Left-right models with light neutrino mass prediction and dominant neutrinoless double beta decay rate

M. K. Parida and Sudhanwa Patri
Center of Excellence in Theoretical and Mathematical Sciences, Siksha ‘O’ Anusandhan University, Bhubaneswar-751030, India

In TeV scale left-right symmetric models, new dominant predictions to neutrinoless double beta decay and light neutrino masses are in mutual contradiction because of large contribution to the latter through popular seesaw mechanisms. We show that in a class of left-right models with high-scale parity restoration, these results coexist without any contravention with neutrino oscillation data and the relevant formula for light neutrino masses is obtained via gauged inverse seesaw mechanism. The most dominant contribution to the double beta decay is shown to be via $W_L^+ - W_R^-$ mediation involving both light and heavy neutrino exchanges, and the model predictions are found to discriminate whether the Dirac neutrino mass is of quark-lepton symmetric origin or without it. We also discuss associated lepton flavor violating decays.

I. INTRODUCTION: Evidences of tiny neutrino masses uncovered by the solar, atmospheric, and reactor oscillation experiments while calling for physics beyond the Standard Model (SM) might be strongly hinting at the fundamental nature of the particle i.e. whether Dirac [1] or Majorana [2]. In fact popular theories based upon seesaw mechanisms like type-I seesaw [3], type-II [4, 5], type-III [6, 7], inverse seesaw [8-11], and others [14-18] come out with natural predictions of light Majorana neutrino masses. With lepton number violating mass insertion term by two units, confirmation of any of the experiments at the experimental search programmes for the neutrinoless double beta decay (0ν2β) would not only indicate the Majorana nature of the particles, but also it would strongly support the underlying seesaw mechanism for their mass generation. There have been attempts [19-23] on the experimental side to observe such a rare process, even with a mass generation. The natural TeV mass scale for RH Majorana neutrinos in conventional low scale LR gauge theories however predicts very large contribution to the light neutrino masses through canonical or type-II seesaw mechanisms [4, 41, 42]. Thus, it turns out that new dominant contributions to observable neutrinoless double beta decay (0ν2β) can not coexist with the experimentally determined tiny neutrino masses [43]. Alternatively, interesting proposals have been advanced where type-II seesaw dominance [33, 34] has been invoked by suppressing Dirac neutrino mass matrix in which case LR gauge theories may have only sub-dominant roles to play in representing charged fermion masses. The purpose of this letter is to provide a class of TeV scale left-right gauge theories mediating 0ν2β in LR gauge theories.

The natural TeV mass scale for RH Majorana neutrinos in conventional LR gauge theories emphasizing upon light neutrino mass generation mechanisms however predicts very large contribution to the light neutrino masses through canonical or type-II seesaw mechanisms [4, 41, 42]. Thus, it turns out that new dominant contributions to observable neutrinoless double beta decay (0ν2β) can not coexist with the experimentally determined tiny neutrino masses [43]. Alternatively, interesting proposals have been advanced where type-II seesaw dominance [33, 34] has been invoked by suppressing Dirac neutrino mass matrix in which case LR gauge theories may have only sub-dominant roles to play in representing charged fermion masses. The purpose of this letter is to provide a class of TeV scale left-right gauge theories mediating 0ν2β in LR gauge theories.

II. THE MODEL: In conventional LR gauge theories, the type-I [5] and type-II seesaw [4] contributions to light neutrino masses are

