Phenomenology of two texture zero neutrino mass in left-right symmetric model with $Z_8 \times Z_2$

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ABSTRACT: We have done a phenomenological study on the neutrino mass matrix $M_\nu$ favouring two zero texture in the framework of left-right symmetric model (LRSM) where type I and type II seesaw naturally occurs. The type I SS mass term is considered to be following a Trimaximal mixing (TM) pattern. The symmetry realizations of these texture zero structures has been realized using the discrete cyclic abelian $Z_8 \times Z_2$ group in LRSM. We have studied six of the popular texture zero classes named as A1, A2, B1, B2, B3 and B4 favoured by neutrino oscillation datas in our analysis. We basically focused on the implications of these texture zero mass matrices in low energy phenomenon like Neutrinoless double beta decay (NDBD) and lepton flavour violation (LFV) in LRSM scenerio. For NDBD, we have considered only the dominant new physics contribution coming from the diagrams containing purely RH current and another from the charged Higgs scalar while ignoring the contributions coming from the left-right gauge boson mixing and heavy light neutrino mixing. The mass of the extra gauge bosons and scalars has been considered to be of the order of TeV scale which is accessible at the colliders.

KEYWORDS: Discrete flavour symmetry, lepton number violation, lepton flavour violation
1 INTRODUCTION

With the landmark discovery of neutrino oscillation and corresponding realization that neutrinos are massive and they mix during propagation have brought into limelight several interesting consequences like necessity of going beyond the successful standard model (SM). Global analysis of neutrino oscillation data has quite precisely determined the best fit and $3\sigma$ ranges of neutrino parameters, viz., the mixing angles, mass squared differences, the Dirac CP phase $\delta$ [1], but the absolute neutrino mass and the additional CP phase (for Majorana particles) $\alpha$ and $\beta$ are not accurately found yet. Nevertheless several other questions are yet not perceived amongst which notable is understanding the origin and dynamics of the neutrino mass and the lepton flavour structures of the fermions. The role of symmetry in particle physics [2] cannot be overestimated. It is utmost important to understand the underlying symmetry inorder to understand the origin of neutrino mass and the leptonic mixings. Symmetries can relate two or more free parameters or can make them vanish, therby making the model more predictive. One of the possible role flavour symmetry can play is to impose texture zeros [3–7] in the mass matrix and to reduce the number of free parameters. For a symmetric $M_\nu$, it has six independent complex entries. If $n$ of them are considered to be vanishing, we arrive at $6C_n = \frac{6!}{n!(6-n)!}$ different textures. A texture of for $n \geq 3$ is not compatible with current experimental data and neutrino mixing angles. Texture zero approaches has been established as a feasible framework for explaining the fermion masses and mixing data in quark as well as lepton sector and has been studied in details in a large number of past works like [8–16]. Specifically two texture zero mass
matrices are considered to be more interesting as they can reduce maximum number of free parameters. Two independent zeroes in the matrix can lead to four relations among the nine free parameters in the neutrino mass matrix which can be checked against the available experimental data.

In the simplest case one can presume the charged lepton mass matrix to be diagonal and then consider the possible texture zeros in the symmetric Majorana mass matrix. Considering the basis in which charged lepton mass matrix is diagonal there are different categories of two zero texture neutrino mass matrix out of which some are ruled out and some are marginally allowed. Glashow et al.[4] have found seven acceptable textures of neutrino mass matrix (out of total fifteen) with two independent vanishing entries in the flavour basis for a diagonal charged lepton mass matrix to be consistent with current experimental data.

Neutrino mass and mixing matrix have different forms based upon some flavour symmetries. Amongst them, the most popular one which is consistent with neutrino oscillation data is the Tribimaximal mixing (TBM) [17] structure as proposed by Harison, Perkins and Scott. The resulting mass matrix in the basis of a diagonal charged lepton mass matrix is both 2-3 symmetric and magic. By magic, it means the row sums and column sums are all identical. The reactor mixing angle $\theta_{13}$ vanishes in TBM because of the bimaximal character of the third mass Eigen state $\nu_3$. However $\theta_{13}$ has been measured to be non zero by experiments like T2K, Daya Bay, RENO and DOUBLE CHOOZ [18–21], which demands for a correction to the TBM form which may be a correction or some perturbation to this type. Henceforth, owing to the current scenario of neutrino oscillation parameters several new models has been theorized and studied by the scientific communities. Amongst several neutrino mass models, Trimaximal mixing (TM) [22–29] is one in which non zero reactor mixing angle can be realized. The mixing matrix consists of identical second column elements similar to the TBM type. However, it relaxes some of the TBM assumptions, since it allows for a non zero $\theta_{13}$ as well as preserves the solar mixing angle prediction. It will be discussed in details in the section III. Besides the zeros in the neutrino mass matrix which is one of currently studied approaches for precisely explaining neutrino masses and mixing can also be examined using the TM mixing.

Inspite of enormous success, there are several unperceived problems in the neutrino sector which includes the absolute scale of neutrino mass, the mass hierarchy, the CP violation, the intrinsic nature of neutrinos, whether Dirac or Majorana. One of the important process which undoubtedly establish the Majorana nature of neutrinos (violation of lepton number by two units) is neutrinoless double beta decay (NDBD) (for a review see[30]). Besides, the observation of NDBD would also throw light on the absolute scale of neutrino mass and in explaining the matter, anti-matter asymmetry of the universe. The NDBD experiments like KamLAND-Zen, GERDA, EXO-200 [31–33] directly measures and provides bounds on the decay half life which can be converted to the effective neutrino mass parameter, $m_{ee}$ with certain uncertainty which arises due to the theoretical uncertainty in the NME. The current best limits on the effective mass $< m_{ee} >$ are of the order of 100 meV. The next generation experiments targets to increase the sensitivity in the 10 meV mass range. Thus, the future NDBD experiments can shed lights on several issues.
in the neutrino sector. Observing this rare decay process with the current experiments would signify new physics contributions beyond the standard model (SM) other than the standard light neutrino contribution.

There are several BSM frameworks, amongst which one of the most fascinating and modest frameworks in which neutrino mass and other unsolved queries can be addressed is the left right symmetric model (LRSM) [34–36] where the gauge group is $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. It has become a topic of interest since long back owing to its indomitable importance and has been studied in details by several groups in different contexts [37–47]. Herein the type I and type II seesaw arises naturally rather than by hand. The neutrino mass in LRSM can be written as a combination of both the type I and type II seesaw mass terms. A brief review of the LRSM has been presented in the next section. As far as NDBD is concerned, LRSM can give rise to several new physics (non standard) contributions coming from LH, RH, mixed, scalar triplet etc. Several analysis has been done already involving NDBD in LRSM [39–42, 42–45] and their compatibility with LHC experiments [40, 48–51].

As cited by several authors [28, 29], the TM mixing can satisfy the current neutrino experimental datas when combined with two zero textures. In this context, we have done a phenomenological study on the neutrino mass matrix $M_\nu$ favouring two zero texture in the framework of LRSM where type I and type II seesaw naturally occurs. The type I SS mass term is considered to be following a TM mixing pattern. The symmetry realizations of these texture zero structures has been realized using the discrete cyclic abelian ($Z_8 \times Z_2$) group in LRSM. In order to obtain the desired two zero textures of the Dirac and Majorana mass matrices, we have added two more LH and RH scalar triplets each. In our analysis, we have studied for the popular 6 texture zero classes being named as A1-A2 and B1-B4. We basically focused in the implications of these texture zero mass matrices in low energy phenomenon like NDBD and LFV in LRSM scenerio. For NDBD, we have considered only the dominant new physics contribution coming from the diagrams containing purely RH current mediated by the heavy gauge boson, $W_R$ by the exchange of heavy right handed neutrino, $N_R$ and another from the charged Higgs scalars mediated by the heavy gauge boson $W_R$ ignoring the contributions coming from the left-right gauge boson mixing and heavy light neutrino mixing as in our previous work [52]. The mass of the extra gauge bosons and scalars has been considered to be of the order of TeV accessible at the colliders.

