrinos, one singlet and one scalar triplet in our model. We show that the model can successfully accommodate the observed neutrino oscillation data and consistent with the results from lepton flavor violation and neutrinoless double beta decay process.

1 Introduction

The most successful theory for particle Physics, Standard Model, can’t describe the properties (like mass, mixing matrix, decay) of neutrinos. Absence of the right-handed partner of neutrinos in Standard Model gives zero-mass to it while several experiments proves that neutrinos do oscillate and thus it should have non-zero mass. And also, cosmological data (Planck data 2018) says that sum of the mass of three neutrinos ($\sum_i m_i$) should have in the range $0.518 - 0.12eV$. So, to explain the small non-zero mass of neutrinos, we have to go beyond Standard Model. Lepton flavor violation (LFV) is also an open-question in particle physics. In the context of SM, lepton number and baryon number are two conserved quantity, and thus LFV is not possible if SM is fully correct. But recent experiments focused on the possibility of LFV with some upper bound on the branching ratio of their decay. In our recent work, we are also focussing the LFV part.

To account for the observed data from neutrino oscillation, in the work we consider $U(1)_{L_e-L_\tau}$ as an extension of SM ($SU(3)_C \times SU(2)_L \times U(1)_Y$) gauge groups. We make use of the type-(I+II) seesaw mechanism for generating the masses of the light active neutrinos.

2 Theoretical Framework

	Particles	$SU(2)_L \times U(1)_Y$	$U(1)_{L_e-L_\tau}$
Fermions	$l_{eL}, l_{\mu L}, l_{\tau L}$	$(\mathbf{2}, -1)$	$1, 0, -1$
	e_R, μ_R, τ_R	$(\mathbf{1}, -2)$	$1, 0, -1$
	$\nu_{eR}, \nu_{\mu R}, \nu_{\tau R}$	$(\mathbf{1}, 0)$	$1, 0, -1$
Scalars	H	$(\mathbf{2}, 1)$	0
	S	$(\mathbf{1}, 0)$	1
	Δ	$(\mathbf{3}, -2)$	-1

Table 1: Particle contents in $U(1)_{L_e-L_\tau}$ model.

The particle content of the model is presented in Table I, where we have taken $\nu_{iR}(i = e, \mu, \tau)$, right-handed three generation neutrinos, one singlet scalar (S), a scalar triplet (Δ) in addition to the SM particles.

The Lagrangian for leptonic part for our model can be written as,

$$\begin{aligned}
\mathcal{L}_{\rm lepton} = & -y^l_\alpha \overline{\ell_{\alpha \rm L}} \alpha_{\rm R} H - \frac{1}{2} y_\Delta \left(\overline{\ell_{\mu \rm L}} \Delta {\rm i}\sigma_2 \ell^{\rm C}_{\tau \rm L} + \overline{\ell_{\tau \rm L}} \Delta {\rm i}\sigma_2 \ell^{\rm C}_{\mu \rm L} \right) - y^\nu_\alpha \overline{\ell_{\alpha \rm L}} \widetilde{H} \nu_{\alpha \rm R} \\
& - \frac{1}{2} y^{\mu\tau}_S \left(\overline{\nu^{\rm C}_{\mu \rm R}} \nu_{\tau \rm R} + \overline{\nu^{\rm C}_{\tau \rm R}} \nu_{\mu \rm R} \right) S - \frac{1}{2} y^{e\mu}_S \left(\overline{\nu^{\rm C}_{e \rm R}} \nu_{\mu \rm R} + \overline{\nu^{\rm C}_{\mu \rm R}} \nu_{e \rm R} \right) S^\dagger \\
& - \frac{1}{2} \left[m^{\mu\mu}_{\rm R} \overline{\nu^{\rm C}_{\mu \rm R}} \nu_{\mu \rm R} + m^{e\tau}_{\rm R} \left(\overline{\nu^{\rm C}_{e \rm R}} \nu_{\tau \rm R} + \overline{\nu^{\rm C}_{\tau \rm R}} \nu_{e \rm R} \right) \right] + {\rm h.c.}\ . \qquad (1)
\end{aligned}$$

After spontaneous symmetry breaking, H, Δ, and S will acquire the vacuum expectation values as: $\langle H^0 \rangle = v_H/\sqrt{2}$, $\langle \Delta^0 \rangle = v_\Delta$, and $\langle S \rangle = v_S/\sqrt{2}$ respectively. The mass matrices (charged lepton Dirac mass, neutral sector Dirac mass, Majorana mass) can be written as respectively: [1–3]

$$M_L = \frac{v_H}{\sqrt{2}} \begin{pmatrix} y_l^e & 0 & 0 \\ 0 & y_l^\mu & 0 \\ 0 & 0 & y_l^\tau \end{pmatrix} \quad , \quad M_{\rm D} = \frac{v_H}{\sqrt{2}} \begin{pmatrix} y_\nu^e & 0 & 0 \\ 0 & y_\nu^\mu & 0 \\ 0 & 0 & y_\nu^\tau \end{pmatrix} \quad , \tag{2}$$