$$m_\nu^I \sim -M_D \frac{1}{M_N} M_D^T, \quad m_\nu^{II} = f \nu_L$$

where the Dirac neutrino mass matrix $M_D$ is similar to the...
charge lepton mass matrix, or the up-quark mass matrix if the model has its origin from Pati-Salam symmetry. The induced triplet vacuum expectation value is $v_L = \lambda_{10} v_0^2 R / M_{\Delta L}$. Then the natural seesaw scales consistent with neutrino oscillation data are $M_N \gtrsim (10^{11} - 10^{14})$ GeV and the TeV scale LR gauge models relevant for $0\nu2\beta$ are ruled out. We now construct a class of LR gauge models where $W_{LR}^L$ and $M_N$ are allowed near the TeV scale which contribute predominantly to $0\nu2\beta$, yet the model does not upset small neutrino mass predictions consistent with the neutrino oscillation data. In our model although the parity restoration scale is large, yet the asymmetric left-right (LR) gauge theory $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C \equiv G_{2213}$ $(g_{2L} \neq g_{2R})$ survives down to the TeV scale subsequent to the D-parity breaking [47]. To implement the idea we use the set of Higgs scalars with their gauge quantum numbers under $G_{2213}$ $(\sigma(1,1,0,1) \oplus \Delta_L(3,1,-2,1) \oplus \Delta_R(1,3,-2,1) \oplus \chi_L(2,-1,1,1) \oplus \chi_R(2,0,1))$ where $\sigma$ is D-parity odd. It is well known that by assigning large parity breaking vacuum expectation value (vev); $(\sigma) \sim M_P$, the model gives all the left-handed (LH) Higgs scalars to have heavy masses i.e. $\cal O(M_P)$ while those of the right-handed (RH) scalars can have much lighter masses near the TeV scale with $M_{\Delta_R}^2 \simeq (\mu^2_R - \lambda(\sigma) M)$ and $M_{\chi_R}^2 \simeq (\mu^2_R - \lambda'(\sigma) M)$ where $M_{\Delta L} \sim M_{\chi L} \sim M \sim \cal O(M_P)$. In fact $M_{\Delta R}$ and $M_{\chi R}$ can have any value upon $M_P$ depending upon the degree of fine tuning in $\lambda$ and $\lambda'$. The asymmetry in the Higgs sector at the energy scales below $\mu \sim M_P$ causes asymmetry in the gauge couplings, $g_{2L} \neq g_{2R}$ for the surviving left-right gauge group. Alternatively, the asymmetric LR model may emerge from high scale Pati-Salam symmetry $SU(2)_L \times SU(2)_R \times SU(4)_C \times D$ $(g_{2L} = g_{2R})$ with similar choice on the Higgs scalars. In particular, we examine the TeV scale phenomenology for neutrino masses and $0\nu2\beta$ with the following two possible cases of symmetry breaking: 

**A:** $\begin{align*}
SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C \times D \\
\equiv G_{2213D} \quad (g_{2L} = g_{2R}) \\
M_{\Delta L} \quad SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C \\
\equiv G_{2213} \quad (g_{2L} \neq g_{2R})
\end{align*}$

**B:** $\begin{align*}
SU(2)_L \times SU(2)_R \times SU(4)_C \times D \\
\equiv G_{224D} \quad (g_{2L} = g_{2R}) \\
M_{\Delta L} \quad SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C \\
\equiv G_{2213} \quad (g_{2L} \neq g_{2R})
\end{align*}$

One important difference between the two scenarios is that in model-A, the Dirac neutrino mass matrix is similar to the charged lepton mass matrix while in model-B, it is similar to the up-quark mass matrix.

In addition to the standard 16-fermions of each generation, we require one additional fermion singlet for each generation $(S_i, i=1,2,3)$ which is essential for the implementation of inverse seesaw mechanism [9] or, the so called extended seesaw mechanism [16-18]. The renormalizable Yukawa Lagrangian near the TeV scale with asymmetric LR gauge theory then turns out to be

$$L_{Yuk} = Y' \bar{\psi}_L \psi_R \Phi + f \bar{\psi}_R \psi_R \Delta_R + F \bar{\psi}_R S \chi_R + S^T \mu_S S + h.c.$$  

