2

Connecting neutrinoless double-beta decay and lepton flavor violation in discrete flavor symmetric left-right symmetric model

In this chapter, we study the possibility of simultaneously addressing lepton number violation and lepton flavor violation in the framework of a minimal left-right symmetric model. LRSM is a very simple extension of the standard model gauge group where parity restoration is obtained at a high energy scale and the fermions are assigned to the gauge group $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ which can be tested in present-day experiments. We build a A_4 flavor symmetric model within the minimal LRSM framework which is combined with Z_2 symmetry to constrain the unwanted couplings in the Yukawa Lagrangian. The structures of mass matrices arising from minimal LRSM blended with A_4 symmetry give rise to correct neutrino mixing with a non-zero reactor mixing angle. Within this model, we have realized both type-I and type-II dominance cases and conducted a detailed analysis of different contributions to the NDBD process which is the LNV process coming from extended particle content of the LRSM and studied different LFV processes such as $\mu \to 3e$ and $\mu \to e\gamma$ and correlated with neutrino mass.

2.1 Introduction:

The importance of the LRSM [80, 82, 150, 81] in generating light neutrino mass and explaining different neutrino phenomenology was discussed in many previous works. LRSM is an interesting framework which can be an alternative to conventional seesaw mechanisms. Type-I [57, 61, 60, 59] and type-II [58, 66, 87, 67] seesaw mechanisms arises naturally within the framework of LRSM. Although it is an extension of the SM by a gauge group $SU(2)_R$, it has the advantage of mass scale which is around the TeV scale and is accessible in future accelerator experiments. In our work, we have considered a minimal LRSM where the scalar sector of SM is extended by two scalar triplets and a Higgs bidoublet.

In this chapter, we present a detailed study of the LNV process i.e. NDBD in the framework of LRSM. As already mentioned, symmetry realization of both type-I and type-II dominance cases in the LRSM is done with A_4 and Z_2 flavor symmetry. Additional flavor symmetry will constrain the structure of mass matrices, which further have an impact on different phenomenology under consideration. We have constructed all the mass matrices involved in LRSM using flavor symmetry which leads to correct neutrino mixing and non-zero reactor mixing angle. In LRSM, there will be many new contributions to the LNV process due to the presence of extended particle content. The impact of additional flavor symmetry on these contributions is studied in detail within the model. We have also considered different CLFV processes such as $\mu \to 3e$ and $\mu \to e\gamma$ and checked the consistency of the model with the constrained mass matrices for relevant experiments. The correlation of the LFV process with neutrino mass is also analyzed in this work. Parameter space of different neutrino oscillation parameters such as CP violating phase δ, atmospheric mixing angle θ_{23} and Majorana phase α are also determined from the correlation plot with effective mass considering different experimental bound coming from experiments such as Planck collaboration, KamLand-ZEN, GERDA, etc.

This chapter is structured as follows. In Section 2.2, present the A_4 flavor symmetric LRSM considering both type-I and type-II dominant cases. The construction of different mass matrices is also discussed in this section. We have discussed different new physics contributions to the amplitude of the NDBD process along with the decay rate of the process in section 2.3. In Section 2.4, we briefly discussed different LFV processes and in section 2.5, we present our numerical analysis and results, and then in Section 2.6, we conclude by giving a brief overview of our work.

2.2 A left right flavor symmetric model:

In particle physics, symmetry plays a very significant role. The flavor structure of a particular model in particle physics can be controlled by non-abelian discrete flavor symmetry. In our work, we have used A_4 flavor symmetry to construct relevant mass matrices. A_4 is a group of permutations of four objects. It is isomorphic to the symmetry group of a tetrahedron. A_4 has three singlets and one triplet irreducible representations denoted by 1, $1'$, $1''$, 3_A and 3_S respectively. Where A and S stand for the anti-symmetric and symmetric terms. Our model contains the usual particle content of LRSM. The lepton doublets transform as triplets under A_4 while Higgs bidoublet and scalar triplets transform as 1 under A_4. Two flavon triplet fields χ^l and χ^ν are included in the model which transforms as triplet under A_4. The Z_2 symmetry excludes the non-desired interactions of the particles in the Lagrangian. Additionally, a flavon singlet ε is used to allow for required charged lepton masses. The particle content and the charge assignments are in the table 2.1.

The Yukawa Lagrangian can be written as:

$$\mathcal{L}_{\mathcal{Y}} = \frac{1}{\Lambda}(\bar{l_L}(Y_\varepsilon \varepsilon + Y_{l1}\chi^l + Y_{l2}\chi^l)\Phi l_R + \bar{l_L}(\tilde{Y}_\varepsilon \varepsilon + \tilde{Y}_{l1}\chi^l + \tilde{Y}_{l2}\chi^l)\tilde{\Phi} l_R$$
$$+ \bar{l^c}_R(Y_R^0 + Y_R^\nu \chi^\nu) i\tau_2 \Delta_R l_R + \bar{l^c}_L(Y_R^0 + Y_R^\nu \chi^\nu) i\tau_2 \Delta_L l_L) \quad (2.1)$$

Field	l_L	l_R	Φ	Δ_L	Δ_R	χ^l	χ^ν	ε
$SU(2)_L$	2	1	2	3	1	1	1	1
$SU(2)_R$	1	2	2	1	3	1	1	1
$U(1)_{B-L}$	-1	-1	0	2	2	0	0	0
A_4	3	3	1	1	1	3	3	1
Z_2	0	0	1	0	0	1	0	1

Table 2.1 Fields and their respective transformations under the symmetry group of the model.

