S3 Symmetric Scotogenic Model for Realistic Neutrino Mixing

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Abstract

In a $S3 \times Z_2$ framework, realistic neutrino mixing was obtained radiatively at one-loop level. When maximal mixing occurs between the two right-handed neutrinos present in the model, one can get the form of the left-handed Majorana neutrino mass matrix for $\theta_{13} = 0$, $\theta_{23} = \pi/4$ and solar mixing of any values corresponding to the Tribimaximal (TBM), Bimaximal (BM) and Golden Ratio (GR) mixing scenarios in this set-up. Once we tweak the maximal mixing between the two right-handed neutrinos, we get non-zero θ_{13}, deviation of θ_{23} from $\pi/4$ and small corrections to solar mixing. This scotogenic model also has two inert $SU(2)_L$ doublet scalars odd under Z_2 the lightest of which can be dark matter.

Keywords: neutrino mass and mixing, radiative model, discrete flavour symmetry $S3$
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1. INTRODUCTION

This talk is based[1] on [1]. The Pontecorvo, Maki, Nakagawa, Sakata – PMNS – matrix, relating the neutrino mass and flavour eigenstates is given by:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & -s_{13}e^{-i\delta} \\ -c_{23}s_{12} + s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} + s_{23}s_{13}s_{12}e^{i\delta} & -s_{23}c_{13} \\ -s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} + c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix}, \tag{1}$$

with $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$. If we put $\theta_{13} = 0$ and $\theta_{23} = \pi/4$, the PMNS matrix in Eq. (1) simply becomes:

$$U^0 = \begin{pmatrix} \cos\theta_{12}^0 & \sin\theta_{12}^0 & 0 \\ -\frac{\sin\theta_{12}^0}{\sqrt{2}} & \frac{\cos\theta_{12}^0}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ -\frac{\sin\theta_{12}^0}{\sqrt{2}} & \frac{\cos\theta_{12}^0}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}. \tag{2}$$

In 2012, the short-baseline reactor anti-neutrino experiments [2] discovered non-zero θ_{13}, before which models were constructed with $\theta_{13} = 0$ and $\theta_{23} = \pi/4$ and θ_{12} varying to the specific values mentioned in Table 1 to yield the Tribimaximal (TBM), Bimaximal (BM) and Golden Ratio (GR) mixing patterns. These TBM, BM and GR scenarios are also called together as popular lepton mixings and have the structure of the mixing as in Eq. (2). The left-handed Majorana neutrino mass matrix in flavour basis for the popular lepton mixings is thus given by:

$$M_{\nu L}^{flavour} = U^0 M_{\nu L}^{mass} U^{0T} = \begin{pmatrix} a & c & c \\ c & b & d \\ c & d & b \end{pmatrix}, \tag{3}$$

where $M_{\nu L}^{mass} \equiv (m_1^0, m_2^0, m_3^0)$ and[2]

$$\begin{aligned} a &= m_1 \cos^2\theta_{12}^0 + m_2 \sin^2\theta_{12}^0, \\ b &= \frac{1}{2}\left(m_1 \sin^2\theta_{12}^0 + m_2 \cos^2\theta_{12}^0 + m_3\right), \\ c &= \frac{1}{2\sqrt{2}} \sin 2\theta_{12}^0 (m_2 - m_1), \\ d &= \frac{1}{2}\left(m_1 \sin^2\theta_{12}^0 + m_2 \cos^2\theta_{12}^0 - m_3\right). \end{aligned} \tag{4}$$

Here,

$$\tan 2\theta_{12}^0 = \frac{2\sqrt{2}c}{b + d - a}. \tag{5}$$

[1] The paper [1] on which this talk is based on was written during my post-doctoral research at Harish-Chandra Research Institute, Allahabad, India.
[2] The three neutrino mass eigenstates viz. m_1^0, m_2^0 and m_3^0 are non-degenerate.

