

Froggatt-Nielsen-like mechanism in the framework of modular symmetry for neutrino mass, mixing, and leptogenesis

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We study a neutrino mass model with Froggatt-Nielsen (FN) like modular symmetry. The FN mechanism requires an additional gauge symmetry, $U(1)_{\text{FN}}$, which is spontaneously broken at high energies. But in this work, we do not need an extra symmetry as modular weights play the role of the FN charges of the additional $U(1)_{\text{FN}}$ symmetry. We have constructed a neutrino mass model using FN-like modular symmetry in the T' group. This model can accommodate neutrino oscillation parameters and also address other phenomena beyond the Standard Model, such as neutrinoless double beta decay and the baryon asymmetry of the Universe.

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I. INTRODUCTION

Despite the immense success of the Standard Model (SM), several unsolved problems remain. One of the most challenging problems is the flavor structure of the Standard Model fermions. The hierarchy between mixing angles and masses in both the quark and neutrino sectors can only be explained by a beyond the SM mechanism. Since in the SM, Yukawa couplings are free parameters, the hierarchy cannot be explained in the framework of the SM.

Recently, modular symmetry was proposed to solve the flavor puzzle of the SM [1]. In this framework, flavor structure can be achieved without requiring many flavon fields, and the flavor symmetry is completely broken by the vacuum expectation value (VEV) of the modulus τ , which is a complex parameter. The Yukawa couplings are also not free parameters. The Yukawa couplings are written in terms of modular forms, which are functions of the modulus τ . They transform nontrivially under the finite modular group Γ_N , and Γ_N is isomorphic to the non-Abelian discrete group. In the literature, there are several modular symmetric models available: $\Gamma_2 \cong S_3$ [2,3], $\Gamma_3 \cong A_4$ [4–9], $\Gamma_4 \cong S_4$ [10–13], $\Gamma_5 \cong A_5$ [14,15] and also double cover modular group Γ'_N such as: $\Gamma'_2 = \Gamma_2 \cong S_3$, $\Gamma'_3 \cong T'$ [16,17], $\Gamma'_4 \cong S'_4$ [18,19] and $\Gamma'_5 \cong A'_5$ [20–22]. In this work, we are constructing a model based on the modular double covering group T' .

The Froggatt-Nielsen (FN) mechanism provides an elegant and economical framework for explaining the flavor structure of the quark and neutrino sectors using a horizontal $U(1)_{\text{FN}}$ symmetry [23–27]. In the original FN mechanism, fermions carry additional FN charge under the gauge group $U(1)_{\text{FN}}$, and Yukawa couplings are forbidden at the tree level. The $U(1)_{\text{FN}}$ symmetry is spontaneously broken by an extra scalar field ϕ , which is a trivial singlet under the SM gauge group. At low energies, the $U(1)_{\text{FN}}$ symmetry is spontaneously broken, and after integrating out the heavy fields, we get effective Yukawa couplings suppressed by its vacuum expectation value $(\langle\phi\rangle/\Lambda)^n$. Here, $\langle\phi\rangle$ is the VEV of the scalar ϕ and n is the difference of $U(1)_{\text{FN}}$ charges between fermion generations. This mechanism has been extensively studied in the quark sector, but its application in the leptonic sector gives rise to new challenges. In the quark sector, the masses and mixing angles all arise from Dirac-like Yukawa couplings. However, the underlying mechanism for neutrino mass generation is currently unknown, which leads to a large variety of possible implementations. In this work, we studied the FN mechanism for the leptonic sector using modular T' groups, and neutrino mass is generated via the type-I seesaw mechanism [28–32].

In this work, we have used an FN-like mechanism in the framework of modular symmetry to study neutrino oscillation parameters and other beyond the SM phenomenology. The FN-like mechanism has been recently used for the quark sector [33,34]. Here we are dealing with an FN-like mechanism for the leptonic sector. In analogy to the FN mechanism, the modular weights of fermion fields serve the role of $U(1)_{\text{FN}}$ charge. The extra scalar field ϕ , which is a singlet under the SM gauge group, compensates for the modular weights of the fermion fields. The Yukawa couplings are also of modular forms, and the effective

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Yukawa couplings that emerge through higher-dimensional operators are suppressed by some powers of $\Phi = (\langle \phi \rangle / \Lambda)$. Φ is called spurion associated with the breaking of $U(1)_{\text{FN}}$.