2.2.1 Type-I dominance:

The VEV of Δ_L (v_L) is considered to be negligible in the case of type-I dominance case. So, the terms involving Δ_L are omitted from the Lagrangian. The Yukawa matrices from the eq(2.2) can be written as-

$$Y_\varepsilon = y_{l0}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$Y_{l1} = y_{l1}\begin{pmatrix} 2\chi_1^l & -\chi_3^l & -\chi_2^l \\ -\chi_2^l & -\chi_1^l & 2\chi_3^l \\ -\chi_3^l & 2\chi_2^l & -\chi_1^l \end{pmatrix}$$

$$Y_{l2} = y_{l2}\begin{pmatrix} 0 & -\chi_3^l & \chi_2^l \\ -\chi_2^l & \chi_1^l & 0 \\ \chi_3^l & 0 & -\chi_1^l \end{pmatrix}$$

Now, Dirac neutrino mass matrix M_D and charge lepton mass matrix M_l are given by-

$$M_l = v_2 Y + v_1 \tilde{Y}, M_D = v_1 Y + v_2 \tilde{Y} \tag{2.2}$$

Where, v_1 and v_2 are vev of the Higgs bidoublet and (Y,$\tilde{Y}$) are Yukawa coupling which is given by:

$$Y = Y_\varepsilon + Y_{l1} + Y_{l2}, \tilde{Y} = \tilde{Y_\varepsilon} + \tilde{Y_{l1}} + \tilde{Y_{l2}} \tag{2.3}$$

Majorana mass matrix can be given as-

$$M_R = v_R Y_R \tag{2.4}$$

Where Y_R is the Majorana coupling.

$$M_R = \frac{v_R y_{R0}}{\Lambda} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} + \frac{v_R y_R}{\Lambda} \begin{pmatrix} 2\chi_1^\nu & -\chi_3^\nu & -\chi_2^\nu \\ -\chi_3^\nu & 2\chi_2^\nu & -\chi_1^\nu \\ -\chi_2^\nu & -\chi_1^\nu & 2\chi_3^\nu \end{pmatrix} \tag{2.5}$$

where Λ is the cut-off scale of the theory. The flavon alignments in our model are taken to be, $\chi^l - (1,0,0), \chi^\nu - (1,\omega,\omega^2)$. Now, the diagonal charged lepton mass matrix is-

$$M_l = \begin{pmatrix} a+2b & 0 & 0 \\ 0 & a+(c-b) & 0 \\ 0 & 0 & a-(b+c) \end{pmatrix}$$

Where $a = v_2 y_{l0} + v_1 \tilde{y_{l0}}/\Lambda$, $b = v_2 y_{l1} + v_1 \tilde{y_{l1}}/\Lambda$ and $c = v_2 y_{l2} + v_1 \tilde{y_{l2}}/\Lambda$.

Now, the Dirac neutrino mass matrix(M_D) can be simplified into the form given below-

$$M_D = \lambda \begin{pmatrix} 1 & 0 & 0 \\ 0 & r_1 & 0 \\ 0 & 0 & r_2 \end{pmatrix}$$

where $\lambda = v_1 y_{l0} + v_2 \tilde{y_{l0}}/\Lambda$, $r_1 = \frac{v_1 y_{l1} + v_2 \tilde{y_{l1}}}{\lambda\Lambda}$ and $r_2 = \frac{v_1 y_{l2} + v_2 \tilde{y_{l2}}}{\lambda\Lambda}$

The Majorana mass mtrix is:

$$M_R = a_R \begin{pmatrix} 2z+1 & -\omega^2 z & -\omega z \\ -\omega^2 z & 2\omega z & 1-z \\ -\omega z & 1-z & 2\omega^2 z \end{pmatrix}$$

Where $a_R = \frac{v_R y_{R0}}{\Lambda}$ and $z = \frac{y_R}{y_{R0}}$. Now, the relevant mass generation formula for type-I dominance-

$$-m_\nu = M_D^T M_R^{-1} M_D \tag{2.6}$$

The light neutrino mass matrix will be:

$$m_\nu = \frac{m}{3z+1} \begin{pmatrix} z+1 & \omega z r_1 & \omega^2 z r_2 \\ \omega z r_1 & \omega^2 \frac{z(3z+2)r_2^2}{3z-1} & \frac{(z-3z^2+1)r_1 r_2}{1-3z} \\ \omega^2 z r_2 & \frac{(z-3z^2+1)r_1 r_2}{1-3z} & \frac{\omega z(3z+2)r_2^2}{3z-1} \end{pmatrix}$$

2.2.2 Type-II dominance:

In case Type-II dominance to break the $\mu-\tau$ symmetry of the resulting mass matrix we need to introduce another flavon ε'. This flavon transforms as $1'$ under A_4. Now, Lagrangian for the neutrino sector will become-

$$\mathcal{L}_{\mathcal{Y}\nu} = \frac{1}{\Lambda}(\bar{l^c}_R(Y_R^0\varepsilon' + Y_R^\nu \chi^\nu) i\tau_2 \Delta_R l_R + \bar{l^c}_L(Y_R^0\varepsilon' + Y_R^\nu \chi^\nu) i\tau_2 \Delta_L l_L) \tag{2.7}$$

So, we can write-

$$m_\nu = v_L Y_L, M_R = v_R Y_R \tag{2.8}$$

where v_L and v_R are the vev of Δ_L and Δ_R respectively. Y_L and Y_R are Majorana Yukawa couplings. In the LRSM, both Y_L and Y_R are taken to be equal. Now, the Majorana mass matrix can be written as:

$$M_R = \frac{v_R y_{R0}}{\Lambda}\begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix} + \frac{v_R y_R}{\Lambda}\begin{pmatrix} 2\chi_1^\nu & -\chi_3^\nu & -\chi_2^\nu \\ -\chi_3^\nu & 2\chi_2^\nu & -\chi_1^\nu \\ -\chi_2^\nu & -\chi_1^\nu & 2\chi_3^\nu \end{pmatrix} \tag{2.9}$$

Using the chosen flavon alignment we get-

$$M_R = a_R \begin{pmatrix} 2z & -\omega^2 z & 1-\omega z \\ -\omega^2 z & 1+2\omega z & -z \\ 1-\omega z & -z & 2\omega^2 z \end{pmatrix}$$

Where $a_R = \frac{v_R y_{R0}}{\Lambda}$ and $z = \frac{y_R}{y_{R0}}$

Similarly, we can compute the light neutrino mass matrix which is given by-

$$m_\nu = a_L \begin{pmatrix} 2z & -\omega^2 z & 1-\omega z \\ -\omega^2 z & 1+2\omega z & -z \\ 1-\omega z & -z & 2\omega^2 z \end{pmatrix}$$