Model	TBM	BM	GR
θ_{12}^0	35.3°	45.0°	31.7°

TABLE 1: Solar mixing angle values for TBM, BM, and GR.

The quantities a, b, c and d has to be non-zero for neutrino masses to be non-degenerate and realistic.

The 3σ global fits of the neutrino mixing angles [3, 4] are:

$$\begin{aligned} \theta_{12} &= (31.42 - 36.05)^\circ, \\ \theta_{23} &= (40.3 - 51.5)^\circ\,, \\ \theta_{13} &= (8.09 - 8.98)^\circ. \end{aligned} \tag{6}$$

They clearly disagree with the popular lepton mixing scenarios such as TBM, BM and GR. Therefore, in order to make the neutrino mixings to be realistic, one has to depart from the structure of the left-handed Majorana neutrino mass matrix[3] in Eq. (3).

In this work we consider a $S3 \times Z_2$ setup[4] to generate the neutrino mixings in agreement with the neutrino oscillation data radiatively at one-loop level. The model contains two Z_2 odd right-handed neutrinos which when mixed maximally can yield the structure of the left-handed Majorana mass matrix specific to $\theta_{13} = 0$ and $\theta_{23} = \pi/4$ as shown in Eq. (3). A slight deviation from this maximal mixing in the right-handed neutrino sector can yield the non-zero θ_{13}, deviation of θ_{23} from $\pi/4$ and small corrections to the solar mixing angle θ_{12} in one stroke as required to be in agreement with the neutrino oscillation data. The model also has two Z_2 odd $SU(2)_L$ doublet scalars $\eta_i \equiv (\eta_i^+, \eta_i^0)^T$, $(i = 1, 2)$ transforming as a doublet under $S3$. The lightest among these two inert $SU(2)_L$ doublet scalars η_i can be a dark matter candidate.

In the scalar sector two more $SU(2)_L$ doublet scalars $\Phi_j \equiv (\phi_i^+, \phi_i^0)$, $(j = 1, 2)$ forming a $S3$ doublet are present that are even under Z_2. In the lepton sector, the left-handed $SU(2)_L$ doublet leptons $L_{\zeta L} \equiv (\nu_\zeta, \zeta^-)_L^T$ with $\zeta = e, \mu, \tau$ are present among which L_μ and L_τ form a doublet under $S3$ while L_e is a singlet under $S3$. All the fields are even under Z_2 except the right-handed neutrinos $N_{\alpha R}$, $(\alpha = 1, 2)$ and η_i, $(i = 1, 2)$. After spontaneous symmetry breaking (SSB), η_i being Z_2 odd does not acquire vev but Φ_j gets vev i.e., $\langle \Phi_j \rangle = v_j$, $(j = 1, 2)$. The quantum numbers of all the fields present in the model can be found in Table 2. Here we consider the neutrino sector only and work in a basis in which the charged lepton mass matrix is diagonal and the whole mixing comes from the neutrinos.

Leptons	$SU(2)_L$	$S3$	Z_2
$L_{e_L} \equiv \begin{pmatrix} \nu_e & e^- \end{pmatrix}_L$	2	1	1
$L_{\zeta_L} \equiv \begin{pmatrix} \nu_\mu & \mu^- \\ \nu_\tau & \tau^- \end{pmatrix}_L$	2	2	1
$N_{\alpha R} \equiv \begin{pmatrix} N_{1R} \\ N_{2R} \end{pmatrix}$	1	2	-1

Scalars	$SU(2)_L$	$S3$	Z_2
$\Phi \equiv \begin{pmatrix} \phi_1^+ & \phi_1^0 \\ \phi_2^+ & \phi_2^0 \end{pmatrix}$	2	2	1
$\eta \equiv \begin{pmatrix} \eta_1^+ & \eta_1^0 \\ \eta_2^+ & \eta_2^0 \end{pmatrix}$	2	2	-1

TABLE 2: Particle content of the model with their respective properties under the symmetries of the model. We consider the neutrino sector only.