The paper has been organized as follows, in the next section we briefly review the LRSM, its particle contents along with texture zero and TM mixing. In section III we present the symmetry realizations of these classes by using a cyclic $Z_8 \times Z_2$ group symmetry with possible particle contents in LRSM to obtain the desired texture zero matrices. Then in section IV we discuss NDBD and LFV in the framework of LRSM which is followed by the numerical analysis and results with the collider signatures in section V. We give the conclusion in section VI.
2 MINIMAL LEFT-RIGHT SYMMETRIC MODEL AND TWO ZERO TEXTURE NEUTRINO MASS

As has been mentioned before LRSM is based on the gauge group SU(3)_c × SU(2)_L × SU(2)_R × U(1)_{B–L} [34–36], a simple extension of the standard model gauge group where parity is conserved at a very high scale. The spontaneous breaking of the left right symmetry then ensures violation of parity as observed at low energy scales. The usual type I and II seesaw are a necessary part of LRSM. The RH neutrinos are a necessary part of LRSM which acquires a Majorana mass when the SU(2)_R symmetry is broken at a scale v_R.

2.1 PARTICLE CONTENTS:

\[ Q'_{L,R} = \begin{bmatrix} u' \\ d' \end{bmatrix}_{L,R}, \quad \Psi_{L,R} = \begin{bmatrix} \nu_i \\ l \end{bmatrix}_{L,R}, \]

which are the quarks and leptons under LRSM where the quarks are assigned with quantum numbers (3, 2, 1, 1/3) and (3, 1, 2, 1/3) and leptons with (1, 2, 1, –1) and (1, 1, 2, –1) respectively under SU(3)_c × SU(2)_L × SU(2)_R × U(1)_{B–L}. The Higgs sector in LRSM consists of the following multiplets,

\[ \phi = \begin{bmatrix} \phi_1^0 & \phi_2^0 \\ \phi_2^- & \phi_1^- \end{bmatrix}, \quad \Delta_{L,R} = \begin{bmatrix} \delta_{L,R}^0 & \delta_{L,R}^{++} \\ \delta_{L,R}^+ & -\delta_{L,R}^{-+} \end{bmatrix}. \]

A bi-doublet with quantum number \( \phi(1, 2, 2, 0) \) and the SU(2)_{L,R} triplets, \( \Delta_L(1, 2, 1, -1), \Delta_R(1, 1, 2, -1) \). The successive spontaneous symmetry breaking occurs as, SU(2)_L×SU(2)_R×U(1)_{B–L} \( \overset{\text{\( \Delta_R \)\, \( \phi \)}}{\longrightarrow} \) SU(2)_L × U(1)_Y \( \overset{\text{\( \phi \)}}{\longrightarrow} \) U(1)_em. The neutral component of the Higgs fields obtains a vacuum expectation value (vev), \( \langle \phi^0_R \rangle = v_R, \langle \phi^0_L \rangle = v_L, \langle \phi_1^- \rangle = k_1 \) and \( \langle \phi_2^- \rangle = k_2 \) thereby providing masses for the the extra gauge bosons (W_R and Z') and for right handed neutrino field (ν_R), W_L and Z bosons, Dirac masses for the quarks and leptons respectively. The vev of \( \Delta_L, v_L \) plays a significant role in the SS relation which is the characteristics of the LRSM and can be written as, \( \langle \Delta_L \rangle = v_L = \frac{\gamma k^2}{v_R} \).

The Yukawa Lagrangian in the lepton sector is given by,

\[ \mathcal{L} = h_{ij} \overline{\Psi}_{L,i} \phi \Psi_{R,j} + \overline{\tilde{\Psi}}_{L,i} \tilde{\phi} \Psi_{R,j} + f_{L,ij} \Psi_{L,i}^T C i \sigma_2 \Delta_L \Psi_{L,j} + f_{R,ij} \Psi_{R,i}^T C i \sigma_2 \Delta_R \Psi_{R,j} + h.c., \]

where, the indices \( i, j = 1, 2, 3 \) represents the three generations of fermions. \( C = i \gamma_2 \gamma_0 \) is the charge conjugation operator, \( \tilde{\phi} = \tau_2 \phi^* \tau_2 \) and \( \gamma_\mu \) are the Dirac matrices. Considering discrete parity symmetry, the Majorana Yukawa couplings \( f_L = f_R \). Equation (3.20) leads to 6 × 6 neutrino mass matrix as,

\[ M_\nu = \begin{bmatrix} M_{LL} & M_D \\ M_D^T & M_{RR} \end{bmatrix}, \]

where

\[ M_D = \frac{1}{\sqrt{2}}(k_1 h + k_2 \tilde{h}), \]

\[ M_{LL} = \sqrt{2} \nu_L f_L, M_{RR} = \sqrt{2} \nu_R f_R, \]
\[ M_L, M_{LL} \text{ and } M_{RR} \text{ being the Dirac neutrino mass matrix, left handed and right handed Majorana mass matrix respectively. Assuming } M_L \ll M_D \ll M_R, \text{ the light neutrino mass, generated within a type I+II seesaw can be written as,} \]

\[ M_\nu = M_{\nu}^I + M_{\nu}^{II}, \quad (2.6) \]

\[ M_\nu = M_{LL} + M_D M_{RR}^{-1} M_D^T = \sqrt{2} v_L f_L + \frac{k^2}{\sqrt{2} v_R} h_D f_R^{-1} h_D^T. \quad (2.7) \]

Where the first and second terms in equation (2.7) corresponds to type II seesaw and type I seesaw respectively. Here,

\[ h_D = \frac{(k_1 h + k_2 \tilde{h})}{\sqrt{2k}}, \quad k = \sqrt{|k_1|^2 + |k_2|^2} \quad (2.8) \]

In [53], authors introduced a dimensionless parameter \( \gamma \) as,

\[ \gamma = \frac{\beta_1 k_1 k_2 + \beta_2 k_1^2 + \beta_3 k_2^2}{(2 \rho_1 - \rho_3) k^2}, \quad (2.9) \]

with the terms \( \beta, \rho \) being the Higgs potential parameters. The VEV for left handed triplet \( v_L \) can be then be written as,

\[ v_L = \gamma \frac{M_W^2}{v_R}, \quad M_W = \frac{g k}{2} \quad (2.10) \]

Both type I and type II seesaw terms can be written in terms of \( M_{RR} \) in LRSM. Thus equation (2.7) can be written as,

\[ M_\nu = \gamma \left( \frac{M_W}{v_R} \right)^2 M_{RR} + M_D M_{RR}^{-1} M_D^T. \quad (2.11) \]

2.2 TWO ZERO TEXTURE AND TM MIXING

Non vanishing \( \theta_{13} \) excluded \( \mu - \tau \) symmetry to be an exact symmetry of the neutrino mass matrix which opts for a perturbation in \( \mu - \tau \) symmetric mass matrix or a different form which gives rise to non zero \( \theta_{13} \). Going through literature, we have seen that another form of symmetry known as magic symmetry can serve the purpose [54]. The corresponding mass matrix known as magic symmetric mass matrix can be made more predictive by imposing certain constraints in it. Adding zeroes in certain elements of the matrix can make it more anticipating. Certain types of one zero and two zero textures in neutrino mass matrix are consistent with neutrino data. We here study two zero texture zeros in neutrino mass matrix \( M_\nu \) which was first considered in[4, 5] and subsequently by several other groups [6–8, 10–14, 55, 56]. Trimaximal mixing (TM) in two texture zero has been extensively studied in literature [28, 29]. In TM, \( \mu - \tau \) symmetry is broken but the magic symmetry is kept intact. It has been again named as TM\(_1\) or TM\(_2\) based upon whether the second or the first column of the TBM mixing matrix remains intact respectively. We have studied these allowed texture zeros in the magic neutrino mass matrix (satisfying
TM$_2$ mixing) which is the type I SS mass term in our case and studied its implications for low energy processes like NDBD and LFV. Two zero textures ensures two independent vanishing entries in the neutrino mass matrix. There are a total of $6C_2$ i.e., 15 texture zeros of $M_\nu$ which has been further classified into 6 sub categories and can be named as- A1, A2; B1, B2, B3, B4; C1; D1, D2; E1, E2, E3; F1, F2, F3. Out of the above, E1-E3; F1-F3 were ruled out, D1,D2 are marginally allowed and now has been experimentally ruled out at 3$\sigma$ level. We are only left with 7 allowed cases of 2 zero textures, viz., A1-A2; B1-B4 and C1, we are concerned with six of the above classes which are of the form ,

$$A_1 = \begin{bmatrix} 0 & 0 & X \\ 0 & X & X \\ X & X & X \end{bmatrix}, \quad A_2 = \begin{bmatrix} 0 & X & 0 \\ X & X & X \\ 0 & X & X \end{bmatrix} \quad (2.12)$$

$$B_1 = \begin{bmatrix} X & X & 0 \\ X & 0 & X \\ 0 & X & X \end{bmatrix}, \quad B_2 = \begin{bmatrix} X & 0 & X \\ 0 & X & X \\ 0 & 0 & X \end{bmatrix}, \quad B_3 = \begin{bmatrix} X & 0 & X \\ 0 & 0 & X \\ X & X & X \end{bmatrix}, \quad B_4 = \begin{bmatrix} X & X & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \quad (2.13)$$