Where $a_L = \frac{v_L y_{R0}}{\Lambda}$ and $z = \frac{y_R}{y_{R0}}$

2.3 Neutrinoless double beta decay(NDBD)in LRSM:

There are many new contributions to the NDBD process arises due to the presence of extended scalar sector with particle such as triplet scalars and Higgs bidoublet in the scheme of LRSM [80, 82, 150, 81, 151]. NDBD process implies lepton number violation, which is directly related to the issue of the nature of the neutrinos. Because of this reason, the phenomenological importance of the NDBD process in neutrino physics is very high. In our work, we have studied different contributions to the NDBD process coming from different particles of LRSM in a flavor symmetry-based model realized by $A_4 \times Z_2$. Many earlier works [152–157] have extensively studied the NDBD process within LRSM in a model independent manner. The effective mass which governs the NDBD process mediated by light neutrino is given by-

$$m_{ee}^\nu = U_{ei}^2 m_{\nu i} \tag{2.10}$$

where, U_{ei} are the elements of the first row of the U_{PMNS}. U_{PMNS} is the mixing matrix which is dependent on parameters such as mixing angle θ_{13},θ_{12},θ_{23} and Dirac CP-violating phase δ along with Majorana phases α and β. The light neutrino mass matrix, m_ν is diagonalized by U_{PMNS}

$$m_\nu = U_{PMNS} M_\nu^{(diag)} U_{PMNS}^T \tag{2.11}$$

where, $M_\nu^{(diag)} = diag(m_1, m_2, m_3)$ and,

$$U_{PMNS} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & -c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{bmatrix} P \tag{2.12}$$

where P is a diagonal matrix containing Majorana phases α and β and given as $P = diag(1, e^{i\alpha}, e^{i\beta})$. We can parameterize the effective Majorana mass in terms of the elements of diagonalizing matrix and the mass eigenvalues as,

$$m_{ee}^\nu = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\alpha} + m_3 s_{13}^2 e^{2i\beta} \tag{2.13}$$

Within the framework of LRSM, the NDBD process receives an additional contribution from extended scalar, vector, and fermionic fields along with the standard contribution coming from light Majorana neutrino exchange. Many of the earlier works [158–161] have explained these contributions to the NDBD process explicitly. We have summarized various contributions to the NDBD transition rate below-

1) Standard contribution to NDBD rate with W_L^- Bosons and light neutrinos as mediator particles. The leptonic mixing matrix elements and light neutrino masses determine the amplitude of this process.

2) Heavy right-handed neutrinos contribute to the NDBD process through W_L^- Bosons. In this process, the amplitude is determined by the mixing between light and heavy neutrinos as well the mass of the heavy neutrinos.

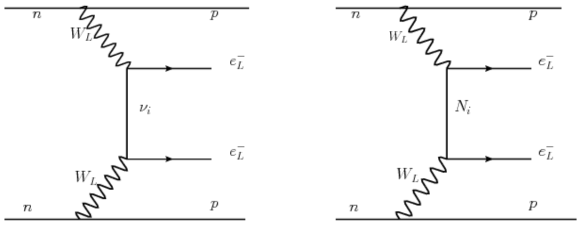


Fig. 2.1 Neutrinoless double beta decay contribution from light and heavy Majorana neutrinos from two W_L exchange.

3) Light neutrino contribution to the NDBD process, mediated by W_R^- Bosons. The amplitude is directly related to the mixing between light and heavy neutrinos as well as the mass of the right-handed gauge boson, W_R^- boson.

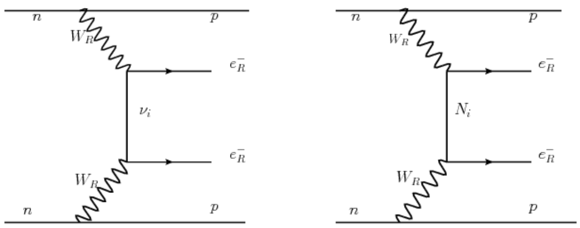


Fig. 2.2 Neutrinoless double beta decay contribution from light and heavy Majorana neutrinos from two W_R exchange

4) The contribution to NDBD comes from heavy right-handed neutrinos where the mediator particles are the W_R^- Bosons. The amplitude of this process can be calculated from the elements of the right-handed leptonic mixing matrix and the mass of the W_R^- boson as well as the mass of the heavy right-handed Majorana neutrinos.

5) There is also a contribution to the NDBD process from light neutrino mediated by gauge bosons, W_L^- and W_R^-. The amplitude of this process can be calculated from mixing between light and heavy mixing, leptonic mixing element, and mass of the light neutrino and W_L^- and W_R^- Boson.

6) New contribution to the NDBD process comes from heavy neutrino mediated by gauge bosons, W_L^- and W_R^-. The amplitude of this process can be calculated from mixing between

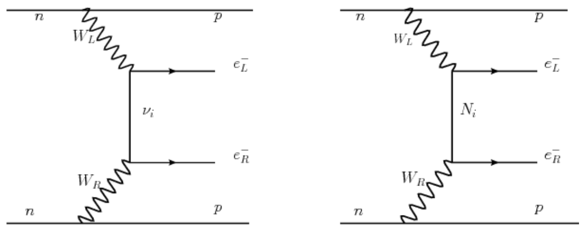


Fig. 2.3 Neutrinoless double beta decay contribution from light and heavy Majorana neutrino intermediate states from both left and right-handed gauge bosons exchange at each vertex.

light and heavy mixing, right-handed leptonic mixing element, and mass of heavy neutrino and W_L^- and W_R^- Boson.

7) The contribution to the NDBD process from left-handed triplet Higgs $\triangle_L$ is mediated by W_L^- bosons. The amplitude of the process can be evaluated from masses of the W_L^- bosons, left-handed triplet Higgs, $\triangle_L$ as well as their coupling to leptons.

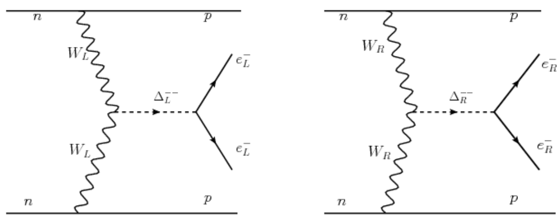


Fig. 2.4 Neutrinoless double beta decay contribution from the charged Higgs intermediate states from W_L and W_R exchange.