[3] Prior to this such enterprises had also been pursued in [5, 6]. In [6] a similar scotogenic model at one-loop level for realistic neutrino mixings based on $A4$ symmetry can be found. A detailed analysis of the vacuum expectation value (*vev*) structures of the scalars present in [6] in the context of alignment was done in [7].

[4] In [1] detailed discussion about $S3$ flavour symmetry can be found.

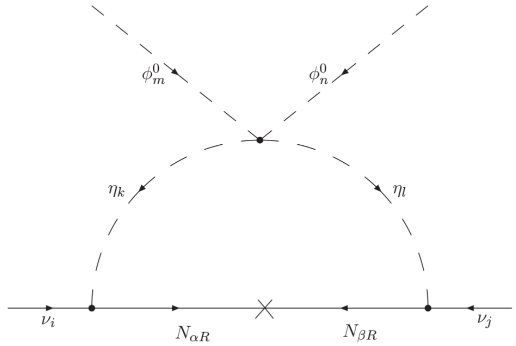

FIGURE 1: Neutrino mass at one-loop in a scotogenic $S3 \times Z_2$ setup.

2. THE MODEL

The neutrino mass at one-loop level can be given by Fig. (1). The relevant terms[5] of the $S3 \times Z_2$ invariant scalar potential that can contribute to the left-handed Majorana neutrino mass matrix via the four-point scalar vertex in Fig. (1):

$$\begin{aligned} V_{relevant} \quad &\supset \quad \lambda_1 \left[\left\{ (\eta_2^\dagger \phi_2 + \eta_1^\dagger \phi_1)^2 \right\} + h.c. \right] + \lambda_2 \left[\left\{ (\eta_2^\dagger \phi_2 - \eta_1^\dagger \phi_1)^2 \right\} + h.c. \right] \\ &+ \quad \lambda_3 \left[\left\{ (\eta_1^\dagger \phi_2)(\eta_2^\dagger \phi_1) + (\eta_2^\dagger \phi_1)(\eta_1^\dagger \phi_2) \right\} + h.c. \right]. \end{aligned} \tag{7}$$

The couplings λ_j ($j = 1, 2, 3$) are real.

At each of the vertices in Fig. 1 all the symmetries are conserved. The $S3 \times Z_2$ invariant Yukawa terms are:

$$\mathscr{L}_{Yukawa} = y_1 \left[(\overline{N}_{2R} \eta_2^0 + \overline{N}_{1R} \eta_1^0) \nu_e \right] + y_2 \left[(\overline{N}_{1R} \eta_2^0) \nu_\tau + (\overline{N}_{2R} \eta_1^0) \nu_\mu \right] + h.c. \tag{8}$$

The $S3 \times Z_2$ conserving right-handed neutrino direct mass terms:

$$\mathscr{L}_{right-handed\,neutrinos} = \frac{1}{2} m_{R_{12}} \left[N_{1R}^T C^{-1} N_{2R} + N_{2R}^T C^{-1} N_{1R} \right]. \tag{9}$$

If $S3$ is conserved then one gets only non-zero off-diagonal terms in the right-handed Majorana neutrino mass matrix. The $S3$ symmetry is broken softly by[6]:

$$\mathscr{L}_{soft} = \frac{1}{2} \left[m_{R_{11}} N_{1R}^T C^{-1} N_{1R} + m_{R_{22}} N_{2R}^T C^{-1} N_{2R} \right], \tag{10}$$

to obtain non-zero diagonal terms in the right-handed Majorana neutrino mass matrix and write it as[7]:

$$M_{\nu_R} = \frac{1}{2} \begin{pmatrix} m_{R_{11}} & m_{R_{12}} \\ m_{R_{12}} & m_{R_{22}} \end{pmatrix}. \tag{11}$$

The Z_2 symmetry in the model is responsible for stabilizing the dark matter candidate. We have Z_2 odd fields η_i, ($i = 1, 2$) and $N_{\alpha R}$, ($\alpha = 1, 2$) in our model. The right-handed neutrinos $N_{\alpha R}$ are chosen to be heavier than η_i. Thus the lightest of the η_i scalars can behave as a dark matter candidate[8].