The neutrino mass matrix is said to be invariant under a magic symmetry and the corresponding mixing symmetry is known as trimaximal mixing (TM) with the TM$_2$ mixing matrix given by (cite),

$$U_{TM2} = \begin{bmatrix} \sqrt{\frac{2}{3}} \cos \theta + \frac{1}{\sqrt{3}} \exp(i\phi) \sin \theta & \frac{1}{\sqrt{3}} \exp(-i\phi) \sin \theta & \frac{1}{\sqrt{3}} \exp(i\phi) \sin \theta \\ -\frac{1}{\sqrt{6}} \cos \theta - \frac{1}{\sqrt{3}} \sin \theta & \frac{1}{\sqrt{3}} \sin \theta & \frac{1}{\sqrt{3}} \sin \theta \\ -\frac{1}{\sqrt{6}} \sin \theta - \frac{1}{\sqrt{3}} \cos \theta & \frac{1}{\sqrt{3}} \cos \theta & \frac{1}{\sqrt{3}} \cos \theta \end{bmatrix}, \quad (2.14)$$

where $\theta$ and $\phi$ being the free parameters. It diagonalizes the magic neutrino mass matrix, which can be parameterized as,

$$M_{\text{magic}} = \begin{bmatrix} p & q & r \\ q & r & p + r - s \\ r & p + r - s & q - r + s \end{bmatrix} \quad (2.15)$$

The different allowed classes of two zero texture along with their respective constraint equations are as shown below: Using these constraint equations, we can arrive at the different classes of two zero textured neutrino mass matrix favouring TM$_2$ mixing.
3 SYMMETRY REALIZATIONS IN LRSM

Several earlier works [6–8, 10–14, 55, 56] have explained two zero texture which has been explored beyond standard model to address neutrino masses and mixing. In this work, we have extended the minimal left-right symmetric model by introducing two more left handed and right handed scalar triplets represented by $\Delta_L', \Delta_L''$ and $\Delta_R', \Delta_R''$ respectively to realize the desired textures of Dirac and Majorana mass matrix, $M_D$ and $M_{RR}$ while keeping in mind that the charged lepton mass matrix is diagonal. The symmetry realizations of these texture zero structures has been worked out using the discrete abelian $(Z_8 \times Z_2)$ group in the framework of LRSM which are explained below.

**Class A1:**
The symmetry realization for the class A1 is shown in tabular form as below,

| $l_L$ | $Z_8 \times Z_2$ | $l_R$ | $Z_8 \times Z_2$ | Higgs(LH) | $Z_8 \times Z_2$ | Higgs(RH) | $Z_8 \times Z_2$ |
|-------|-----------------|-------|-----------------|-----------|-----------------|-----------|-----------------|
| $l_{Le}$ | $(\omega^6, -1)$ | $l_{Re}$ | $(\omega^6, -1)$ | $\Delta_L$ | $(\omega^7, 1)$ | $\Delta_R$ | $(\omega, 1)$ |
| $l_{L\mu}$ | $(\omega^3, -1)$ | $l_{R\mu}$ | $(\omega^3, -1)$ | $\Delta_L'$ | $(\omega^2, 1)$ | $\Delta_R'$ | $(\omega^6, 1)$ |
| $l_{L\tau}$ | $(\omega^3, -1)$ | $l_{R\tau}$ | $(\omega^3, -1)$ | $\Delta_L''$ | $(\omega^2, -1)$, $\Delta_R''$ | $(\omega^6, -1)$ |

**Table 1. Particle assignments for A1**

In all the classes the bidoublets $\phi$ and $\tilde{\phi}$ transforms as singlets $(1 \times 1)$ under the cyclic group $Z_8 \times Z_2$. The diagonal Dirac and the charged lepton mass term(which is same for all the cases), in the matrix form can be written as,

$$ M_D = \begin{bmatrix} 1 & \omega^3 & \omega^3 \\ \omega^5 & 1 & -1 \\ \omega^5 & -1 & 1 \end{bmatrix} + \begin{bmatrix} 1 & \omega^3 & \omega^3 \\ \omega^5 & 1 & -1 \\ \omega^5 & -1 & 1 \end{bmatrix} = 2 \begin{bmatrix} 1 & \omega^3 & \omega^3 \\ \omega^5 & 1 & -1 \\ \omega^5 & -1 & 1 \end{bmatrix} \approx \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (3.1) $$

The corresponding Dirac Yukawa Lagrangian for all the cases can be written as,

$$ \mathcal{L}_D = Y_{ee} \bar{L}_{Le} \phi L_{Re} + Y_{e\mu} \bar{L}_{Le} \phi L_{R\mu} + Y_{e\tau} \bar{L}_{Le} \phi L_{R\tau} + Y_{\mu\mu} \bar{L}_{L\mu} \phi L_{R\mu} + Y_{\mu\tau} \bar{L}_{L\mu} \phi L_{R\tau} + Y_{\tau\tau} \bar{L}_{L\tau} \phi L_{R\tau} \quad (3.2) $$

Under these symmetry realizations, we get the Majorana mass terms (LH and RH) and the type I SS mass terms for the class A1, in the matrix form as,

$$ M_{RR} = \begin{bmatrix} \omega^5 & -1 & 1 \\ -1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}, \quad M_{LL} = \begin{bmatrix} \omega^3 & -1 & 1 \\ -1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}, \quad M^l = \begin{bmatrix} 0 & 0 & x \\ 0 & x & x \\ x & x & x \end{bmatrix} \quad (3.3) $$

The Majorana Yukawa Lagrangian (LH and RH) for A1 is thus given as,

$$ \mathcal{L}_{MR} = Y_{R\tau e} L_{Re}^T \Delta_R' L_{R\tau} + Y_{R\tau \tau} L_{Re}^T \Delta_R' L_{R\tau} + Y_{R\mu \mu} L_{R\mu}^T \Delta_R' L_{R\mu} + Y_{R\mu e} L_{R\mu}^T \Delta_R' \sigma L_{Re} + Y_{R\mu \tau} L_{R\mu}^T \Delta_R' \sigma L_{R\tau} + Y_{R\tau \mu} L_{R\tau}^T \Delta_R' \sigma L_{R\mu} + Y_{R\tau \tau} L_{R\tau}^T \Delta_R' \sigma L_{R\tau}. \quad (3.4) $$
\[
\mathcal{L}_{\text{MC}} = Y_{L\ell} L_{\ell} e^T \Delta_L L_{\ell \ell} + Y_{L\tau} L_{\tau} e^T \Delta_L L_{\ell \ell} + Y_{L\mu} L_{\mu} e^T \Delta_L L_{\ell \ell} +
\]
\[
Y_{L\nu} L_{\nu} e^T \Delta_L L_{\ell \ell} + Y_{L\mu} L_{\mu} e^T \Delta_L L_{\ell \ell} + Y_{L\tau} L_{\tau} e^T \Delta_L L_{\ell \ell} .
\]

Class A2:

For the class A2, to get the desired texture zero structures for the mass matrices, the following symmetry realization has been adopted.