(3)

where $\mu_S$ is the singlet fermion mass matrix. We break the LR gauge theory spontaneously to SM by the vev $(\Delta_R^0) = v_R \simeq M_R$ while the vev $(\chi_R^0) = v_\chi \leq M_R$ is used to generate the $N - S$ mixing. The SM breaks to the low energy symmetry by the VEV of the SM Higgs doublet in $\Phi$. With this structure of the Yukawa Lagrangian, the full $(9 \times 9)$ neutrino mass matrix in the $(\nu_L, N_R, S_L)$ basis is given by

$$M = \begin{pmatrix}
0 & M_D & 0 \\
M_D^T & M_N & M \\
0 & M^T & \mu_S
\end{pmatrix}$$  

(4)

where $M = F v_\chi$, $M_D = Y' \langle \Phi \rangle$, and $M_N = f v_R$. Here $M_D$ and $M$ are $3 \times 3$ complex matrices in flavor space and $\mu_S$ is the $3 \times 3$ complex symmetric matrix.

For implementation of the light neutrino mass generation mechanism the desired hierarchy $M_N \gg M_D \gg \mu_S$ with a fine tuned small lepton number violating parameter $\mu_S$ can be easily satisfied in the model after spontaneous symmetry breaking. Since the right-handed neutrinos are assumed to be larger than other mass scales, they eventually decouple at low scales $[16-18]$. It is important to note that this extended seesaw scenario is very different from the inverse seesaw scenario $[3,9,11]$ due to the simultaneous presence of both the heavy and small lepton number violating scales $M_N$ and $\mu_S$. Complete block diagonalization of eq. (4) gives the usual inverse seesaw formula for light neutrino masses

$$m_\nu = \left( \frac{M_D}{M} \right) \mu_S \left( \frac{M_D}{M} \right)^T,$$  

(5)

as well as the heavy neutrino mass matrices $m_N \simeq M_N$ and $m_S \simeq M^2 \frac{\mu_S}{M} M^T$. It is important to note that with $M_N \gg M \gg M_D$, $\mu_S$, the type-I seesaw contribution to the light neutrino mass matrix, i.e. $-M_D \frac{\mu_S}{M} M_D^T$ cancels out after complete block diagonalization. Also these block diagonal mass matrices $m_\nu$, $m_S$ and $m_N$ can further be diagonalized to give physical masses for all neutral leptons by respective unitary mixing matrices: $U_\nu$, $U_S$ and $U_N$ where

$$U_\nu^T m_\nu U_\nu^* = \hat{m}_\nu = \text{diag} \left[ m_{\nu_1}, m_{\nu_2}, m_{\nu_3} \right],$$

$$U_S^T m_S U_S^* = \hat{m}_S = \text{diag} \left[ m_{S_1}, m_{S_2}, m_{S_3} \right],$$

$$U_N^T m_N U_N^* = \hat{m}_N = \text{diag} \left[ m_{N_1}, m_{N_2}, m_{N_3} \right].$$  

(6)
The relevant charged current interactions of leptons for this TeV scale LR gauge theory in the flavor basis is given by

$$\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} \sum_{\alpha=L,R} \left[ \overline{W}_\alpha \gamma^\mu \nu_{\alpha L} W_\mu^\nu + \overline{T}_\alpha \gamma^\mu N_{\alpha R} W_\mu^\nu \right] + \text{h.c.}$$

where, in terms of mass eigenstates ($\nu_{m_1}$, $S_{m_2}$, $N_{m_3}$) [35],

$$\nu_{\alpha L} \sim N_{\alpha i} \nu_{m_i} + U^e_{\alpha j} S_{m_j} + U^e_{\alpha k} N_{m_k},$$

$$N_{\alpha R} \sim \nu_{\alpha N} \nu_{m_N} + \nu_{\alpha S} S_{m_S} + \nu_{\alpha k} N_{m_k},$$

$$\mathcal{N}_{\alpha i} = \{ \left( 1 - \frac{1}{2} X' X^\dagger \right) U^e_{\alpha i} \},$$

$$\mathcal{R}_{\alpha k} = \{ \left( 1 - \frac{1}{2} X'^\dagger X'' \right) U^N_{\alpha k} \},$$

$$U^e_{\alpha j} = \{-X U S\}_{\alpha j}, \quad U^e_{\alpha k} = \{-X' U N\}_{\alpha k},$$

$$\nu_{\alpha N} = \{X' U S\}_{\alpha i}, \quad \nu_{\alpha S} = \{-X'^\dagger U N\}_{\alpha j}.$$ (7)

The non-unitarity matrices in our model are $X = \frac{M_D}{M'}$, $X' = \frac{M_{D'}}{M''}$, and $X'' = \frac{M'''}{M'''}$ due to $\nu - S, \nu - N$, and $S - N$ mixings, respectively.