Next we briefly discuss the contribution coming from the loop in Fig. (1) to the left-handed Majorana neutrino mass matrix [8]. For simplicity, let λ represent commonly all the quartic couplings i.e., λ_1, λ_2 and λ_3 present in the $S3 \times Z_2$ conserving scalar potential in Eq. (7). We also neglect the mass splittings between η_1 and η_2 and define m_0 as their common mass. If η_{Rj} and η_{Ij} be the real and imaginary parts of the η_j^0, then generally one can have the mass difference between η_{Rj} and η_{Ij} to be proportional to λv_j. Taking m_R to be the average mass of N_{1R} and N_{2R} and defining $z \equiv \frac{m_R^2}{m_0^2}$ we can write the second diagonal element of $M_{\nu_L}^{flavour}$ as[9]:

$$(M_{\nu_L}^{flavour})_{22} = \lambda \frac{v_m v_n}{8\pi^2} \frac{y_2^2}{m_{R_{22}}} [\ln z - 1]. \tag{12}$$

[5]The total $S3 \times Z_2$ invariant scalar potential is given in [1] out of which only the $(\eta^\dagger \phi)(\eta^\dagger \phi)$ terms contribute to the neutrino mass matrix as at the four-point scalar vertex in Fig. (1), two η fields are created and two ϕ fields are annihilated.

[6]The $S3$ symmetry is broken softly at the scale at which the right-handed neutrinos acquire their mass.

[7]The symmetric nature of the matrix in Eq. (11) is due to its Majorana nature.

[8]It might appear that the $S3$ symmetry will cause the η_i fields to be equal in masses, but since the $S3$ symmetry is softly broken at the scale in which $N_{\alpha R}$ gets mass, a small mass splitting between the two η_i fields can be achieved.

[9]For detailed discussion, see [1].

when $m_R^2 >> m_0^2$. From Eq. (8), one can notice that ν_μ couples only with N_{2R} at both the Yukawa vertices in Fig. (1), y_2 being the corresponding Yukawa coupling. Thus in Eq. (12) we only have contributions from y_2 and $m_{R_{22}}$ of Eq. (11). Similarly the $(M_{\nu_L}^{flavour})_{33}$ can also be read off by replacing $m_{R_{22}}$ by $m_{R_{11}}$ in the expression of $(M_{\nu_L}^{flavour})_{22}$ in Eq. (12). For the (2,3) off-diagonal entry of $M_{\nu_L}^{flavour}$, we have ν_μ at one Dirac Yukawa vertex and ν_τ at the other Dirac Yukawa vertex of Fig. (1) that couple to N_{2R} and N_{1R} respectively, y_2 being the Yukawa coupling at both the vertices. Thus $(M_{\nu_L}^{flavour})_{23}$ will depend on $m_{R_{12}}$ together with $m_{R_{11}}$ and $m_{R_{22}}$ of Eq. (11). Thus,

$$(M_{\nu_L}^{flavour})_{23} = \lambda \frac{v_m v_n}{8\pi^2} \frac{y_2^2 m_{R_{12}}}{m_{R_{11}} m_{R_{22}}} \left[\ln z - 1\right]. \tag{13}$$

Similarly we can get the other entries of $M_{\nu_L}^{flavour}$. In order to make the equations look simpler we can absorb everything else in the expressions of $(M_{\nu_L}^{flavour})_{\alpha\beta}$, $(\alpha, \beta = 1,2,3)$ except the vevs, the Yukawa couplings and the quartic couplings in some loop-contributing factors $r_{\alpha\beta}$ given by:

$$\begin{aligned} r_{11} &\equiv \frac{1}{8\pi^2 m_{R_{11}}} \left[\ln z - 1\right], \\ r_{22} &\equiv \frac{1}{8\pi^2 m_{R_{22}}} \left[\ln z - 1\right], \\ r_{12} &\equiv \frac{m_{R_{12}}}{8\pi^2 m_{R_{11}} m_{R_{22}}} \left[\ln z - 1\right]. \end{aligned} \tag{14}$$

for the expressions of elements of $M_{\nu_L}^{flavour}$ in Eqs. (12) and (13).