| \(l_L\) | \(Z_8 \times Z_2\) | \(l_R\) | \(Z_8 \times Z_2\) | Higgs(LH) | \(Z_8 \times Z_2\) | Higgs(RH) | \(Z_8 \times Z_2\) |
|---|---|---|---|---|---|---|---|
| \(l_{Le}\) (\(\omega^0, -1\)) | \(l_{Re}\) (\(\omega^0, -1\)) | \(\Delta_L\) | \(\Delta_L\) | \(\omega^3\) | \(\omega^3\) | \(\omega^3\) | \(\omega^3\) |
| \(l_{L\mu}\) (\(\omega^0, 1\)) | \(l_{R\mu}\) (\(\omega^0, 1\)) | \(\Delta_L\) | \(\Delta_L\) | \(\omega^3\) | \(\omega^3\) | \(\omega^3\) | \(\omega^3\) |
| \(l_{L\tau}\) (\(\omega^0, -1\)) | \(l_{R\tau}\) (\(\omega^0, -1\)) | \(\Delta_L\) | \(\Delta_L\) | \(\omega^3\) | \(\omega^3\) | \(\omega^3\) | \(\omega^3\) |

Table 2. Particle assignments for A2

The Majorana mass terms (LH and RH) and the type I SS mass terms, in the matrix form has been obtained as,

\[
M_{RR} = \begin{bmatrix} \omega^4 & 1 & -1 \\ 1 & 1 & 1 \\ -1 & 1 & 1 \end{bmatrix}, M_{LL} = \begin{bmatrix} \omega^3 & 1 & -1 \\ 1 & 1 & 1 \\ -1 & 1 & 1 \end{bmatrix}, M^I = \begin{bmatrix} 0 & 0 \\ \times & \times \\ 0 & \times \end{bmatrix}.
\]

The corresponding Majorana Yukawa Lagrangian (LH and RH) for A2 is,

\[
\mathcal{L}_{\text{MC}} = Y_{R\mu} R_{\mu} e^T \Delta_R R_{\mu \mu} + Y_{R\mu} R_{\mu} e^T \Delta_R R_{\mu \mu} + Y_{R\mu} R_{\mu} e^T \Delta_R R_{\mu \mu} +
\]
\[
Y_{R\tau} R_{\tau} e^T \Delta_R R_{\tau \tau} + Y_{R\mu} R_{\mu} e^T \Delta_R R_{\mu \mu} + Y_{R\tau} R_{\tau} e^T \Delta_R R_{\tau \tau} .
\]

Class B1:

The symmetry realizations of the particles under \(Z_8 \times Z_2\) for the class B1 are as show in the table below,

| \(l_L\) | \(Z_8 \times Z_2\) | \(l_R\) | \(Z_8 \times Z_2\) | Higgs(LH) | \(Z_8 \times Z_2\) | Higgs(RH) | \(Z_8 \times Z_2\) |
|---|---|---|---|---|---|---|---|
| \(l_{Le}\) (\(\omega, -1\)) | \(l_{Re}\) (\(\omega, -1\)) | \(\Delta_L\) | \(\Delta_L\) | \(\omega^0\) | \(\omega^0\) | \(\omega^0\) | \(\omega^0\) |
| \(l_{L\mu}\) (\(\omega^0, 1\)) | \(l_{R\mu}\) (\(\omega^0, 1\)) | \(\Delta_L\) | \(\Delta_L\) | \(\omega^3\) | \(\omega^3\) | \(\omega^3\) | \(\omega^3\) |
| \(l_{L\tau}\) (\(\omega^0, -1\)) | \(l_{R\tau}\) (\(\omega^0, -1\)) | \(\Delta_L\) | \(\Delta_L\) | \(\omega^3\) | \(\omega^3\) | \(\omega^3\) | \(\omega^3\) |

Table 3. Particle assignments for B1

These transformations leads to the Majorana mass matrices (LH and RH) as,

\[
M_{RR} = \begin{bmatrix} 1 & 1 & \omega^4 \\ 1 & \omega^7 & 1 \\ \omega^4 & 1 & 1 \end{bmatrix}, M_{LL} = \begin{bmatrix} 1 & 1 & \omega^4 \\ 1 & \omega^1 & 1 \\ \omega^4 & 1 & 1 \end{bmatrix}, M^I = \begin{bmatrix} \times & \times & 0 \\ \times & 0 \times \\ 0 \times \times \end{bmatrix}.
\]
The corresponding $Z_8 \times Z_2$ invariant Majorana Yukawa Lagrangian (LH and RH) for B1 is,

$$\mathcal{L}_{MR} = Y_{RRe} L_{Re}^T \Delta_R L_{Re} + Y_{Rr\tau} L_{Rr}^T \Delta_R L_{Rr} + Y_{Rr\mu} L_{Rr}^T \Delta_R' L_{Rr} +$$

$$Y_{R\mu} L_{R\mu}^T \Delta_R'' L_{R\mu}, \quad (3.10)$$

$$\mathcal{L}_{ML} = Y_{LLe} L_{Le}^T \Delta_L L_{Le} + Y_{Lr\tau} L_{Lr}^T \Delta_L L_{Lr} + Y_{Lr\mu} L_{Lr}^T \Delta_L' L_{L\mu} +$$

$$Y_{L\mu} L_{L\mu}^T \Delta_L'' L_{L\mu}, \quad (3.11)$$

**Class B2:**

The symmetry realizations to obtain the desired textures of the class B1 are as shown in the table below.

| $l_L$ | $Z_8 \times Z_2$ | $l_R$ | $Z_8 \times Z_2$ | Higgs(LH) | $Z_8 \times Z_2$ | Higgs(RH) | $Z_8 \times Z_2$ |
|-------|------------------|-------|------------------|-----------|------------------|-----------|------------------|
| $l_{Le}$ | $(\omega^5, -1)$ | $l_{Re}$ | $(\omega^3, -1)$ | $\Delta_L$ | $(\omega^6, 1)$ | $\Delta_R$ | $(\omega^2, 1)$ |
| $l_{L\mu}$ | $(\omega^3, 1)$ | $l_{R\mu}$ | $(\omega^5, 1)$ | $\Delta_L'$ | $(\omega^2, 1)$ | $\Delta_R'$ | $(\omega^6, 1)$ |
| $l_{LT}$ | $(\omega^3, -1)$ | $l_{R\tau}$ | $(\omega^3, -1)$ | $\Delta_L''$ | $(1, -1)$ | $\Delta_R''$ | $(1, -1)$ |

**Table 4. Particle assignments for B2**

The Majorana mass matrices (LH and RH) and the type I SS mass matrix under these transformation has been obtained as,

$$M_{RR} = \begin{bmatrix} 1 & \omega^2 & 1 \\ \omega^2 & 1 & 1 \\ 1 & 1 & \omega^6 \end{bmatrix}, M_{LL} = \begin{bmatrix} 1 & \omega^2 & 1 \\ \omega^2 & 1 & 1 \\ 1 & 1 & \omega^6 \end{bmatrix}, M^I = \begin{bmatrix} \times & 0 & \times \\ 0 & \times & \times \\ \times & \times & \times \end{bmatrix} \quad (3.12)$$

The corresponding Majorana Yukawa Lagrangian (LH and RH) for the class B2 is,

$$\mathcal{L}_{MR} = Y_{RRe} L_{Re}^T \Delta_R L_{Re} + Y_{Rr\tau} L_{Rr}^T \Delta_R L_{Rr} + Y_{Rr\mu} L_{Rr}^T \Delta_R' L_{R\mu} +$$

$$Y_{R\mu} L_{R\mu}^T \Delta_R'' L_{R\mu}, \quad (3.13)$$

$$\mathcal{L}_{ML} = Y_{LLe} L_{Le}^T \Delta_L L_{Le} + Y_{Lr\tau} L_{Lr}^T \Delta_L L_{Lr} + Y_{Lr\mu} L_{Lr}^T \Delta_L' L_{L\mu} +$$

$$Y_{L\mu} L_{L\mu}^T \Delta_L'' L_{L\mu}, \quad (3.14)$$

**Class B3:**

The symmetry realizations of the particles to obtain the desired mass terms of class B3 is shown in table V.