**III. NEUTRINOLESS DOUBLE BETA DECAY:** It is clear from the charged current interaction of this left-right gauge theory that, in addition to the standard contribution to $0\nu\beta\beta$ via light Majorana neutrino exchange, there are non-standard contributions due to the exchanges of heavy RH Majorana neutrinos and heavy sterile Majorana neutrinos. In addition, the extended seesaw ansatz manifests in non-standard contributions to lepton flavor violations and non-unitarity effects. In particular, we show that a dominant contribution to $0\nu\beta\beta$ arises due to mixed diagrams with simultaneous mediation of $W^-_L$ and $W^-_R$ bosons accompanied by light left-handed neutrinos and heavy right-handed Majorana neutrinos [34, 45] as shown in Fig. 1. We present analytic expressions for two most dominant contributions to the effective mass term and compare them with the standard contribution,

- $m^{ee}_{\nu}$, which is analogous to the standard contributions, in this model,

$$m^{ee}_{\nu} = N^2_{ei} m_{\nu_i},$$ (8)

- $m^{ee}_{NN}$: which originates from the mediation of two $W_R$'s with the exchange of heavy RH Majorana neutrinos,

$$m^{ee}_{NN} = p^2 \frac{M^2_{W_R}}{M_{W_R}} \left( \mathcal{R}_{ei} \right)^2,$$ (9)

- $m^{ee}_{N\nu}$: which originates from simultaneous mediation of $W_L$ and $W_R$ and involves the Dirac mass matrix $M_D$

$$m^{ee}_{N\nu} \simeq p \left( \zeta_{LR} + \frac{M^2_{W_R}}{M_{W_R}} \right) N_{ei} \left( \left[ M_{L^{-1}} M_D U_N \right]_{ei} \right).$$ (10)

where, in our model, $\zeta_{LR} = \text{LR mixing parameter} \leq 10^{-4}$.

**IV. RESULTS AND DISCUSSIONS:** It is clear from equations (5) and (7) that the mass matrices $M_D$, $M$, and $M_N$ are essential for predictions of light neutrino masses and $0\nu\beta\beta$. At first assuming the LR gauge theory to be having its high scale origin from Pati-Salam symmetry and neglecting the renormalization group corrections, the Dirac neutrino mass matrix is approximated as the up-type quark mass matrix via the CKM matrix and the running masses of the three up-type quarks, namely, $m_u = 2.33$ MeV, $m_c = 1.275$ GeV, and $m_t = 160$ GeV [48]

$$M_D \sim V_{CKM} \tilde{M}_u V^T_{CKM} = \begin{pmatrix} 0.67 - 0.004 & 0.302 - 0.022 & 0.55 - 0.53 \\ 0.302 - 0.022 & 1.48 - 0 & 6.534 - 0.009 \\ 0.55 - 0.53 & 6.534 - 0.009 & 159.72 + 0.0 \end{pmatrix} \text{GeV}.$$ (11)