The left-handed Majorana neutrino mass matrix obtained in this setup:

$$M_{\nu_L}^{flavour} = \begin{pmatrix} \chi_1 & \chi_4 & \chi_5 \\ \chi_4 & \chi_2 & \chi_6 \\ \chi_5 & \chi_6 & \chi_3 \end{pmatrix} \tag{15}$$

with,

$$\begin{aligned} \chi_1 &\equiv y_1^2 \left[4 r_{12} v_1 v_2 (\lambda_3 + \lambda_1 - \lambda_2) + (r_{11} v_1^2 + r_{22} v_2^2)(\lambda_1 + \lambda_2)\right] \\ \chi_2 &\equiv y_2^2 \left[r_{22}(\lambda_1 + \lambda_2) v_1^2\right] \\ \chi_3 &\equiv y_2^2 \left[r_{11}(\lambda_1 + \lambda_2) v_2^2\right] \\ \chi_4 &\equiv y_1 y_2 \left[r_{12}(\lambda_1 + \lambda_2) v_1^2 + 2 r_{22} (\lambda_3 + \lambda_1 - \lambda_2) v_1 v_2\right] \\ \chi_5 &\equiv y_1 y_2 \left[r_{12}(\lambda_1 + \lambda_2) v_2^2 + 2 r_{11} (\lambda_3 + \lambda_1 - \lambda_2) v_1 v_2\right] \\ \chi_6 &\equiv y_2^2 \left[2 r_{12} (\lambda_3 + \lambda_1 - \lambda_2) v_1 v_2\right] \end{aligned} \tag{16}$$

and $\langle \Phi_j \rangle \equiv v_j$ where $(j = 1, 2)$. If $\chi_1 \neq \chi_2 = \chi_3$ and $\chi_4 = \chi_5$, we get the structure of neutrino mass matrix in Eq. (3) i.e., the one specific to $\theta_{13} = 0$, $\theta_{23} = \pi/4$. One can indeed get this for $v_1 = v_2$ and $r_{11} = r_{22} = r$. Now $r_{11} = r_{22} = r$ basically means $m_{R_{11}} = m_{R_{22}}$ in Eq. (11) which in its turn indicate maximal mixing between the two right-handed neutrino states N_{1R} and N_{2R}. Setting $r_{11} = r_{22} = r$ and $v_1 = v_2$ in Eq. (15) leads to:

$$M_{\nu_L}^{flavour} = v^2 \begin{pmatrix} y_1^2[4 r_{12}\lambda_{123} + 2r\lambda_{12}] & y_1 y_2 [r_{12}\lambda_{12} + 2r\lambda_{123}] & y_1 y_2 [r_{12}\lambda_{12} + 2r\lambda_{123}] \\ y_1 y_2 [r_{12}\lambda_{12} + 2r\lambda_{123}] & y_2^2 r \lambda_{12} & y_2^2 (2 r_{12} \lambda_{123}) \\ y_1 y_2 [r_{12}\lambda_{12} + 2r\lambda_{123}] & y_2^2 (2 r_{12} \lambda_{123}) & y_2^2 r \lambda_{12} \end{pmatrix}. \tag{17}$$

where we have defined $\lambda_{12} \equiv \lambda_1 + \lambda_2$ and $\lambda_{123} \equiv \lambda_3 + \lambda_1 - \lambda_2$. The following identifications are required to match Eq. (17) with Eq. (3).