,

$$M_{\rm R} = \begin{pmatrix} 0 & |y_S^{e\mu}| \frac{v_S}{\sqrt{2}} e^{i\phi} & m_R^{e\tau} \\ |y_S^{e\mu}| \frac{v_S}{\sqrt{2}} e^{i\phi} & m_R^{\mu\mu} & y_s^{\mu\tau} \frac{v_s}{\sqrt{2}} \\ m_R^{e\tau} & y_s^{\mu\tau} \frac{v_s}{\sqrt{2}} & 0 \end{pmatrix} . \tag{3}$$

The active neutrino mass matrix can be obtained by taking type-(I+II) seesaw mechanism and is a function of M_D, M_R, M_L as:

$$M_\nu = M_L - M_D M_R^{-1} M_D^T \,.$$

$$M_\nu = \begin{pmatrix} 0 & 0 & -\frac{v_H^2 y_\nu^e y_\nu^\tau}{2 m_R^{e\tau}} \\ 0 & \frac{v_H^2 (y_\nu^\mu)^2}{2 m_R^{\mu\mu}} & y_\Delta v_\Delta + \frac{v_H^2 |y_S^{e\mu}| v_S y_\nu^\mu y_\nu^\tau}{2\sqrt{2} m_R^{e\tau} m_R^{\mu\mu}} e^{i\phi} \\ -\frac{v_H^2 y_\nu^e y_\nu^\tau}{2 m_R^{e\tau}} & y_\Delta v_\Delta + \frac{v_H^2 |y_S^{e\mu}| v_S y_\nu^\mu y_\nu^\tau}{2\sqrt{2} m_R^{e\tau} m_R^{\mu\mu}} e^{i\phi} & -\frac{v_S^2}{2} \frac{|y_S^{e\mu}|^2 v_H^2 (y_\nu^\tau)^2}{(m_R^{e\tau})^2 m_R^{\mu\mu}} e^{2i\phi} \end{pmatrix} , \tag{4}$$

M_ν is a two-zero A_1 texture which favours normal ordering.

For numerical analysis, we have taken following parameter ranges:

$$\{y_\nu^e, y_\nu^\mu, y_\nu^\tau\} \in \ [10^{-6}, 10^{-7}], \quad y_\Delta v_\Delta \in [0.01, 0.1] \tag{5}$$

And from NuFit, the oscillation parameters [4] are in the range:

$$\begin{aligned} &\Delta m^2_{\rm atm} = [2.47, 2.63] \times 10^{-3}\ {\rm eV}^2,\ \Delta m^2_{\rm sol} = [6.94, 8.14] \times 10^{-5}\ {\rm eV}^2, \\ &\sin^2\theta_{13} = [0.0200, 0.02405],\ \sin^2\theta_{23} = [0.434, 0.610],\ \sin^2\theta_{12} = [0.271, 0.369]\ . \end{aligned} \tag{6}$$

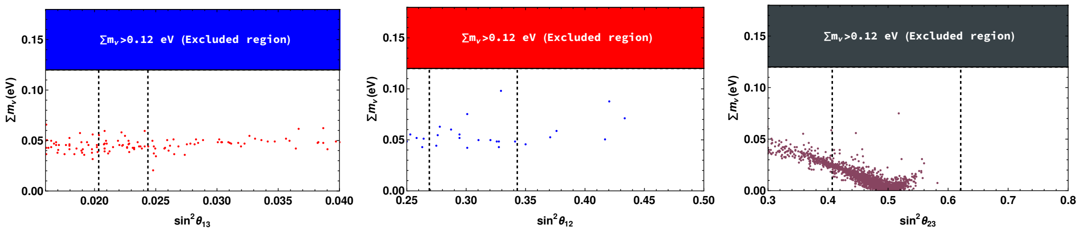

Figure 1: Left [middle] (right) panel shows the variation of $\sin^2\theta_{13}[\sin^2\theta_{12}](\sin^2\theta_{23})$ with respect to sum of active neutrino masses $(\sum m_\nu)$, the blue [red] (magenta) shaded region indicates excluded portion of $\sum m_\nu$ [5].

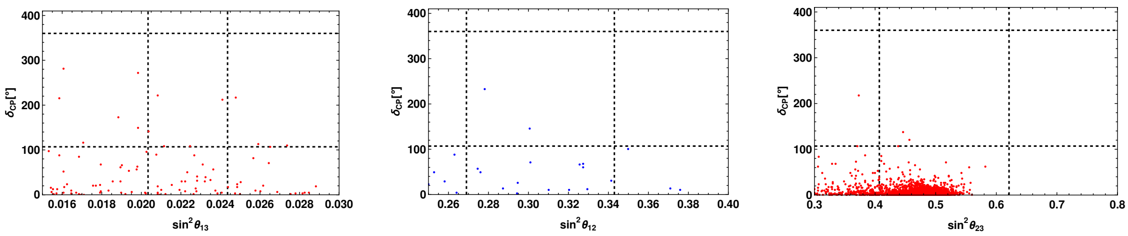

Figure 2: Left [middle] (right) panel shows the variation of $\sin^2\theta_{13}[\sin^2\theta_{12}](\sin^2\theta_{23})$ with respect to δ_{CP}.