Under the condition $M_N \gg M \gg M_D$, the non-unitarity contribution of the extended seesaw model is mainly due to $\eta \simeq \frac{1}{2} X X^\dagger$, giving rise to $\eta_{i\alpha \beta} = \frac{1}{2} \sum_{k=1}^{3} \frac{M_{D_{\alpha k}} M_{D_{\alpha k}}}{M^2_{\alpha}}$ where we have assumed for the sake of simplicity: $M = \text{diag}(M_1, M_2, M_3)$. Then by saturating the available bound on $|\eta_{i\alpha \beta}| \leq 2.7 \times 10^{-3}$ [12, 49], we obtain

$$\frac{1}{2} \left[ \frac{0.5805}{M^2_1} + \frac{42.72}{M^2_2} + \frac{25510.7}{M^2_3} \right] = 2.7 \times 10^{-3}$$ (12)

where the numbers inside the square bracket are in GeV$^2$. We note that the above relation can be satisfied in the partial degenerate case, $M_1 = M_2 \geq 100$ GeV, and $M_3 \geq 2.2$ TeV and also in the non-degenerate case, $M_1 \geq 10$ GeV, $M_2 \geq 50$ GeV and $M_3 \geq 2.2$ TeV, but in the degenerate case, $M_1 = M_2 = M_3 = 2.2$ TeV.

**a. Determination of $\mu_{\Sigma}$ from neutrino oscillation data:** Inverting the neutrino mass formula given in eqn. (5) and using equation (7) and our model parameters, we obtain

$$\mu_\Sigma \text{ (GeV)} = X^{-1} N m_{\nu} N^T (X^T)^{-1} = \begin{pmatrix} 0.01147 + 0.001 & -0.0027 - 0.0024i & 0.0007 + 0.002i \\ -0.0027 - 0.0024i & 0.0006 + 0.0005i & -0.0001 - 0.0004i \\ 0.0007 + 0.002i & -0.0001 - 0.0004i & -0.00004 + 0.0003i \end{pmatrix}$$

where we have used the hierarchical neutrino masses $m_{\nu}^{\text{diag}} = \text{diag}(0.00127 \text{ eV}, 0.00885 \text{ eV}, 0.0495 \text{ eV})$ and global fit to
the neutrino oscillation data including recent values of $\theta_{13} = 9.0^\circ$ and $\delta = 0.8\pi$ \cite{46}.

Thus, in the inverse seesaw approach, the light neutrino masses and large neutrino mixings including non-zero values of $\theta_{13}$ can be easily fitted through the elements of the $\nu_S$ matrix which may have interesting consequences on leptogenesis \cite{13}. Although we have explicitly fitted the hierarchical light neutrino masses, similar fits can be obtained in the inverted hierarchical as well as the quasi-degenerate cases with corresponding elements of $\nu_S$. In the case of $M_D$ being similar to charged lepton mass matrix which holds true in conventional LR gauge theories \cite{4,42} neutrino oscillation data are similarly fitted with the corresponding $\nu_S$ matrix.

b. Neutrinoless double beta decay predictions: As explained in equations (7)-(10), the mixing matrices $X = \frac{M_D}{M'}$, $X' = \frac{M_D}{M''}$, and $X'' = \frac{M_D}{M'''}$ all contribute to non-standard predictions of $0\nu\beta\beta$ amplitude in the present left-right gauge theory. We have assumed the RH heavy Majorana neutrino mass matrix to be diagonal, $M_N = \text{diag}(M_{N1}, M_{N2}, M_{N3})$. Using the model parameters given in eqn. (11) for $M_D, M = \text{diag}(150, 150, 2500) \text{ GeV}, M_N = \text{diag}(5000, 5000, 10000) \text{ GeV}$, $U_\nu = U_{PMNS}, u_N = 1_{3x3}$, and $U_S = 1_{3x3}$, we have derived the relevant elements of the mixing matrices $N_{ei}, R_{ee}, U_{eS}, U_{eN}, V_{ei}, V_{eNS}$.

$$N_{e1} = 0.819, \quad N_{e2} = 0.552, \quad N_{e3} = 0.156,$$
$$R_{e1} = 0.997, \quad R_{e2} = 0.0, \quad R_{e3} = 0.0,$$
$$U_{e1}^{NS} = 0.00045, \quad U_{e2}^{NS} = 0.002, \quad U_{e3}^{NS} = 0.0002,$$
$$U_{e1}^{N} = 0.00001, \quad U_{e2}^{N} = 0.00005, \quad U_{e3}^{N} = 0.000007,$$
$$|U_{N\nu}| \leq 10^{-9}, \quad \text{and} \quad |U^{NS}| \leq 10^{-1}.$$  \hspace{1cm} (13)