8) The contribution to the NDBD process from right-handed triplet Higgs $\triangle_R$ is mediated by W_R^- bosons. The amplitude of the process can be evaluated from masses of the W_L^- bosons, right-handed triplet Higgs, $\triangle_R$ as well as their coupling to leptons.

Although there are a total of eight contributions to the NDBD process in the LRSM, we will consider only three of the above-mentioned contribution in our work. The first one is the standard light neutrino contribution via exchange of W_L^- and the other two are the new contribution to the NDBD process through exchange of W_R^- and Δ_R respectively. In this work, we have assumed that the mass of the heavy particles is in the same range i.e. at the TeV scale ($M_R \approx M_{W_R} \approx M_{\Delta_L^{++}} \approx M_{\Delta_R^{++}} \approx TeV$), which is experimentally verifiable. Under this approximation, the light and heavy contribution remain very negligible as the amplitude of the process is proportional to $\frac{m_D^2}{M_R}$ (As, $m_\nu \approx \frac{m_D^2}{M_R} \approx (0.01-0.1)eV$, $m_D \approx (10^5-10^6)eV$ which implies $\frac{m_D}{M_R} \approx (10^{-7}-10^{-6})$ eV). Thus, we can overlook the contribution coming from light-heavy mixing to the NDBD process in this assumption. The mixing between W_L and W_R bosons also gets suppressed under the same approximation as the amplitude of the process becomes more negligible. From a theoretical point of view, Δ_R mediated process can contribute to the mass of W_R in the TeV scale. Considering the LFV constraints, it is found that almost all the parameter space $\frac{M_N}{M_\Delta} < 0.1$ and thus contributions from Δ_R can be ignored. However, we have considered the case $M_N \approx M_\Delta$. In the next section, we discussed lepton flavor violation in the framework of LRSM and after that, we present a detailed analysis of our work and we have divided it into different subsections, firstly the standard light neutrino contribution to NDBD and then the new physics contribution to NDBD considering both type-I and then type-II dominant cases. And we have also tested our model by incorporating LFV constraints coming from different relevant experiments.

2.4 Lepton flavor violation:

LFV [162–164] and its phenomenological implications have been one of the most focused areas of research in the field of high energy physics both theoretically and experimentally. The most discussed and prominent low-energy LFV decay channels are $\mu \to e\gamma$, $\mu \to 3e$, and $\mu \to e$ conversion in the nuclei. These decays are experimentally analyzable in the current standard. The analytical expression of branching ratios(BR) [161] of these decays can be given as-

$$BR_{\mu\to e\gamma} = \frac{\Gamma(\mu^+ \to e^+\gamma)}{\Gamma_\mu} \tag{2.14}$$

$$BR^{Z}_{\mu\to e} = \frac{\Gamma(\mu^- + A(N,Z) \to e^- + A(N,Z)}{\Gamma^{Z}_{capt}} \tag{2.15}$$

$$BR_{\mu\to 3e} = \frac{\Gamma(\mu^+ \to e^+ e^- e^+)}{\Gamma_\nu} \tag{2.16}$$

In our model, we have considered $\mu \to e\gamma$ and $\mu \to 3e$ decays. The SINDRUM experiment [165] has put the constraint branching ratio of the process $\mu \to 3e$ to be $< 1.0 \times 10^{-12}$. This bound is expected to improve by four orders in Mu3e collaboration [121]. The constraint on the process $\mu \to e\gamma$ is $< 4.2 \times 10^{-13}$ given by the MEG collaboration [41]. Considering different contributions coming from heavy right-handed neutrinos and Higgs scalars, the expected branching ratios and conversion rates of the LFV processes are calculated from the model for analysis in this work.

For the process $\mu \to 3e$, branching ratio is given by-

$$BR_{\mu\to 3e} = \frac{1}{2}|h_{\mu e} h^*_{ee}|^2 \left(\frac{m_{W_L^4}}{M^4_{\Delta_L^{++}}} + \frac{m_{W_R^4}}{M^4_{\Delta_R^{++}}} \right) \tag{2.17}$$

where h_{ij} stands for lepton Higgs coupling in the LRSM, given by-

$$h_{ij} = \sum_{n=1}^{3} V_{in} V_{jn} \left(\frac{M_n}{M_{W_R}} \right), i,j = e,\mu,\tau \tag{2.18}$$

Now, the branching ratio of $\mu \to e\gamma$ process is given by-

$$BR_{\mu\to e\gamma} = 1.5 \times 10^{-7} |g_{lfv}|^2 \left(\frac{1TeV}{M_{W_R}} \right)^4 \tag{2.19}$$

where g_{lfv} is defined as-

$$g_{lfv} = \sum_{n=1}^{3} V_{\mu n} V^*_{en} \left(\frac{M_n}{M_{W_R}} \right)^2 = \frac{\left[M_R M_R^* \right]_{\mu e}}{M_{W_R}} \tag{2.20}$$

This equation is summed over heavy neutrino. V is the right-handed neutrino mixing matrix and $M^{++}_{\Delta_{L,R}}$ are the mass of doubly charged boson.

2.5 Numerical analysis and Results:

In our present work, we have constructed a flavor symmetric model for both type-I and type-II dominance and studied LNV (NDBD) for standard as well as non-standard contributions for the effective mass as well as the half-life governing the decay process along with different LFV processes in the framework of LRSM. We also checked the consistency of the model by varying different neutrino oscillation parameters with the light neutrino contribution to the effective mass coming from the model for both type-I and type-II dominant cases. In this section, we present a detailed analysis of our work and we have divided it into different subsections, firstly the standard light neutrino contribution to NDBD and then the new physics contribution to NDBD considering both type II and then type I dominance case. We have also studied lepton flavor violating processes such as $\mu \rightarrow 3e$ and $\mu \rightarrow e\gamma$ and correlated with neutrino mass within the model.