The Majorana mass terms (LH and RH) and the type I SS mass terms, in the matrix form can be written as,

$$M_{RR} = \begin{bmatrix} 1 & -1 & 1 \\ -1 & \omega^4 & 1 \\ 1 & 1 & 1 \end{bmatrix}, M_{LL} = \begin{bmatrix} 1 & \omega^6 & 1 \\ \omega^6 & \omega^6 & 1 \\ 1 & 1 & 1 \end{bmatrix}, M^I = \begin{bmatrix} \times & 0 & \times \\ 0 & \times & \times \\ \times & \times & \times \end{bmatrix} \quad (3.15)$$
Table 5. Particle assignments for B3

| l_L | Z8 × Z₂ | l_R | Z8 × Z₂ | Higgs(LH) | Z8 × Z₂ | Higgs(RH) | Z8 × Z₂ |
|-----|---------|-----|---------|-----------|---------|-----------|---------|
| l_Le | (ω⁵, -1) | l_Re | (ω³, -1) | Δ_L | (ω⁶, 1) | Δ_R | (ω², 1) |
| l_Lµ | (ω³, 1) | l_Rµ | (ω³, 1) | Δ_L' | (1, -1) | Δ_R' | (ω⁶, 1) |
| l_LT | (ω³, 1) | l_RT | (ω³, 1) | Δ_L'' | (ω², 1) | Δ_R'' | (1, -1) |

The corresponding Majorana Yukawa Lagrangian (LH and RH) for B3 is,

\[
\mathcal{L}_{MR} = Y_{R_{ee} L_{ee}} T \Delta_R L_{Re} + Y_{R_{e\tau} L_{e\tau}} T \Delta''_R L_{R\tau} + Y_{R_{\tau\tau} L_{\tau\tau}} T \Delta'_R L_{R\tau} + Y_{R_{\tau\tau} L_{R\tau}} T \Delta'_R L_{R\tau}
\]

\[
\mathcal{L}_{MC} = Y_{L_{ee} L_{ee}} T \Delta_L L_{Le} + Y_{L_{e\tau} L_{e\tau}} T \Delta_L' L_{L\tau} + Y_{L_{\tau\tau} L_{\tau\tau}} T \Delta_L' L_{L\tau} + Y_{L_{\tau\tau} L_{\tau\tau}} T \Delta''_L L_{L\tau}
\]

Class B4:

Similarly we give the transformations for the class B4 as shown in table VI to obtain the desired texture zero mass matrices.

| l_L | Z8 × Z₂ | l_R | Z8 × Z₂ | Higgs(LH) | Z8 × Z₂ | Higgs(RH) | Z8 × Z₂ |
|-----|---------|-----|---------|-----------|---------|-----------|---------|
| l_Le | (ω⁵, -1) | l_Re | (ω³, -1) | Δ_L | (ω⁶, 1) | Δ_R | (ω², 1) |
| l_Lµ | (ω³, 1) | l_Rµ | (ω³, 1) | Δ_L' | (1, -1) | Δ_R' | (ω⁶, 1) |
| l_LT | (ω³, 1) | l_RT | (ω³, 1) | Δ_L'' | (1, -1) | Δ_R'' | (1, -1) |

Table 6. Particle assignments for B4

Under these symmetry realizations, we obtain the Majorana mass terms (LH and RH) and the type I SS mass terms as,

\[
M_{RR} = \begin{bmatrix} 1 & 1 & \omega^4 \\ 1 & 1 & 1 \\ \omega^4 & 1 & \omega^6 \end{bmatrix}, \quad M_{LL} = \begin{bmatrix} 1 & 1 & \omega^4 \\ 1 & 1 & 1 \\ \omega^4 & 1 & \omega^6 \end{bmatrix}, \quad M^I = \begin{bmatrix} \times & \times & 0 \\ \times & \times & \times \\ 0 & \times & 0 \end{bmatrix}
\]

The Majorana Yukawa Lagrangian (LH and RH) for B4 thus becomes,

\[
\mathcal{L}_{MR} = Y_{R_{ee} L_{ee}} T \Delta_R L_{Re} + Y_{R_{e\tau} L_{e\tau}} T \Delta''_R L_{R\tau} + Y_{R_{\tau\tau} L_{\tau\tau}} T \Delta'_R L_{R\tau} + Y_{R_{\tau\tau} L_{R\tau}} T \Delta'_R L_{R\tau}
\]

\[
\mathcal{L}_{MC} = Y_{L_{ee} L_{ee}} T \Delta_L L_{Le} + Y_{L_{e\tau} L_{e\tau}} T \Delta_L' L_{L\tau} + Y_{L_{\tau\tau} L_{\tau\tau}} T \Delta_L' L_{L\tau} + Y_{L_{\tau\tau} L_{\tau\tau}} T \Delta''_L L_{L\tau}
\]

The type II SS mass term in LRSM is directly proportional to the Majorana mass term as evident from equation 2.11, so it will have the same structure as \(M_{RR}\) and \(M_{LL}\). LRSM being a combination of type I and type II SS mass terms would give us the final mass matrix that would obey the structure of two zero texture mass matrix. It has been shown in tabular form in the numerical analysis.
4 NEUTRINOLESS DOUBLE BETA DECAY AND LEPTON FLAVOUR VIOLATION IN LEFT-RIGHT SYMMETRIC MODEL

The very facts of LRSM and the presence of several new heavy particles leads to many new contributions to NDBD apart from the standard light neutrino contribution. This has been extensively studied in several earlier works [39–42, 42–45, 52, 57]. Amongst the non standard contribution, notable are, heavy RH neutrino contribution to NDBD in which the mediator particles are the $W_L^-$ and $W_R^-$ boson individually, light neutrino contribution to NDBD in which the intermediate particles are $W_R^-$ bosons, light neutrino contribution mediated by both $W_L^-$ and $W_R^-$, heavy neutrino contribution mediated by both $W_L^-$ and $W_R^-$, triplet Higgs $\Delta_L$ contribution mediated by $W_L^-$ bosons and RH triplet Higgs $\Delta_R$ contribution to NDBD in which the mediator particles are $W_R^-$ bosons. The amplitude of these processes are dependent on the mixing between light and heavy neutrinos, the mass of the heavy neutrino, $N_i$, the mass of the gauge bosons, $W_L^-$ and $W_R^-$, the elements of the RH leptonic mixing matrix, LH and RH triplet Higgs, $\Delta_L$ and $\Delta_R$ as well as their coupling to leptons, $f_L$ and $f_R$.

Besides the observation of neutrino oscillation also provides compelling evidence for charged lepton flavour violation (CLFV) [58–60]. Since LFV which is generated at high energy scales are beyond the reach of the colliders, searching them in low energy scales amongst the charged leptons is widely accepted as an alternate procedure to probe LFV at high scales. Many previous works [39, 45, 52, 57, 61, 62] have focussed on the lepton flavour violating decay modes of muon, ($\mu \to 3e$, $\mu \to e\gamma$, $\mu \to e$ conversion in the nuclei). Considerable CLFV occurs in LRSM owing to the contributions that arises from the heavy RH neutrino and Higgs scalars. The relevant branching ratios (BR) has been derived and studied in [58]. The LFV processes $\mu \to 3e$, $\mu \to e\gamma$ provides the most relevant constraints on the masses of the RH neutrinos and the doubly charged scalars. In this work we would consider the process $\mu \to e\gamma$, the BR of which is given by,

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

where, $g_{lfv}$ is defined as,

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

The current experimental constraints for the BRs of these processes has been obtained as $< 1.0 \times 10^{-12}$ for $\mu \to 3e$ at 90% CL was obtained by the SINDRUM experiment. While it is $< 4.2 \times 10^{-13}$ [63] for the process $\mu \to e\gamma$, established by the MEG collaboration.