One of the outstanding problems of neutrino physics is whether neutrinos are Dirac or Majorana in nature. Neutrinoless double beta decay ($0\nu\beta\beta$) [35–38] is a hypothetical nuclear reaction that emits two electrons without accompanying neutrinos. The observation of this reaction would confirm that neutrinos are Majorana particles, i.e., they are their own antiparticles. In this work, we have studied our model prediction for this reaction.

Numerous observational findings indicate an imbalance between matter and antimatter in our Universe. The SM does not have enough ingredients to explain this imbalance, and we need to go beyond the SM to explain this. This longstanding matter antimatter asymmetry puzzle is known as the baryon asymmetry of universe (BAU). For the dynamical generation of baryon asymmetry, the three Sakharov conditions need to be satisfied [39]: *baryon number (B) violation, C or CP violation, and out of equilibrium condition*. In the seesaw framework, all three conditions are satisfied naturally. Therefore, the process responsible for generating the baryon asymmetry, known as leptogenesis, becomes an integral part of the seesaw framework. In this work, we will establish the baryon asymmetry of the universe via *thermal leptogenesis* in a FN-like modular model.

This work is organized as follows. In Sec. II. We briefly addressed the modular symmetry and the T' group. We explicitly addressed all the components of the model framework in Sec. III. Numerical analysis for the neutrino sector, neutrinoless double beta decay, and thermal leptogenesis is discussed in Sec. IV. Finally, we concluded our analysis in Sec. V.

II. MODULAR SYMMETRY AND T' GROUP

A. Modular symmetry

$\bar{\Gamma}$ is the modular group that attains a linear fractional transformation γ which acts on modulus τ linked to the upper-half complex plane whose transformation is given by [1]

$$\gamma \longrightarrow \gamma\tau = \frac{a\tau + b}{c\tau + d}, \quad (1)$$

where $a, b, c, d \in \mathbb{Z}$, and $ad - bc = 1$, $\text{Im}[\tau] > 0$, where it is isomorphic to the transformation $PSL(2, \mathbb{Z}) = SL(2, \mathbb{Z})/\{I, -I\}$. The S and T transformation helps in generating the modular transformation defined by

$$S: \tau \longrightarrow -\frac{1}{\tau}, \quad T: \tau \longrightarrow \tau + 1, \quad (2)$$

and hence the algebraic relations so satisfied are as follows,

$$S^2 = \mathbb{I}, \quad (ST)^3 = \mathbb{I}. \quad (3)$$

Here, series of groups are introduced, $\Gamma(N)$ ($N = 1, 2, 3, \dots$) and defined as

$$\Gamma(N) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in SL(2, \mathbb{Z}), \right. \\ \left. \begin{pmatrix} a & b \\ c & d \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \pmod{N} \right\}. \quad (4)$$

Definition of $\bar{\Gamma}(2) \equiv \Gamma(2)/\{I, -I\}$ for $N = 2$. Since $-I$ is not associated with $\Gamma(N)$ for $N > 2$ case, one can have $\bar{\Gamma}(N) = \Gamma(N)$, which are infinite normal subgroups of $\bar{\Gamma}$ known as principal congruence subgroups. Quotient groups come from the finite modular group, defined as $\Gamma_N = \bar{\Gamma}/\bar{\Gamma}(N)$. The imposition of $T^N = \mathbb{I}$ is done for these finite groups Γ_N . Thus, the groups Γ_N ($N = 2, 3, 4, 5$) are isomorphic to S_3 , A_4 , S_4 , and A_5 , respectively. N level modular forms are holomorphic functions $f(\tau)$ which are transformed under the influence of $\Gamma(N)$ as follows:

$$f(\gamma\tau) = (c\tau + d)^k f(\tau), \quad \gamma \in \Gamma(N) \quad (5)$$

where k is the modular weight. The prefactor $(c\tau + d)^k$ is referred to as the automorphy factor. Since linear combinations of the modular forms of level N and weight k are also modular forms of level N and weight k . Hence they form a linear space $\mathcal{M}_k(\Gamma_N)$. The modular forms from the unitary representations of the quotient group $\Gamma_N = \Gamma/\Gamma(N)$ are given by

$$f_i(\gamma\tau) = (c\tau + d)^k \rho(\gamma)_{ij} f_j(\tau) \quad (6)$$

is where f_i is a basis of $\mathcal{M}_k(\Gamma_N)$, and ρ is a unitary representation of Γ_N . From the automorphy factor, it can be seen that the modular group is divided by its center, and therefore, modular forms are well defined only for even modular weight. The Γ is called the inhomogeneous modular group to distinguish it from the double covering group of the modular group Γ' , which is homogeneous. Similar to Γ_N its quotient group Γ'_N is obtained as follows:

$$\Gamma'_N = \Gamma'/\Gamma'(N), \quad (7)$$

where $\Gamma'(N)$ is a subgroup of Γ' . Γ' is nothing but $SL(2, \mathbb{Z})$ itself. The following relations are satisfied by the generators of Γ'_N

$$S^2 = R, \quad (ST)^3 = I, \quad T^N = I, \quad TR = RT, \quad R^2 = I. \quad (8)$$