2.5.1 Standard light neutrino contribution:

The effective mass governing the process is as given in equation (2.10) for NDBD mediated by the light Majorana neutrinos. We first evaluated the effective light neutrino mass within the standard mechanism using the formula (2.10) where U_{Li} are the elements of the first row of the neutrino mixing matrix. U_{PMNS} is the mixing matrix i.e the diagonalizing matrix of m_ν,

$$m_\nu = U_{PMNS} {M_\nu}^{(diag)} {U_{PMNS}}^T \tag{2.21}$$

where $M_\nu^{diag} = diag(m_1, m_2, m_3)$. For three generations of neutrino, there are two possible neutrino mass hierarchy

1) Normal Hierarchy (NH) stands for $m_1 < m_2 << m_3; \Delta m_{12}^2 << \Delta m_{23}^2$

1) Inverted Hierarchy (IH) is nothing but $m_3 << m_1 \approx m_3; \Delta m_{12}^2 << |\Delta m_{13}^2|$

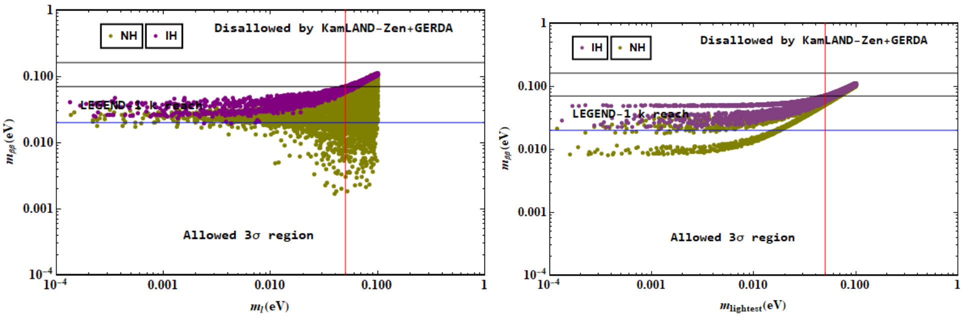


Fig. 2.5 The light neutrino contribution to neutrinoless double beta decay process for typeI(left) and typeII(right) considering both NH and IH cases. The band of two black solid line and the red solid line represents the KamLAND-Zen bound on the effective mass and the Planck bound on the sum of the absolute neutrino mass respectively. And, the blue line represent the future sensitivity on effective mass in Legend-1k reach [166].

$\Delta m^2_{12} = \Delta m^2_{solar}$ for both the mass ordering. $\Delta m^2_{23} = \Delta m^2_{atm}$ in case of NH and for IH,$|\Delta m^2_{13}| = \Delta m^2_{atm}$

The neutrino masses m_2 and m_3 are connected with the lightest mass m_1 in case of NH by the relation,

$$m_2 = \sqrt{m_1^2 + \Delta m^2_{solar}}; m_3 = \sqrt{m_1^2 + \Delta m^2_{solar} + \Delta m^2_{atm}}$$

In the case of IH, the lightest mass is m_3 and can be related to m_1 and m_2,

$$m_1 = \sqrt{m_3^2 + \Delta m^2_{atm}}; m_2 = \sqrt{m_3^2 + \Delta m^2_{solar} + \Delta m^2_{atm}}$$

We have computed the light neutrino mass matrix from the model described at the beginning for both type-I and type-II cases, which are-

$$m_\nu(type-I) = \frac{m}{3z+1}\begin{pmatrix} z+1 & \omega z r_1 & \omega^2 z r_2 \\ \omega z r_1 & \omega^2 \frac{z(3z+2)r_2^2}{3z-1} & \frac{(z-3z^2+1)r_1 r_2}{1-3z} \\ \omega^2 z r_2 & \frac{(z-3z^2+1)r_1 r_2}{1-3z} & \frac{\omega z(3z+2)r_2^2}{3z-1} \end{pmatrix}$$

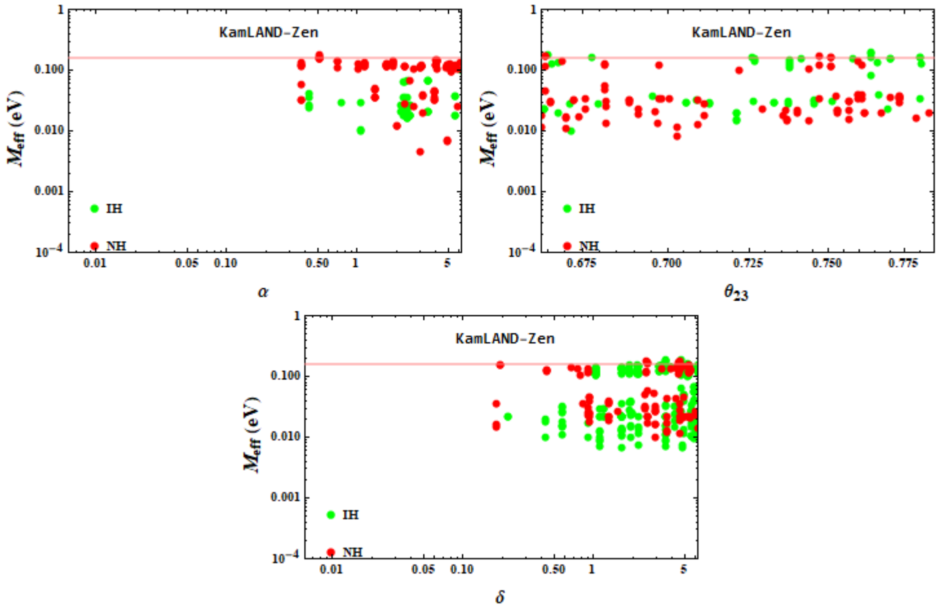


Fig. 2.6 Variation of α, θ_{23} and δ with effective mass for type-II dominance case.

$$m_\nu(type-II) = a_L \begin{pmatrix} 2z & -\omega^2 z & 1-\omega z \\ -\omega^2 z & 1+2\omega z & -z \\ 1-\omega z & -z & 2\omega^2 z \end{pmatrix}$$

As discussed before, the structures of the different matrices involved are formed using the discrete flavor symmetry $A_4 \times Z_2$ and we obtain the resulting light neutrino mass matrix. The light neutrino mass matrix arising from the model is consistent with non-zero θ_{13} as A_4 product rules lead to the light neutrino mass matrix in which the $\mu - \tau$ symmetry is explicitly broken. Using the 3σ [36] ranges of the neutrino oscillation parameters we solve for the different model parameters of the model. Then we calculated the effective mass for both cases. The effective mass assumes different values depending on whether the neutrino mass states follow a normal hierarchy (NH) or inverted hierarchy (IH). The variation is shown in Fig2.5. It is seen from the figure that the light neutrino contribution to the NDBD process can saturate the bound imposed by KamLAND-ZEN. It is observed that, for type-I and