3 Lepton flavor violation

One of the conclusions of Standard Model is that, lepton numbers in any nuclear reaction will be conserved independently and separately. But recent experiments shows some of the lepton flavor violation reactions with some upper limit uncertainities. Our $L_e - L_\tau$ model have a sizable contribution in that section also. Our model have succeded to show the acceptable upper limit of branching ratio to the lepton flavor violation equations like: $\tau \to e\gamma$, and $\tau \to \mu\bar{\mu}\mu$.

3.1 Implication on LFV

The braching ratios for the lepton flavor violating decay modes:- $\tau \to e\gamma, \tau \to \mu\bar{\mu}\mu$ are [6,7]

$$\mathrm{Br}(\tau \to e\gamma) = \frac{27\alpha_{em}|\langle m^2\rangle_{e\tau}|^2}{256\pi G_F^2 v_\Delta^4 M_\Delta^4} < 5.6 \times 10^{-8} \,, \tag{7}$$

$$\mathrm{Br}(\tau \to \mu\bar{\mu}\mu) = \frac{|m_{\tau\mu}|^2 |m_{\mu\mu}|^2}{16 G_F^2 v_\Delta^4 M_\Delta^4} < 2.1 \times 10^{-8} \,, \tag{8}$$

where α_{em} is the fine stucture constant=$\frac{1}{137}$ and $G_F = 1.17 \times 10^{-5}\ GeV^2$ =Fermi coupling. Our model shows the value of Br($\tau \to e\gamma$) and Br($\tau \to \mu\bar{\mu}\mu$) with respect to $m_{e\tau}, m_{\mu\mu}, m_{\mu\tau}$ in such a way that the branching ratios are in the allowed region(fig. 3).

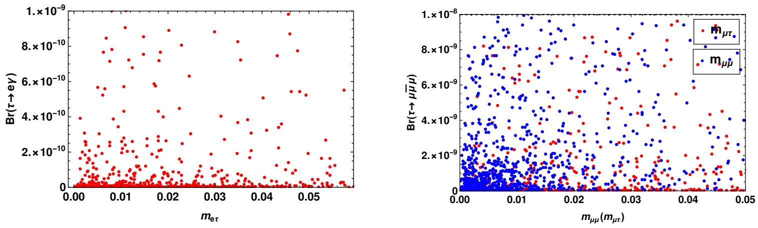

Figure 3: Left(right) panel shows the correlation between the branching ratio of $\tau \to e\gamma$ ($\tau \to \mu\bar{\mu}\mu$) and the mass element $m_{e\tau}$ ($m_{\mu\mu}$ and $m_{\mu\tau}$).

4 Neutrinoless double beta decay

One of the most important decay for confirming the nature of neutrino (is it Dirac or Majorana) is $0\nu\beta\beta$ decay. In the decay, two neutrons are going to decay into protons and two electrons (without emiting any neutrino):

$$2n \to 2p + 2e^- \tag{9}$$

The existence of $0\nu\beta\beta$ deacy will confirm the Majorana nature of neutrino as for that, neutrino is its own antiparticle.

The expression for $0\nu\beta\beta$ decay mass is:

$$m_{ee} = |m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{i\alpha_{21}} + m_3|U_{e3}|^2 e^{i(-2\delta_{CP}+\alpha_{31})}| \tag{10}$$

where $m_i, i = 1, 2, 3$ are the mass of active neutrinos and U_{ij} are the flavor mixing matrix elements for active neutrino. The proposed model has a consistent upper limit of m_{ee} with experimental data.

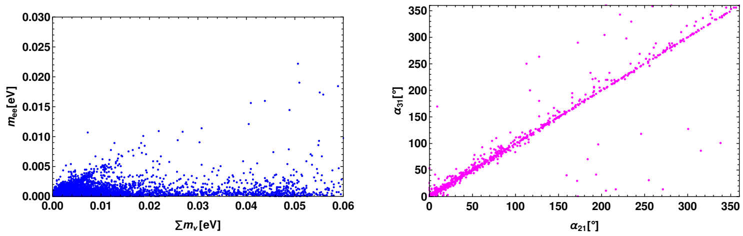

Figure 4: Left panel signify the correlation between the effective neutrinoless double beta decay mass parameter $\langle m_{ee}\rangle$ w.r.t sum of active neutrino mass $\sum m_i$ whereas right panel shows the correlation between the Majorana phases i.e.α_{21} and α_{31}.

5 Conclusion

We have established the neutrino model with $e-\tau$ gauged symmetry which can explain neutrino flavor mixing phenomenology. By taking three right-handed neutrinos, one scalar singlet and one scalar triplet in our model, the model has shown consistent upper limit of branching ratios for lepton flavor violating reactions: $\tau \rightarrow e\gamma, \tau \rightarrow \mu\bar{\mu}\mu$. The mass of $0\nu\beta\beta$ decay is found to be within experimental limit.

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