With $|p| = 100 \text{ MeV}, M_{W_R} = 5 \text{ TeV}$ and using equations (7)- (10), we predict the effective mass for $0\nu\beta\beta$ transition rate for hierarchical light neutrino masses,

$$|m_{ee}^\nu| = N_{e1}^2 m_{\nu_1} + N_{e2}^2 m_{\nu_2} + N_{e3}^2 m_{\nu_3} = 0.00157 \text{ eV},$$  \hspace{1cm} (14)

$$|m_{eN}^\nu| = 6 \times 10^{-4} \text{ eV},$$  \hspace{1cm} (15)

$$|m_{eN}^\nu| \sim 1 \text{ eV}.$$  \hspace{1cm} (16)

Our numerical predictions are shown in Fig. 2 as a function of $W_R$ mass. With Dirac neutrino mass matrix having quark-lepton symmetric origin, the most dominant contribution due to $W_L^- - W_R^-$ mediation is found to be $m_{eN}^\nu \simeq 1 \text{ eV}$ and $0.04 \text{ eV}$ for $M_{W_R} = 5 \text{ TeV}$, and $10 \text{ TeV}$, respectively. These predictions are reduced to $m_{eN}^\nu \simeq 0.07 \text{ eV}$ and $0.03 \text{ eV}$ for the corresponding values of the $M_{W_R}$ when the Dirac neutrino mass matrix is similar to the charged lepton mass matrix. In other words, we predict that the $0\nu\beta\beta$ process would be able to discriminate LR gauge models having their roots in quark-lepton symmetry. We note that the sub-dominant contribution due to $W_R^- - W_R^-$ mediation given in eqn. (15) is suppressed as compared to the standard contribution due to $W_L^- - W_L^-$ mediation given in eqn. (14) for the same $M_{W_R}$ masses shown in Fig. 3.

For the sake of comparison with the prediction for the inverse $0\nu\beta\beta$ processes in the golden channel $e^- e^- \rightarrow W_L^- W_R^-$ \cite{45} which might be phenomenologically important for Linear Collider searches we used $M_{W_R} \geq 2.5 \text{ TeV}$ \cite{43} to determine $\eta_L = \frac{M_{W_R}}{M_{W_R}} N_{e1} (M_{N}^{-1} M_D U_N)_{ei}$ which enters in cross-section for this process. Our model predicts this parameter to be $8.6 \times 10^{-6}$ whereas the limit on this parameter is $\eta_L \leq 9 \times 10^{-7}$ derived from the current experimental limit on $0\nu\beta\beta$ transition rate.