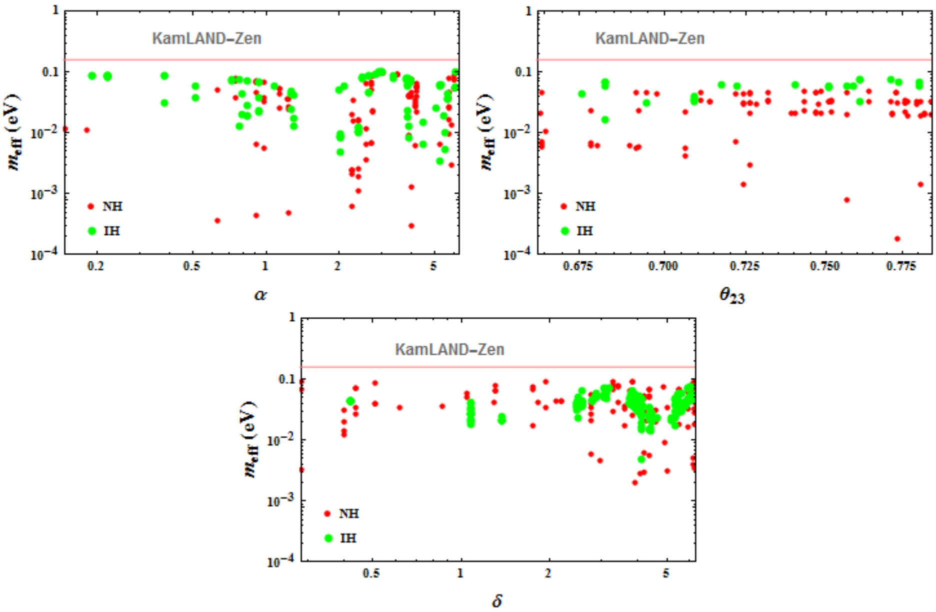


Fig. 2.7 Variation of α,θ_{23} and δ with effective mass for type-I dominance case.

type-II dominant case, the effective mass governing NDBD is found to be of the order of $10^{-3}-10^{-1}$ eV in case of the NH and for the IH it is found to be $10^{-2}-10^{-1}$ eV and are within and much below the current experimental limit. However, in all the cases, the light neutrino contribution can saturate the experimental limit for the lightest neutrino mass (m1/m3) for (NH/IH) of around 0.1 eV.

In light of standard light neutrino contribution to the effective mass, we varied different neutrino oscillation parameters to check the viability of the model. In Fig2.6 and Fig2.7, we have shown different variational plots of neutrino oscillation parameters with effective mass for type-II and type-I dominant cases. From these plots, we can say that the parameters Majorana phase α, mixing angle θ_{23} and CP-violating phase δ are well within the experimental limits.

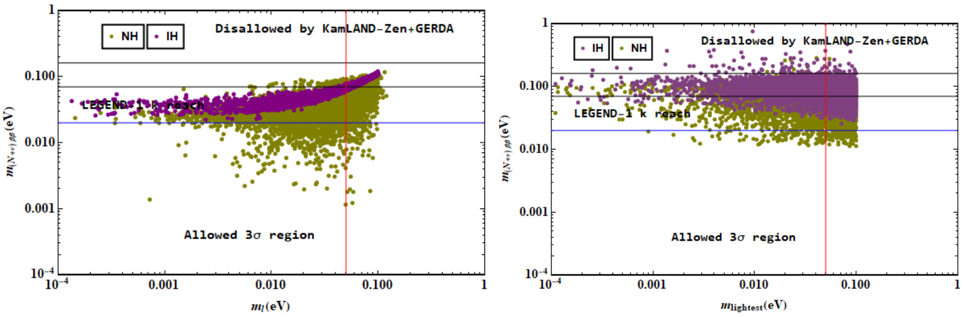


Fig. 2.8 The total contribution to neutrinoless double beta decay process considering new physics contribution coming from heavy neutrino i.e $|m_{N+\nu}{}^{eff}|$ for type-I(left) and type-II(right) considering both NH and IH cases. The band of two black solid line and the red solid line represents the KamLAND-Zen bound on the effective mass and the Planck bound on the sum of the absolute neutrino mass respectively. And, the blue line represent the future sensitivity on effective mass in Legend-1k reach.

2.5.2 New physics contribution to NDBD:

We have also considered the contribution to NDBD from the right-handed current and triplet Higgs(Δ_R). Although the contribution of the Δ_R can be suppressed if we invoke the constraints from LFV decays. We will discuss this contribution in certain conditions.

The contribution coming from right-handed current can be written as-

$$m_{ee}{}^{N} = p^2 \frac{M_{W_L}{}^4}{M_{W_R}{}^4} \frac{U_{Rei}{}^{*2}}{M_i} \tag{2.22}$$

$< p^2 >= m_e m_p \frac{\mathcal{M}_{\mathcal{N}}}{\mathcal{M}_\nu}$ stands for the typical momentum exchange of the process, where m_p and m_e are the mass of the proton and electron respectively and $\mathcal{M}_{\mathcal{N}}$ is the NME corresponding to the RH neutrino exchange. We have taken the values M_{W_R} = 10 TeV, M_{W_L} = 80 GeV, M_{Δ_R} ≈3TeV, the heavy RH neutrino ≈ TeV which are within the recent collider limits. The allowed value of p, the virtuality of the exchanged neutrino is in the range ∼ (100-200) MeV and we have considered p ≃180 MeV.

Thus,

$$p^2\frac{{M_{W_L}}^4}{{M_{W_R}}^4} \simeq 10^{10} eV^2. \tag{2.23}$$

However, equation (2.23) is valid only in the limit ${M_i}^2 \gg |<p^2>|$ and ${M_\Delta}^2 \gg |<p^2>|$.