$$\begin{aligned} a &\equiv y_1^2 v^2 [4 r_{12} \lambda_{123} + 2 r \lambda_{12}] = y_1^2 v^2 [4 r_{12} (\lambda_3 + \lambda_1 - \lambda_2) + 2r(\lambda_1 + \lambda_2)] \\ b &\equiv y_2^2 v^2 r \lambda_{12} = y_2^2 v^2 r (\lambda_1 + \lambda_2) \\ c &\equiv y_1 y_2 v^2 [r_{12}\lambda_{12} + 2r\lambda_{123}] = y_1 y_2 v^2 [r_{12}(\lambda_1 + \lambda_2) + 2r(\lambda_3 + \lambda_1 - \lambda_2)] \\ d &\equiv y_2^2 v^2 (2 r_{12} \lambda_{123}) = y_2^2 v^2 [2 r_{12} (\lambda_3 + \lambda_1 - \lambda_2)]. \end{aligned} \tag{18}$$

With the form of left-handed Majorana mass matrix for $\theta_{13} = 0$ and $\theta_{23} = \pi/4$ achieved within the model framework, let us now try to get the realistic mixing angles i.e., $\theta_{13} \neq 0$, deviations of θ_{23} from $\pi/4$ as well as small corrections to the solar mixing. In order to get that, as already mentioned, we will shift from the condition $r_{11} = r_{22} = r$ by a small amount i.e., apply $r_{22} = r_{11} + \epsilon$

keeping $v_1 = v_2 = v$ fixed. The criterion $r_{22} = r_{11} + \epsilon$ makes $m_{R_{11}} \neq m_{R_{22}}$ in Eq. (11) causing small deviation from the maximal mixing between N_{1R} and N_{2R}. Using $r_{22} = r_{11} + \epsilon$ with $v_1 = v_2 = v$ in Eq. (17) one can write $M_{\nu_L}^{flavour}$ as $M_{\nu_L}^{flavour} = M^0 + M'$, where M^0 is the dominant part and M' is a small contribution proportional to ϵ. Thus,

$$M^0 = v^2 \begin{pmatrix} y_1^2[4r_{12}\lambda_{123} + 2r_{11}\lambda_{12}] & y_1y_2[r_{12}\lambda_{12} + 2r_{11}\lambda_{123}] & y_1y_2[r_{12}\lambda_{12} + 2r_{11}\lambda_{123}] \\ y_1y_2[r_{12}\lambda_{12} + 2r_{11}\lambda_{123}] & y_2^2 r_{11}\lambda_{12} & y_2^2(2r_{12}\lambda_{123}) \\ y_1y_2[r_{12}\lambda_{12} + 2r_{11}\lambda_{123}] & y_2^2(2r_{12}\lambda_{123}) & y_2^2 r_{11}\lambda_{12} \end{pmatrix}, \tag{19}$$

and

$$M' = \epsilon \begin{pmatrix} x & y & 0 \\ y & x' & 0 \\ 0 & 0 & 0 \end{pmatrix}, \tag{20}$$

with

$$\begin{aligned} x &\equiv y_1^2 v^2 \lambda_{12} = y_1^2 v^2 (\lambda_1 + \lambda_2) \\ x' &\equiv y_2^2 v^2 \lambda_{12} = y_2^2 v^2 (\lambda_1 + \lambda_2) \\ y &\equiv y_1 y_2 v^2 \lambda_{123} = y_1 y_2 v^2 (\lambda_3 + \lambda_1 - \lambda_2). \end{aligned} \tag{21}$$