Similar to Γ_N , for $N < 6$ the Γ'_N is also isomorphic to non-Abelian group: $\Gamma'_2 \simeq S_3$, $\Gamma'_3 \simeq T'$, $\Gamma'_4 \simeq S'_4$, and $\Gamma'_5 \simeq A'_5$. In the double covering of the modular group, we can define modular forms of odd modular weights as well. In this work, we consider a modular symmetric model based on Γ' , and all the matter fields are represented by chiral

superfields. These fields transform as the modular forms of level N and weight k as follows:

$$\gamma: \Phi_i \rightarrow (c\tau + d)^{k_i} \rho_\Phi(\gamma)_{i,j} \Phi_j, \quad (9)$$

where Φ_i is a matter field and $\rho_\Phi(\gamma)$ is a unitary matrix. The action of chiral superfields Φ_i is given by

$$S = \int d^4x d^2\theta d^2\bar{\theta} K(\Phi^i, \bar{\Phi}^i, \tau, \bar{\tau}) + \int d^4x d^2\theta W(\Phi^i, \tau) + \text{H.c.}, \quad (10)$$

where K and W are the Kähler potential and the superpotential, respectively. The modular invariant K and W is given as follows:

$$K = \sum_i \frac{\Phi_i \bar{\Phi}_i}{\text{Im } \tau^{-k_i}} \\ W = \sum (f_{i_1 i_2 \dots i_n}(\tau) \Phi_{i_1} \Phi_{i_2} \dots \Phi_{i_n})_1 \quad (11)$$

where $f_{i_1 i_2 \dots i_n}(\tau)$ is a modular form of weight k satisfying

$$k + k_{i_1} + k_{i_2} + \dots + k_{i_n} = 0, \quad (12)$$

so that the modular weight of the superpotential is zero. The allowed Yukawa couplings are also given in the modular forms so that they remain invariant under modular symmetry.

B. T' group

In the section above, we have discussed that Γ'_3 is isomorphic to T' [16,34,40]. This group is a double covering of the tetrahedral group A_4 . The T' has 24 elements, and all these elements can be generated by the three generators S , T , and R fulfilling the following relations:

$$S^2 = R, \quad (ST)^3 = I, \quad T^3 = I, \quad R^2 = I, \quad RT = TR. \quad (13)$$

This group has seven irreducible representations, which are mentioned below

$$1, \quad 1', \quad 1'', \quad 2, \quad 2', \quad 2'', \quad 3. \quad (14)$$

The multiplication rule for this representation under T' is

$$\begin{aligned} 1 \otimes 1 &= 1' \otimes 1'' = 1, & 1 \otimes 1' &= 1'' \otimes 1'' = 1', & 1 \otimes 1'' &= 1' \otimes 1' = 1'', \\ 2 \otimes 2 &= 2' \otimes 2'' = 3 \oplus 1', & 2 \otimes 2' &= 2'' \otimes 2'' = 3 \oplus 1'', & 2 \otimes 2'' &= 2' \otimes 2' = 3 \oplus 1, \\ 2 \otimes 3 &= 2 \oplus 2' \oplus 2'', & 2' \otimes 3 &= 2 \oplus 2' \oplus 2'', & 2 \otimes 3 &= 2 \oplus 2' \oplus 2'', \\ 3 \otimes 3 &= 1 \oplus 1' \oplus 1'' \oplus 3_S \oplus 3_A. \end{aligned} \quad (15)$$