The time period governing the NDBD process can be given by

$$\Gamma^{0\nu} = \frac{1}{{T_{\frac{1}{2}}}^{0\nu}} = G^{0\nu}(Q,Z)\left|M^{0\nu}\right|^2 \frac{\left|m_{ee}^{N+\nu}\right|^2}{{m_e}^2}. \tag{2.24}$$

where

$$\left|m_{ee}^{N+\nu}\right|^2 = \left|m_{ee}^{N} + m_{ee}^{\nu}\right|^2. \tag{2.25}$$

To evaluate $m_{ee}^{(N+\nu)}$, we need the diagonalizing matrix of the heavy right-handed Majorana mass matrix M_R, U_{Rei} and its mass eigenvalues, M_i. We have computed the right-handed neutrino mass matrix from the model described for both type-I and type-II cases. Using the values of the model parameters, we evaluated the right-handed current contribution to the NDBD. From this, we calculated the total effective mass for the NDBD process. Variation of lightest neutrino mass with the total new contribution to effective mass and half-life of NDBD process are given in Fig 2.8 and Fig 2.9 for type-I and type-II dominant cases respectively. The total contribution considering new physics contribution from heavy neutrino for type-I and type-II(NH/IH) dominant case and the half-life (Xe-136) of the process shows results within the recent experimental bound for the lightest mass varying from (0.0001-0.1) eV.

2.5.3 Scalar triplet contribution to NDBD:

The Majorana masses of light and heavy neutrinos come naturally in the left-right model because of the two triplets $\Delta_{L,R}$. The contribution from Δ_L is much suppressed as compared to the dominant contributions. However, the Δ_R contribution is controlled by the factor $\frac{M_i}{M_{\Delta_R}}$. In the total contribution, we have not included the contribution due to the triplet Higgs contribution under the assumption $\frac{M_i}{M_{\Delta_R}} < 0.1$, which is obtained from LFV processes.

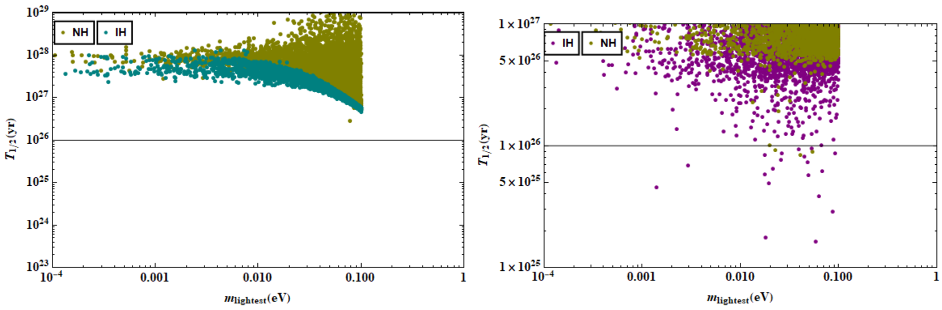


Fig. 2.9 The new physics contribution to half-life of neutrinoless double beta decay process for type-I(left) and type-II(right) considering both NH and IH case. The horizontal line represents the KamLAND-Zen lower bound on the half-life of NDBD.

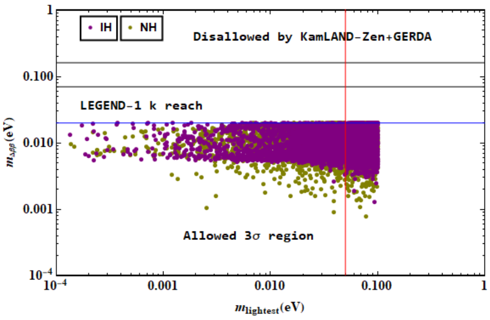
However, this approximation though valid in a large part of the parameter space there are some allowed mixing parameters for which this ratio can be higher. In that case, we need to include this contribution. We discuss the impact of this contribution in the limit, $M_{\Delta_R} = M_{heaviest}$. Now, we can write down the contribution of scalar triplet(Δ_R) to the effective mass as-

$$|m_{ee}^{\Delta}| = |p^2 \frac{{M_{W_L}}^4}{{M_{W_R}}^4} \frac{2M_N}{M_{\Delta_R}}| \tag{2.26}$$

We have evaluated the contribution from scalar triplet to the NDBD process and plotted the contribution of the effective mass due to the triplets with the lightest neutrino mass for type-I and type-II seesaw cases which are given in the Fig 2.10. Scalar triplet contribution for type-I(NH/IH) dominant are found to be in the range 10^{-2} eV and 10^{-3} eV in the light neutrino mass range (0.0001-0.1) eV and for type-II(NH/IH) dominant case it is found to be 10^{-4} eV and 10^{-2} eV in the light neutrino mass range (0.0001-0.1) eV .

2.5.4 Correlating LFV and neutrino mass

We have correlated lightest neutrino mass and LFV constraints for both type-I and type-II dominant cases considering $\mu \to e\gamma$ and $\mu \to 3e$ processes. The BR of these processes has a strong dependency on flavor and heavy neutrino mixing. $\mu \to e\gamma$ process dependent on lepton



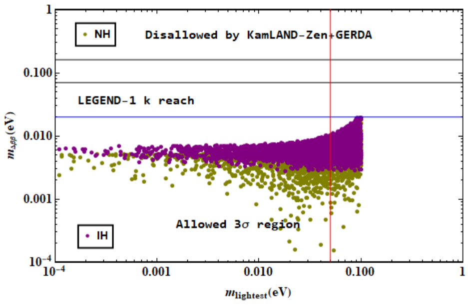


Fig. 2.10 The scalar triplet contribution to neutrinoless double beta decay process for type-I(left) and type-II(right) considering both NH and IH case.The band of two black solid line and the red solid line represents the KamLAND-Zen bound on the effective mass and the Planck bound on the sum of the absolute neutrino mass respectively. And, the blue line represent the future sensitivity on effective mass in Legend-1k reach.

and Higgs coupling whereas $\mu \to 3e$ is controlled by right-handed neutrino mixing. We have used the expression given in (2.17) and (2.19) to calculate the BR. The lepton Higgs coupling h_{ij} can be computed explicitly for a given RH neutrino mass matrix by diagonalizing the RH neutrino mass matrix and obtaining the mixing matrix element, V_i and the eigenvalues M_i. The variation of BR with the lightest neutrino mass for both type-I and type-II dominant cases are shown in the Fig (2.12) and Fig(2.11) respectively. From these plots, it can be inferred that the type-I dominant case shows results that are more consistent with the experimental bounds.