c. Lepton flavor violation: Besides the neutrinoless double beta decay process, the light and heavy neutrinos in this model can actively mediate different lepton flavor violating processes, $\mu \rightarrow e + \gamma, \tau \rightarrow e + \gamma$, and $\tau \rightarrow \mu + \gamma$ which are currently under active experimental investigation. The dominant contributions are mainly through the exchange of the six
heavy neutrinos \[15\] with branching ratio
\[
\text{Br} (\ell_\alpha \to \ell_\beta + \gamma) = \frac{G_{\alpha\ell}^2}{2M^4 W_{\ell}} \left| G_{\alpha\beta}^N + G_{\alpha\beta}^S \right|^2
\]
where \[17\]
\[
G_{\alpha\beta}^N = \sum_k (U^N)_{\alpha k} (U^N)_{\beta k}^* \mathcal{F} \left( \frac{m_{N_k}^2}{M_{W_L}^2} \right),
\]
\[
G_{\alpha\beta}^S = \sum_j (U^S)_{\alpha j} (U^S)_{\beta j}^* \mathcal{F} \left( \frac{m_{S_j}^2}{M_{W_L}^2} \right),
\]
\[
\mathcal{F}(x) = -\frac{2x^3 + 5x^2 - x}{4(1-x)^3} - \frac{3x^3 \ln x}{2(1-x)^4}.
\]
Within the allowed range of model parameters \[M_N \gg M \gg M_D\], it is clear that the first term in \[17\] is negligible. The second term involving the heavy sterile neutrinos gives dominant contributions which is proportional to \[\sum_j (U^S)_{\alpha j} (U^S)_{\beta j}^* \simeq 2\eta_{\alpha\beta}\] and our model predictions are
\[
\begin{align*}
\text{Br}(\mu \to e + \gamma) &= 1.36 \times 10^{-15}, \\
\text{Br}(\tau \to e + \gamma) &= 1.06 \times 10^{-13}, \\
\text{Br}(\tau \to \mu + \gamma) &= 3.17 \times 10^{-12}.
\end{align*}
\]
Noting that the present experimental limit at 90% C.L., \[\text{Br}(\mu \to e + \gamma) \leq 1.2 \times 10^{-11}\] is almost three orders of magnitude stronger than the limits \[\text{Br}(\tau \to e + \gamma) \leq 3.3 \times 10^{-8}\] or \[\text{Br}(\tau \to \mu + \gamma) \leq 4.4 \times 10^{-8}\] appears to justify why the limit on \[|\eta_{\tau\mu}|\] is at least one order of magnitude better than the ones on \[|\eta_{\tau\tau}|\] and \[|\eta_{\tau\tau}|\]. The projected reach of future sensitivities for ongoing searches are \[\text{Br}(\tau \to e + \gamma) \leq 10^{-9}\], \[\text{Br}(\tau \to \mu + \gamma) \leq 10^{-9}\] and \[\text{Br}(\mu \to e + \gamma) \leq 10^{-18}\] throughout which the model predictions can be easily verified or falsified.

**V. CONCLUSION:** We have shown that in a class of left-right gauge theories, the light neutrino masses naturally arise though gauged inverse seesaw mechanism consistent with the current neutrino oscillation data. The associated TeV scale masses of \(W_R^\pm\) and \(M_N\) can give dominant non-standard contributions to neutrinoless double beta decay which might be important for experimental searches. Specifically, we have demonstrated that the mixed diagram, via simultaneous mediation of \(W_R^\pm\) and \(W_R^-\) accompanied by the naturally predicted Dirac neutrino mass terms, gives the dominant contribution to \(\nu\beta\beta\) rate. Also this mixed diagram has rich phenomenological implication at ILC for the detection of the inverse process like \(e^- e^- \to W_R^- W_R^-\). We have explicitly shown that this Dirac neutrino mass matrix could be similar to the up quark mass matrix which may have its high scale quark-lepton symmetric origin, or it may be similar to the charged lepton mass matrix expected from left-right gauge theory. The effective mass prediction in the former case being nearly 10 times larger than the latter case, we suggest that \(\omega\beta\beta\) signatures may probe high scale quark-lepton symmetry. As in our approach it is not necessary to fine tune the Dirac mass matrices, the left-right models could serve as promising theories for charged fermion masses. The TeV scale masses of \(W_R^\pm\) and \(Z_R^\pm\) bosons are accessible to ongoing searches at LHC \[54\].

The predicted branching ratios for lepton flavor violating decays, being closer to the current experimental search limits, could be used to verify or falsify the left-right model framework considered in this letter.