For the modular form of weight 1 and level 3, we can construct a doublet of $\Gamma'_3 \cong T'$

$$Y_2^{(1)} = \begin{pmatrix} Y_1(\tau) \\ Y_2(\tau) \end{pmatrix}. \quad (16)$$

The q -expansion of the component of the doublet modular form $Y_2^{(1)}$ is given by

$$\begin{aligned} Y_1(\tau) &= \sqrt{2} e^{i7\pi/12} q^{1/3} (1 + q + 2q^2 + 2q^4 + q^5 + 2q^6 + \dots), \\ Y_2(\tau) &= 1/3 + 2q + 2q^3 + 2q^4 + 4q^7 + 2q^9 + \dots \end{aligned} \quad (17)$$

where $q = e^{i2\pi\tau}$. The detailed derivation of this can be found in [34]. Higher modular weight Yukawa couplings can be constructed from the weight 1 Yukawa coupling $Y_2^{(1)}$ using the T' multiplication rule. For modular weight $k = 2$, we have the following modular forms:

$$\begin{aligned} Y_1^{(2)} &= \left(Y_2^{(1)} Y_2^{(1)} \right)_1 = Y_1 Y_2 - Y_2 Y_1 = 0, \\ Y_3^{(2)} &= (Y_2^{(1)} Y_2^{(1)})_3 = \left(e^{i\pi/6} Y_2^2, \sqrt{2} e^{i7\pi/12} Y_1 Y_2, Y_1^2 \right)^T. \end{aligned} \quad (18)$$

For modular weight 3, we can have the following modular forms:

$$\begin{aligned} Y_2^{(3)} &= \left(Y_2^{(1)} Y_3^{(2)} \right)_2 = \left(3e^{i\pi/6} Y_1 Y_2^2, \sqrt{2}e^{i5\pi/12} Y_1^3 - e^{i\pi/6} Y_2^3 \right)^T, \\ Y_{2'}^{(3)} &= \left(Y_2^{(1)} Y_3^{(2)} \right)_{2'} = (0, 0)^T, \\ Y_{2''}^{(3)} &= \left(Y_2^{(1)} Y_3^{(2)} \right)_{2''} = (Y_1^3 + (1-i)Y_2^3, -3Y_2 Y_1^2)^T. \end{aligned} \quad (19)$$

Similarly, for weight 4, the following nonvanishing and independent modular forms can be constructed:

$$\begin{aligned} Y_3^{(4)} &= \left(Y_2^{(1)} Y_3^{(3)} \right)_3 = \left(\sqrt{2}e^{i7\pi/12} Y_1^3 Y_2 - e^{i\pi/3} Y_2^4, -Y_1^4 - (1-i)Y_1 Y_2^3, 3e^{i\pi/6} Y_1^2 Y_2^2 \right)^T, \\ Y_{1'}^{(4)} &= \left(Y_2^{(1)} Y_3^{(3)} \right)_{1'} = \sqrt{2}e^{i5\pi/12} Y_1^4 - 4e^{i\pi/6} Y_1 Y_2^3, \\ Y_1^{(4)} &= -4Y_1^3 Y_2 - (1-i)Y_2^4. \end{aligned} \quad (20)$$

The following relations give the weight 5 nonvanishing and independent modular forms:

$$\begin{aligned} Y_2^{(5)} &= \left(Y_2^{(1)} Y_3^{(4)} \right)_2 = \left(2\sqrt{2}e^{i7\pi/12} Y_1^4 Y_2 + e^{i\pi/3} Y_1 Y_2^4, 2\sqrt{2}e^{i7\pi/12} Y_1^3 Y_2^2 + e^{i\pi/3} Y_2^5 \right)^T, \\ Y_{2'}^{(5)} &= \left(Y_2^{(1)} Y_3^{(4)} \right)_{2'} = \left(-Y_1^5 + 2(1-i)Y_1^2 Y_2^3, -Y_1^4 Y_2 + 2(1-i)Y_1 Y_2^4 \right)^T, \\ Y_{2''}^{(5)} &= \left(Y_2^{(1)} Y_3^{(4)} \right)_{2''} = \left(5e^{i\pi/6} Y_1^3 Y_2^2 - (1-i)e^{i\pi/6} Y_2^5, -\sqrt{2}e^{i5\pi/12} Y_1^5 - 5e^{i\pi/6} Y_1^2 Y_2^3 \right)^T. \end{aligned} \quad (21)$$

We can construct other higher weight modular forms similar way. But in this work, we are dealing with up to weight 5 modular forms.