2.6 Summary

In this chapter, we have contemplated the implications of NDBD in the LRSM framework which is realized through $A_4 \times Z_2$ flavor symmetric model. Because of the presence of new scalars and gauge bosons in this model, various additional sources would give rise to contributions to the NDBD process, which involves RH neutrinos, RH gauge bosons, scalar Higgs triplets as well as the mixed LH-RH contributions. We have realized LRSM for both

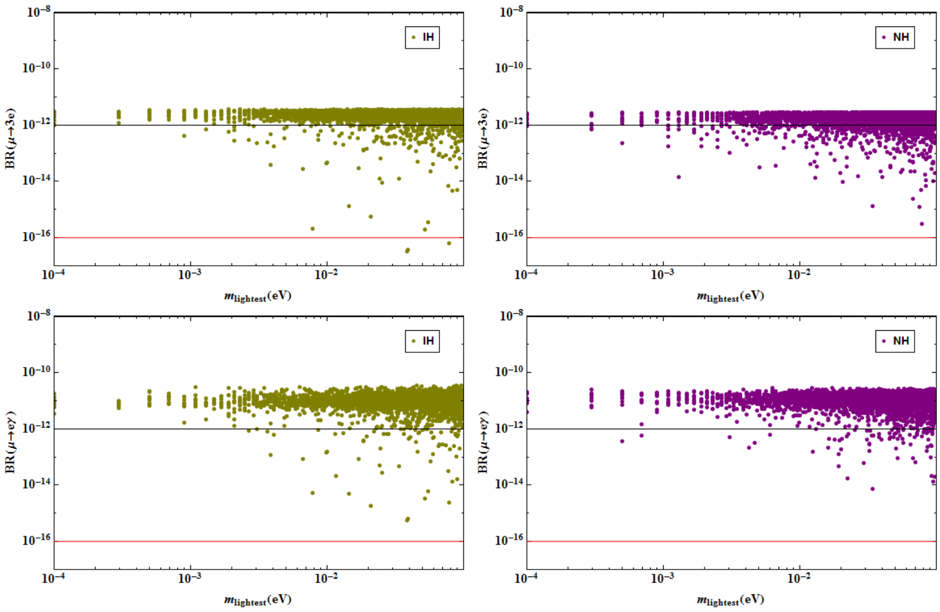


Fig. 2.11 Total contribution to lepton flavour violation shown as a function of the lightest neutrino mass for in case of type-II dominance case for both $\mu \to 3e$ and $\mu \to e\gamma$ .The blue and red horizontal line shows the limit of BR as given by the SINDRUM experiment and the recently proposed limit of $\mu \to 3e$ experiment respectively

type-I and type-II dominant cases. For a simplified analysis, we have ignored the left-right gauge boson mixing and heavy light neutrino mixing. We have assumed the extra gauge bosons and scalars to be of the order of TeV and evaluated all the contributions to the NDBD process under this simplified approximation. The evaluated results are validated with the experimental bounds provided by KamLAND-ZEN and GERDA experiment. In light of standard light neutrino contribution to the effective neutrino mass, we varied different neutrino oscillation parameters to check the viability of the model. Different neutrino oscillation parameters are analyzed with effective neutrino mass calculated from the model for type-II and type-I dominant cases. From these results, we can say that the parameters Majorana phase α, mixing angle θ_{23}, and CP-violating phase δ are well within the experimental limits. We have also checked the consistency of the model by investigating different LFV processes such as $\mu \to e\gamma$ and $\mu \to 3e$ in light of SINDRUM and MEG collaboration. We have analyzed

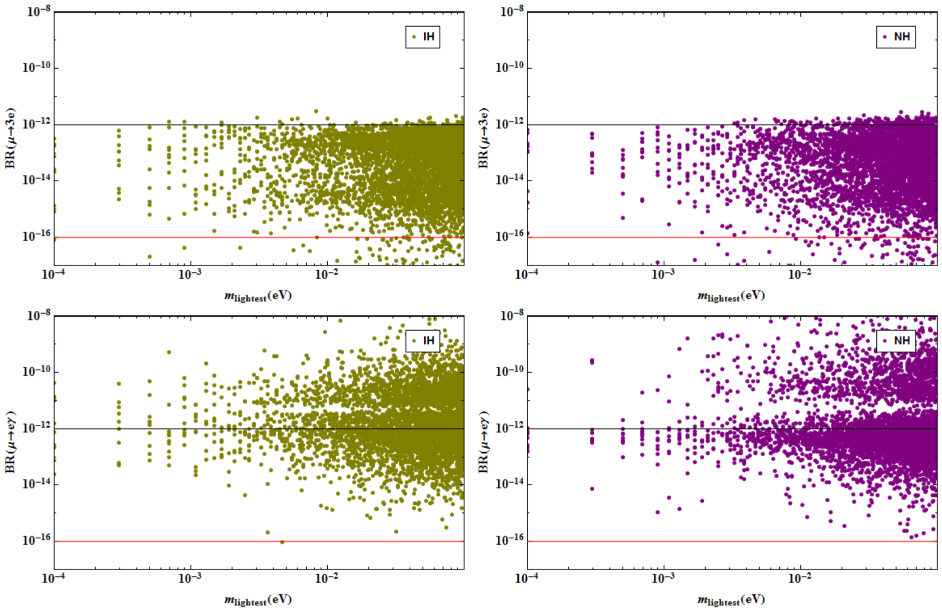


Fig. 2.12 Total contribution to lepton flavour violation shown as a function of the lightest neutrino mass for in case of type-I dominance case for both $\mu \to 3e$ and $\mu \to e\gamma$ .The blue and red horizontal line shows the limit of BR as given by the SINDRUM experiment and the recently proposed limit of $\mu \to 3e$ experiment respectively

the branching ratios of these processes with the lightest neutrino mass for both type-I and type-II dominant cases considering both NH and IH. From the results, it can be inferred that the type-I dominant case shows results that are more consistent with the experimental bounds than the type-II dominant case.