5 NUMERICAL ANALYSIS AND RESULTS

- In LRSM, we can write the light neutrino mass matrix as a combination of type I and type II mass terms as,

$$M_{\nu} = M_{\nu}^{I} + M_{\nu}^{II}$$
Here, we consider $M_{\nu}^I$ to be favouring the TM mixing with magic symmetry, so as to obtain the desired two zero texture. The different magic neutrino mass matrix with two zeroes can be obtained from the most general magic mass matrix which can be parameterized as\cite{28, 29},
\[
M_{\text{magic}} = \begin{pmatrix}
p & q & r \\
q & r & p + r - s \\
r & p + r - s & q - r + s
\end{pmatrix}
\]
which can be diagonalized by the trimaximal mixing matrix as,
\[
M_{\text{diag}} = U_{TM2}^T M_{\text{magic}} U_{TM2}
\]
where $U_{TM2}$ is the diagonalizing matrix for the magic mass matrix and is given in equation 2.14

- Using the constraint relations for various classes with two zero textures, we can arrive at the mass matrices as,
\[
M_{\nu}^I(A1) = \begin{pmatrix} 0 & 0 & r \\ 0 & s & r - s \\ r & r - s & -r + s \end{pmatrix}, M_{\nu}^I(A2) = \begin{pmatrix} 0 & q & 0 \\ q & s & -s \\ 0 & -s & q + s \end{pmatrix}
\]
\[
M_{\nu}^I(B1) = \begin{pmatrix} p & q & 0 \\ q & 0 & p \\ 0 & p & q \end{pmatrix}, M_{\nu}^I(B2) = \begin{pmatrix} p & 0 & r \\ 0 & r & p \\ r & p & 0 \end{pmatrix}
\]
\[
M_{\nu}^I(B3) = \begin{pmatrix} p & 0 & r \\ 0 & 0 & p + r \\ r & p + r & -r \end{pmatrix}, M_{\nu}^I(B4) = \begin{pmatrix} p & q & 0 \\ q & -q & p + q \\ 0 & p + q & 0 \end{pmatrix}
\]
Again, $M_{\nu}^I = U_{TM2} U_{\text{Maj}} M_{\nu}^{\text{diag}} U_{\text{Maj}}^T U_{TM2}^T$ where $U_{\text{Maj}}$ consists of the Majorana phases $\alpha$ and $\beta$, $M_{\nu}^{\text{diag}} = \text{diag} (m_1, m_2, m_3)$ which can be written as,
\[
- \text{diag} \left( m_1, \sqrt{m_1^2 + \Delta m_{\text{sol}}^2}, \sqrt{m_1^2 + \Delta m_{\text{sol}}^2 + \Delta m_{\text{atm}}^2} \right) \text{ (In NH)},
\]
\[
- \text{diag} \left( \sqrt{m_3^2 + \Delta m_{\text{atm}}^2}, \sqrt{m_3^2 + \Delta m_{\text{sol}}^2 + \Delta m_{\text{atm}}^2}, m_3 \right) \text{ (In IH)},
\]
in terms of the lightest neutrino mass. Thus, by comparing $M_{\nu}^I$ with $M_{\nu}^I$ for different classes we can solve for the unknown parameters $(p, q, r, s)$ in the corresponding matrices and obtain $M_{\nu}^I$ for different classes.

- Since now we have $M_{\nu}^I$, we can evaluate $M_{\nu}^{II}$ using equation 5.1. Again, we have in LRSM, $M_{RR} = \gamma \left( \frac{\Lambda_{\text{LE}}}{\Lambda_{\text{YR}}} \right)^2 M_{\nu}^{II}$, where $\gamma$ is a dimensionless parameter which follows directly from the minimization of the Higgs potential, here we consider its value to be $10^{-10}$. Thus we can find out $M_{RR}$ for our further analysis.
Using the constraint relations for the respective classes, we have compared the neutrino mass matrix, \( M_\nu = U_{\text{PMNS}} M_\nu \) diag \( U_{\text{PMNS}}^T \) with the neutrino mass matrices \( (M_\nu^I + M_\nu^H) \) containing two zeros. \( U_{\text{PMNS}} \) being the diagonalizing matrix of the light neutrino mass matrix, \( M_\nu \) and is given by,

\[
U_{\text{PMNS}} = \begin{bmatrix}
    c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta} \\
    -c_{23} s_{12} - s_{23} s_{13} c_{12} e^{i\delta} & c_{23} c_{12} - s_{23} s_{13} s_{12} e^{i\delta} & s_{23} c_{13} \\
    s_{23} s_{12} - c_{23} s_{13} c_{12} e^{i\delta} & -s_{23} c_{12} - c_{23} s_{13} s_{12} e^{i\delta} & c_{23} c_{13}
\end{bmatrix} U_{\text{Maj}}.
\] (5.6)

The abbreviations used here are \( c_{ij} = \cos \theta_{ij}, \ s_{ij} = \sin \theta_{ij} \), \( \delta \) is the Dirac CP phase. \( U_{\text{Maj}} \) is diag(1, \( e^{i\alpha}, e^{i\beta} \)) contains the Majorana phases \( \alpha \) and \( \beta \). Varying the parameters, \( \theta_{12}, \theta_{13}, \delta \) in its 3\( \sigma \) range \([1]\) and writing the mass Eigen values in terms of lightest neutrino mass \( m_1/m_3 \) for \( (\text{NH/II}) \) and varying from 0.0001 to 0.1, we have solved for the parameters \( \alpha, \beta \) and \( \theta_{23} \). We have chosen these parameters as the Majorana phases are unknown yet and the precise measurement of \( \theta_{23} \) and octant degeneracy is yet to be determined although experiments like NOvA, T2K have reported some values.

The different structures of the neutrino mass matrix in the LRSM using two texture zero are shown in table 7. The symmetry realizations of the texture zeros using the cyclic groups \( Z_8 \times Z_2 \) are as shown in the previous section.

Owing to the presence of new scalars and gauge bosons in the LRSM, various additional sources would give rise to contributions to NDBD process, which involves RH neutrinos, RH gauge bosons, scalar Higgs triplets as well as the mixed LH-RH contributions. We will study LNV (NDBD) for the non standard contributions for the effective mass in the framework of LRSM. For a simplified analysis we would ignore the left-right gauge boson mixing \( (W_L - W_R) \) which is very less and heavy light neutrino mixing which is dependent upon \( \frac{M_{\text{M}\nu}}{M_{\text{M}\nu}} \approx 10^{-6} \). Furthermore, contributions from the left handed Higgs triplets is suppressed by the light neutrino mass. Thus considering the mixing between LH and RH sector to be so small, their contributions to \( 0\nu\beta\beta \) can be neglected. The total effective mass is thus given by the formula as used in earlier works like, \([42, 52]\)

\[
m_{N+\Delta}^{\text{eff}} = p^2 \left( \frac{2M_{\text{W}_L}}{M_{\text{W}_R}}\frac{4}{4} U_{\text{Rei}} \frac{4}{4} U_{\text{Rei}}^2 M_i \right) + p^2 \frac{M_{\text{W}_L}}{M_{\text{W}_R}} \frac{4}{4} U_{\text{Rei}}^2 \left( \frac{1}{M_{\Delta_R}^2} + \frac{1}{M_{\Delta_R'}^2} + \frac{1}{M_{\Delta_R''}^2} \right).
\] (5.7)

Here, \( \Delta \) in LHS represents the three RH scalar triplets \( \Delta_R, \Delta_R' \) and \( \Delta_R'' \), \( <p^2> = m_p m_e \frac{M_N}{M_N} \) is the typical momentum exchange of the process, where \( m_p \) and \( m_e \) are the mass of the proton and electron respectively and \( M_N \) is the NME corresponding to the RH neutrino exchange. \( U_{\text{Rei}} \) in equation (5.7) denotes the elements of the first row of the unitary matrix diagonalizing the right handed neutrino mass matrix \( M_{\text{RR}} \) with mass Eigen values \( M_i \). Since we have \( M_{\text{RR}} \), we can evaluate \( U_{\text{Rei}} \).
by diagonalizing it as, $M_{RR} = U_R M_{RR}^{\text{diag}} U_R^T$. The $M_{RR}$ we obtain would consists of the mixing angles in the TM mass matrix, $\theta$ and $\phi$ along with the other parameters of our concern. As shown in paper [27, 28], $\theta$ and $\phi$ are related to the oscillation parameters $\theta_{23}$ and $\theta_{12}$ as,

$$\sin^2 \theta_{12} = \frac{1}{3 - 2 \sin^2 \theta}, \quad \sin^2 \theta_{23} = \frac{1}{2} \left( 1 + \sqrt{3} \sin 2 \theta \cos \phi \right)$$  \tag{5.8}$$

We thus obtained the parameter space for $\theta$ and $\phi$ by varying the parameters $\theta_{12}$ and $\theta_{23}$ in its 3 $\sigma$ range which is shown in figure 1. We have seen that the trimaximal mixing angle $\theta$ lies within the range (0.05 to 0.5) radian for the 3$\sigma$ range of the solar mixing angle $\theta_{12}$ although it doesn’t show significant dependence. The other mixing angle $\phi$ shows some dependence on the atmospheric mixing angle $\theta_{23}$ for both normal and inverted ordering of neutrino mass. It’s values lies within (1.56-1.66)radian for the 3$\sigma$ range of $\theta_{23}$. The plot shows an exponential decrease and then increase in $\phi$ with the increase in $\theta_{23}$ with a fall at around the best fit value.