---

1 Electronic address: paridamk@southernuniversity.ac.in
2 Electronic address: sudha.astro@gmail.com

[1] P. A. M. Dirac; Proceedings of the Royal Society of London, 109, 752 (Dec. 1, 1925), pp. 642-653.
[2] E. Majorana; N. Cim. 14 (1937) 171.
[3] P. Minkowski, Phys. Lett. B 67, 421 (1977); T. Yanagida, proceedings of the Workshop on Unified Theories and Baryon Number in the Universe, Tsukuba, 1979, eds. A. Sawada, A. Sugamoto, KEK Report No. 79-18, Tsukuba; S. Glashow, in Quarks and Leptons, Cargèse 1979, eds. M. Lévy et al., (Plenum, 1980, New York); M. Gell-Mann, P. Ramond, R. Slansky, proceedings of the Supergravity Stony Brook Workshop, New York, 1979, eds. P. Van Nieuwenhuizen, D. Freeman (North-Holland, Amsterdam); R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44, 912 (1980).
[4] R. N. Mohapatra and G. Senjanovic, Phys. Rev. D 23, 165 (1981);
[5] G. Lazarides, Q. Shafi and C. Wetterich, Nucl. Phys. B 181, 287 (1981); J. Schechter and J. W. F. Valle, Phys. Rev. D 22, 2227 (1980).
[6] R. Foot, H. Lew, X. G. He and G. C. Joshi, Z. Phys. C 44, 441 (1989); E. Ma and D. P. Roy, Nucl. Phys. B 644, 290 (2002) [arXiv:hep-ph/0206150].
[7] R. Bajc, G. Senjanovic, JHEP 0708, 014 (2007) [hep-ph/0612029]; B. Bajc, M. Nemevsek, G. Senjanovic, Phys. Rev. D 76 (2007) 055011 [hep-ph/0703080]; A. Arhrib, B. Bajc, D. K. Ghosh, T. Han, G. -Y. Huang, I. Puljak, G. Senjanovic, Phys. Rev. D 83, 053004 (2010) [arXiv:0904.2390 [hep-ph]].
[8] R. N. Mohapatra, Phys. Rev. Lett. 56, 561-563 (1986); R. N. Mohapatra, J. W. F. Valle, Phys. Rev. D 34, 1642 (1986).
[9] D. Wyler, L. Wolfenstein, Nucl. Phys. B 218, 205 (1983); E. Witten, Nucl. Phys. B 268, 79 (1986).
[10] J. L. Hewett, T. G. Rizzo, Phys. Rept. 183, 193 (1989).
[11] P. S. B. Dev, R. N. Mohapatra, Phys. Rev. D81, 013001 (2010) [arXiv:0910.3924 [hep-ph]].
[12] Ram Lal Awasthi and Mina K. Parida, Phys.Rev. D 86 (2012) 093004. e-Print: arXiv:1112.1826 [hep-ph].
[13] S. Blanchet, P. S. B. Dev, R. N. Mohapatra, Phys. Rev. D 82, 115025 (2010) [arXiv:1010.1477 [hep-ph]].
[14] A. Pilaftsis, Z. Phys. C 55, 275 (1992) [hep-ph/9901206].
[15] J. Kersten and A. Y. Smirnov, Phys. Rev. D 76, 073005 (2007) [arXiv:0705.3221 [hep-ph]]; R. Adhikari and A. Raychaudhuri, Phys. Rev. D 84, 033002 (2011) [arXiv:1004.5111 [hep-ph]].
[16] A. Ilakovac, A. Pilaftsis, Nucl. Phys. B437, 491 (1995) [hep-ph/9504398]; F. Deppisch, J. W. F. Valle, Phys. Rev. D72, 036001 (2005) [hep-ph/0406040]; C. Arina, F. Bazzocchi, N. Fornengo, J. C. Romao, J. W. F. Valle, Phys. Rev. Lett. 101, 161802 (2008) [arXiv:0806.3225 [hep-ph]]; M. Malinsky, T. Ohlsson, Z. -z. Xing, H. Zhang, Phys. Lett. B679, 242-248 (2009) [arXiv:0905.2889 [hep-ph]]; M. Hirsch, T. Kermeire, J. C. Romao, A. Villanova del Moral, JHEP 1001, 103 (2010) [arXiv:0910.2435 [hep-ph]]; F. Deppisch, T. S. Kosmas, J. W. F. Valle, Nucl. Phys. B752, 80-92 (2006) [arXiv:0910.3924 [hep-ph]].