Again if we identify:

$$\begin{aligned} a' &\equiv y_1^2 v^2 [4r_{12}\lambda_{123} + 2r_{11}\lambda_{12}] = y_1^2 v^2 [4r_{12}(\lambda_3 + \lambda_1 - \lambda_2) + 2r_{11}(\lambda_1 + \lambda_2)] \\ b' &\equiv y_2^2 v^2 r_{11}\lambda_{12} = y_2^2 v^2 r_{11}(\lambda_1 + \lambda_2) \\ c' &\equiv y_1 y_2 v^2 [r_{12}\lambda_{12} + 2r_{11}\lambda_{123}] = y_1 y_2 v^2 [r_{12}(\lambda_1 + \lambda_2) + 2r_{11}(\lambda_3 + \lambda_1 - \lambda_2)] \\ d' &\equiv y_2^2 v^2 (2r_{12}\lambda_{123}) = y_2^2 v^2 [2r_{12}(\lambda_3 + \lambda_1 - \lambda_2)] \end{aligned} \tag{22}$$

M^0 will be giving the form of Eq. (3). Let us define:

$$\gamma \equiv (b' - 3d' - a') \text{ and } \rho \equiv \sqrt{a'^2 + b'^2 + 8c'^2 + d'^2 - 2a'b' - 2a'd' + 2b'd'} \tag{23}$$

and apply non-degenerate perturbation theory correct up-to first order and calculate the third first-order corrected ket:

$$|\psi_3\rangle = \begin{pmatrix} \frac{\epsilon}{\gamma^2 - \rho^2}\left[\rho(\sqrt{2}y\cos 2\theta_{12}^0 - x'\sin 2\theta_{12}^0) - \gamma\sqrt{2}y\right] \\ -\frac{1}{\sqrt{2}}[1 + \xi\epsilon] \\ \frac{1}{\sqrt{2}}[1 - \xi\epsilon] \end{pmatrix}, \tag{24}$$

where,

$$\xi \equiv [\gamma x' + \rho(x'\cos 2\theta_{12}^0 + \sqrt{2}y\sin 2\theta_{12}^0)]/(\gamma^2 - \rho^2). \tag{25}$$

One can compare Eq. (24) with the third column of the PMNS matrix in Eq. (1) and write:

$$\sin\theta_{13} = \frac{\epsilon}{\gamma^2 - \rho^2}\left[\rho(\sqrt{2}y\cos 2\theta_{12}^0 - x'\sin 2\theta_{12}^0) - \gamma\sqrt{2}y\right]. \tag{26}$$

for a CP-conserving case that gives us non-zero θ_{13}. From Eq. (24), we get the shift in θ_{23} from $\pi/4$ as:

$$\tan\varphi \equiv \tan(\theta_{23} - \pi/4) = \xi\epsilon. \tag{27}$$

The corrections to θ_{12} is given by:

$$\tan\theta_{12} = \frac{\sin\theta_{12}^0 + \epsilon\beta\cos\theta_{12}^0}{\cos\theta_{12}^0 - \epsilon\beta\sin\theta_{12}^0}, \tag{28}$$

where,

$$\beta \equiv \frac{\left[\frac{y}{\sqrt{2}}\cos 2\theta_{12}^0 + \frac{1}{2}(x - \frac{x'}{2})\sin 2\theta_{12}^0\right]}{\rho}. \tag{29}$$

Lepton flavour violating decays are completely forbidden in this model set-up owing to the $S3$ symmetry. A detailed discussion can be found in [1].

3. CONCLUSIONS

In this radiative neutrino mass model based on $S3 \times Z_2$ symmetry at one-loop level, we have two Z_2 odd right-handed neutrinos N_{1R} and N_{2R}. When N_{1R} and N_{2R} are mixed maximally we get the left-handed Majorana neutrino mass matrix form needed for $\theta_{13} = 0$ and $\theta_{23} = \pi/4$ and solar mixing of any values corresponding to the popular lepton mixings like TBM, BM and GR as shown in Table 1. Deviating from maximal mixing between N_{1R} and N_{2R} yields realistic neutrino mixings in agreement with neutrino oscillation data i.e., non-zero θ_{13}, shits of θ_{23} from $\pi/4$ and small corrections to θ_{12}. The lightest of the two Z_2 odd inert $SU(2)_L$ doublet scalars η_i, ($i = 1, 2$) can become a dark matter candidate. Thus the model is scotogenic.

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