The effective mass governing NDBD from the new physics contribution coming from RH neutrino and scalar triplet can be obtained from equation 5.7. We have shown the plots for the effective mass versus $\theta$, $\phi$, lightest neutrino mass and the Majorana phases $\alpha$ and $\beta$ in figures 2, 3, 4, 5 and 6 for different classes of two zero textures.

### Table 7

| Class | $M_D$ | $M_{RR}$ | $M_\nu^I$ | $M_\nu^{II}$ | $M_\nu$ |
|-------|-------|---------|-----------|-------------|---------|
| A1    | $x \ 0 \ 0$ | 0 0 A   | 0 0 a     | 0 0 W       | 0 0 W + a |
|       | $0 \ y \ 0$ | 0 B C   | 0 b c     | 0 X Y       | 0 X + b Y + c |
|       | $0 \ 0 \ z$ | A C D   | a c d     | W Y Z       | W + a Y + c Z + d |
| A2    | $x \ 0 \ 0$ | 0 A 0   | 0 a 0     | 0 W 0       | 0 W + a 0 |
|       | $0 \ y \ 0$ | A B C   | a b c     | W X Y       | W + a X + b Y + c |
|       | $0 \ 0 \ z$ | 0 C D   | 0 c d     | 0 Y Z       | 0 Y + c Z + d |
| B1    | $x \ 0 \ 0$ | A 0 B   | a 0 b     | W 0 X       | W + a X + b |
|       | $0 \ y \ 0$ | B 0 C   | b 0 c     | X 0 Y       | X + b 0 Y + c |
|       | $0 \ 0 \ z$ | B C D   | 0 c d     | X Z 0       | X + b Y + c Z + d |
| B2    | $x \ 0 \ 0$ | A 0 B   | a 0 b     | W 0 X       | W + a 0 X + b |
|       | $0 \ y \ 0$ | B 0 C   | b 0 c     | 0 0 Y       | 0 0 Y + c |
|       | $0 \ 0 \ z$ | B C D   | b c d     | X Y Z       | X + b Y + c Z + d |
| B3    | $x \ 0 \ 0$ | A 0 B   | a 0 b     | W 0 X       | W + a X + b |
|       | $0 \ y \ 0$ | B 0 C   | b c d     | X Y Z       | X + b Y + c Z + d |
|       | $0 \ 0 \ z$ | B C D   | 0 c d     | 0 Z 0       | 0 Z + d 0 |
| B4    | $x \ 0 \ 0$ | A 0 B   | a 0 b     | W 0 X       | W + a X + b |
|       | $0 \ y \ 0$ | B 0 C   | b c d     | X Y Z       | X + b Y + c Z + d |
|       | $0 \ 0 \ z$ | B C D   | 0 d 0     | 0 Z 0       | 0 Z + d 0 |

The structures of $M_D$, $M_{RR}$, $M_\nu^I$ and $M_\nu^{II}$ and $M_\nu$ for different classes of two zero textures.
In figure 2 shows the parameter space corresponding to effective mass and the trimaximal angle $\theta$. In A1 and A2 both normal and inverted hierarchies shows almost similar results and $m_{\text{eff}}$ lies close to the experimental bound although in A1 (NH), it saturates the limit for greater values of $\theta$. For the classes B1, B2, B3, there is an increase in the difference of the order of magnitude of the effective mass for NH and IH and IH lies closer to the limit propounded by KamLAND-Zen. In the case of B3(NH), there is a linear increase in the value of effective mass with $\theta$. Interestingly, it is seen that for the case of B4, IH has lower effective mass than for NH which is unlike the other classes. Similar results are seen for the variation of effective mass with the other TM mixing angle $\phi$ which is shown in figure 3.

In figure 4 we have shown the effective mass versus the lightest neutrino mass which is $m_1/m_3$ for NH/IH. While plotting we have considered all the oscillation parameters in their $3\sigma$ range, TM mixing angles in their obtained range and randomly varied the Majorana phases within the allowed range. It is seen that classes A1 and A2 are independent of the mass ordering. Whereas, the classes B1 to B3 shows a slight variation of effective mass by about an order for NH and IH with IH lying closer to the experimentally propounded lower limit which is the reverse in the case of class B4. In all the classes, we have seen a considerable spreading of effective mass values for greater values of lightest neutrino mass.

In figure 5 and 6, we have shown the variation of NDBD governing effective mass with the Majorana phases $\beta$ and $\alpha$. We have randomly varied the phases within its allowed range from 0 to $2\pi$, as we have considerably taken lesser values most of which lies from (1-4)radian. In figure 5, classes A1 and A2 are independent of the mass hierarchies, B1-B3 shows a slight increase in the variation of effective mass for IH and NH with IH lying closer to the experimental bound. And like previous plots, IN B4 again, NH predicted higher values of effective mass than IH. The variation of effective mass with $\alpha$ also shows almost similar results. However, the effective mass is widely scattered from 0.01 to 0.1 in class A1. For NH, the results saturates the limit for the classes A2 and B3. Here, we have seen that for the classes A2 and B4 the effective mass covers a greater range of the Majorana phases which is otherwise constrained to a smaller range for the other phases.

Plots 7 to 10 shows the parameter space corresponding to effective mass versus with the model parameters $W$, $X$, $Y$, $Z$ which appears in the type II seesaw mass matrix as shown in table VII. From the plots it is clear that these model parameters are severely constrained to obtained the effective Majorana mass within the experimental bound. For the class B4 in all the plots very less parameter space is found. Although in all the cases NH seems to be a better predicted as compared to IH.

We have shown one plot showing the variation of one model parameter with one of the Majorana phase $\beta$ in figure 11. We have randomly varied the Majorana phase in its allowed range which gives the values of W ranging from 0.01 to 0.1. For the class A1, both NH and IH almost gives similar results, while there is a variation in
the value of $W$ in the other classes for NH and IH with IH giving a greater value. However, for the class B3 we have not obtained any result for IH.

- For lepton flavour violation, we have evaluated the BR for the process $\mu \rightarrow e\gamma$ using equation 4.1, Where $V$ is the mixing matrix of the right handed neutrinos with the electrons and muons. $M_n (n = 1, 2, 3)$ are the right handed neutrino masses. We evaluated the BR with the Majorana phase $\beta$ and atmospheric mixing angle $\theta_{23}$ as shown in figures 12 and 13.

Figures 12 and 13 shows the prediction of LFV parameter, BR for the decay process $(\mu \rightarrow e\gamma)$ with the Majorana phase $\beta$ and the mixing angle $\theta_{23}$. Interestingly, it is seen that most of the classes are unable to give BR within the limit propounded by experiment. The plots clearly excludes B4 in explaining LFV for both the mass hierarchies. IH is excluded for the classes A1, B1 and B3. A2 can be excluded for the variation of BR with $\theta_{23}$ whereas with $\beta$ only IH seem to be allowed to some extent. Out of all the classes, only B2 has allowed values of BR for both the NH and IH although IH seems to have better predictions.

Figure 1. Variation of the TM mixing angle $\phi$ and $\theta$ with the atmospheric and solar mixing angle, $\theta_{23}$ and $\theta_{12}$. 

Figure 2. New physics contribution to effective mass governing NDBD for different classes of two zero textures for NH and IH shown as a function of $\theta$. The grey horizontal line indicates the upper limit on effective Majorana mass given by KamLAND-Zen experiment.

Figure 3. New physics contribution to effective mass governing NDBD for different classes of two zero textures for NH and IH shown as a function of $\phi$. The grey horizontal line indicates the upper limit on effective Majorana mass given by KamLAND-Zen experiment.
**Figure 4.** New physics contribution to effective mass governing NDBD for different classes of two zero textures for NH and IH shown as a function of $\beta$. The grey horizontal line indicates the upper limit on effective Majorana mass given by KamLAND-Zen experiment.

**Figure 5.** New physics contribution to effective mass governing NDBD for different classes of two zero textures for NH and IH shown as a function of $\beta$. The grey horizontal line indicates the upper limit on effective Majorana mass given by KamLAND-Zen experiment.
Figure 6. New physics contribution to effective mass governing NDBD for different classes of two zero textures for NH and IH shown as a function of $\alpha$. The grey horizontal line indicates the upper limit on effective Majorana mass given by KamLAND-Zen experiment.

Figure 7. New physics contribution to effective mass governing NDBD for different classes of two zero textures for NH and IH shown as a function of model parameter W. The grey horizontal line indicates the upper limit on effective Majorana mass given by KamLAND-Zen experiment.
Figure 8. New physics contribution to effective mass governing NDBD for different classes of two zero textures for NH and IH shown as a function of model parameter X. The grey horizontal line indicates the upper limit on effective Majorana mass given by KamLAND-Zen experiment.

Figure 9. New physics contribution to effective mass governing NDBD for different classes of two zero textures for NH and IH shown as a function of model parameter Y. The grey horizontal line indicates the upper limit on effective Majorana mass given by KamLAND-Zen experiment.
Figure 10. New physics contribution to effective mass governing NDBD for different classes of two zero textures for NH and IH shown as a function of model parameter $Z$. The grey horizontal line indicates the upper limit on effective Majorana mass given by KamLAND-Zen experiment.

Figure 11. Variation of model parameter $W$ with the Majorana phase $\beta$ for NH/IH for different classes of two zero textures.
Figure 12. BR for $\mu \rightarrow e\gamma$ shown as a function of the Majorana phase $\beta$. The horizontal solid line shows the limit of BR as given by MEG experiment.

Figure 13. BR for $\mu \rightarrow e\gamma$ shown as a function of the atmospheric mixing angle. The horizontal solid line shows the limit of BR as given by MEG experiment.
5.1 COLLIDER SIGNATURES

Physics at TeV scale has obtained great importance owing to the fact that it can be probed at the colliders. Characteristic signatures of the LRSM (which is the framework of our concern) at the hadron collider experiments like LHC emerges from the production and decay of triply and doubly charged scalars of the scalar quadruplet. In TeV scale LRSM, the presence of RH gauge interactions as well as the mixing between the heavy and light neutrinos lead via production of the RH gauge boson, $W_R$ to significant signal strength for the $t^\pm t^\pm jj$ channel. In the colliders $W_R$ could be produced through Drell-Yan, which decays to RH neutrino and a charged lepton. The RH neutrino (which are Majorana particles) can further decay to charged leptons/antileptons and jets. With negligible mixing between heavy and light neutrinos as well as left and right W bosons, both $W_R$ and $N_R$ couple through RH currents. Several constraints have been put forward on the mass of the RH gauge boson, $W_R$, the breaking scale of LRSM based on low energy processes like leptogenesis, supersymmetry, neutrinoless double beta decay etc. Most stringent experimental constraints on the masses of $W_R$, $M_N$ in MLRSM as explained in [64] are provided by $t^\pm t^\pm jj$ searches in ATLAS, dijet searches by ATLAS (CMS), neutral hadron transitions and search for NDBD. When the breaking scale of LRSM is low enough, LNV can be seen and hence the Majorana nature of the neutrino mass can be probed in the colliders and in future experiments in a wider range of parameter space. Since we are considering the low energy phenomenon like NDBD and LFV, we are considering the experimental bounds on these mass provided by the search for these phenomenon. The NDBD experiments are mainly focused in determining the effective Majorana neutrino mass $< m_{\beta\beta} >$ which is related to the observed NDBD lifetime as,

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q, Z)|M_{0\nu}|^2 |m_{\beta\beta}|^2/m_e^2, \tag{5.9}$$

where the terms $G_{0\nu}$, $M_{\nu}$ and $m_e$ represents the phase space factor, the nuclear matrix element (NME) and the electron mass respectively. $\Gamma$ represents the decay width for $0\nu\beta\beta$ decay process. The best lower limits on the NDBD half life has been obtained for the isotopes Ge-76, Te-130, Xe-136 in notable experiments like GERDA-II, CUORE, KamLAND-Zen respectively. The non observation of NDBD constraints the masses of $W_R$ and $N_R$ as, $\sum \frac{Y_{\nu e}^2}{M_{\nu}, M_{W_R}} \leq (0.082-0.076) \text{ TeV}^{-5}$ using 90% CL from the limit propounded by KamLAND-Zen $T_{1/2}^{0\nu} > 1.07 \times 10^{26}$ which corresponds to an effective mass of $| < m_{\text{eff}} > | < (0.061 - 0.065) eV \ [65]$ where the range corresponds to the uncertainties in the NMEs of the relevant process. For $M_{W_R}$ of 3 (5 TeV), the mass of the RH $\nu \geq 150-162$ GeV (19.5-21)GeV. Again, Tello et al. [66] found the lower bound on mass of $\Delta_R^{++}$ to be

$$M^{++}_{\Delta_R} \geq 500 \left( \frac{3.5 \text{ TeV}}{M_{W_R}} \right)^2 \times \sqrt{\frac{M_N}{3 \text{ TeV}}} \tag{5.10}$$

Considering these experimental bounds in mind, we have considered the mass of $W_R$ as 3.5 TeV in accordance with the collider probes and the other heavy particles of the order of TeV.
6 CONCLUSION

The importance of texture zero neutrino mass and its phenomenological consequence has gained utmost significance in present day research. In this context two zero texture neutrino mass matrices are more relevant as they provides the minimal free parameters for precise study. We have performed a systematic study of the Majorana neutrino mass matrix with two independent zeros. As has been pointed out in several earlier works that seven out of fifteen patterns namely (A1, A2, B1-B4, C1) can survive the current experimental datas at 3σ level. We tried to study the constraints of the allowed patterns of texture zero neutrino mass matrices in the framework of LRSM from low energy phenomenon like NDBD and LFV. We have shown that one can obtain the desired two zero texture mass matrices by implementing a abelian discrete symmetric group $\mathbb{Z}_8 \times \mathbb{Z}_2$ in the framework of left-right symmetric model. The two zero textured neutrino mass matrix in our case is able to explain NDBD with the effective Majorana mass within the experimental limit propounded by experiment (KamLAND-Zen). However all the different allowed classes of two zero textures shows different results for different neutrino mass hierarchies. Based on our results, having done a careful comparison of the plots obtained for different classes of two zero textures, in the case of effective mass governing NDBD in LRSM we can say that although all the classes gives results within the experimental bounds, the class A1 is more predictive as it is more in the vicinity of the probable experimental bound and irrespective of the mass hierarchies. We have considered six different allowed classes of two zero texture neutrino mass matrices which satisfies TM mixing in our case. Again the type II SS model parameters are heavily constrained for a very limited parameter space from which we can say that the contributions from the type II SS in NDBD is relatively less. Interestingly the present results ruled out B4 (NH/IH), A1, B1, B3 (IH) in explaining the experimentally allowed regions of charged lepton flavour violation with only the class B2 giving probable results for both the mass hierarchies. However, the sensitivity of NDBD experiments to the effective mass governing NDBD will probably reach around 0.05 eV in future experiments which might exclude or marginally allow some of the two zero texture patterns in nearby future. Nonetheless, an indepth study of the texture zero classes considering all the model parameters and its implications for NDBD, LFV could be done for a even more strong conclusion.

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