III. MODEL FRAMEWORK

In this work, we have constructed a model based on modular $\Gamma_3' \equiv T'$. To study the type I seesaw mechanism for neutrino mass generation, we have considered the charged assignment for different superfields as given in the Table I. The different modular weight Yukawa couplings used for this analysis is given in the Table II. We assign T' triplet **3** to the three generation of left-handed lepton doublet L while the three right-handed charged lepton e_R^c, μ_R^c and τ_R^c transform as **1**, **1''**, and **1'** respectively under T' . Two of the three right-handed neutrinos ($N_{R_1}^c, N_{R_2}^c$) are embedded into a T' doublet **2** while the remaining $N_{R_3}^c$ is assigned as **1**.

TABLE I. Superfield content of the model with their T' and modular charges k_I .

Symmetry	Superfield content and charge								
	L	e_R^c	μ_R^c	τ_R^c	N_{R_1, R_2}^c	$N_{R_3}^c$	H_u	H_d	ϕ
$SU(2)_L$	2	1	1	1	1	1	2	2	1
$U(1)_Y$	-1	2	2	2	0	0	1	-1	0
T'	3	1	1''	1'	2	1	1	1	1
k_I	-2	3	3	3	2	4	0	0	-1

We also assign trivial singlet **1** under T' to both Higgs doublets $H_{u/d}$. We also introduce a new chiral superfield ϕ called weighton. This ϕ is the trivial singlet under both T' and the SM gauge group. It also carries -1 modular weight. The modular weight for other fields is presented in the Table I. After the breaking of modular symmetry, ϕ develops its VEV, and the effective superpotentials for our FN-like model with T' obtained are discussed below. In all the superpotential terms, Φ stands for $\langle \phi \rangle / \Lambda$, where Λ is the cutoff scale. In this study, we have taken the FN scale the same as the Majorana mass scale $M = \Lambda$ [27].

The charge assignment is shown in Table I gives the following charged lepton superpotential:

$$\begin{aligned} \mathcal{W}_l &= \alpha e_R^c H_d \left(L Y_3^{(2)} \right)_1 \Phi^3 + \beta \mu_R^c H_d \left(L Y_3^{(2)} \right)_{1'} \Phi^3 \\ &\quad + \gamma \tau_R^c H_d \left(L Y_3^{(2)} \right)_{1''} \Phi^3. \end{aligned} \quad (22)$$

TABLE II. Yukawa couplings with their T' and modular charges k_I .

Yukawa couplings			
	$Y_3^{(2)}$	$Y_2^{(3)}$	$Y_{2''}^{(5)}$
T'	3	2	2''
k_I	2	3	5

The charged lepton mass matrix takes the form

$$M_l = v_d \Phi^3 \begin{pmatrix} \alpha e^{\frac{i\pi}{6}} Y_2 Y_2 & \alpha Y_1 Y_1 & \alpha \sqrt{2} e^{\frac{i\pi}{12}} Y_1 Y_2 \\ \beta \sqrt{2} e^{\frac{i\pi}{12}} Y_1 Y_2 & \beta e^{\frac{i\pi}{6}} Y_2 Y_2 & \beta Y_1 Y_1 \\ \gamma Y_1 Y_1 & \gamma \sqrt{2} e^{\frac{i\pi}{12}} Y_1 Y_2 & \gamma e^{\frac{i\pi}{6}} Y_2 Y_2 \end{pmatrix}. \quad (23)$$

$$\begin{aligned} \mathcal{W}_D = & g_1 \left((N_{R_1, R_2}^c L)_{2''} Y_2^{(3)} \right)_1 \Phi^3 H_u \\ & + g_2 \left((N_{R_1, R_2}^c L)_2 Y_{2''}^{(5)} \right)_1 \Phi^5 H_u \\ & + g_3 \left((N_{R_3}^c L)_3 Y_3^{(2)} \right)_1 \Phi^4 H_u. \end{aligned} \quad (24)$$

The Dirac mass matrix is obtained to be

Here, $\langle H_d \rangle = v_d$ is the VEV of Higgs superfield H_d and $\{\alpha, \beta, \gamma\}$ are free parameters. The charged lepton mass matrix is found to be nondiagonal.

The invariant Dirac superpotential involving lepton fields L_i and heavy right-handed fields $N_{R_i}^c$ is given as follows:

$$M_D = v_u \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{pmatrix} \quad (25)$$

where the elements of the matrix are given as follows:

$$\begin{aligned} m_{11} &= g_2 \Phi^5 \left(5e^{\frac{i\pi}{6}} (Y_1)^3 (Y_2)^2 - (1-i)e^{\frac{i\pi}{6}} (Y_2)^5 \right) \\ m_{12} &= \left[g_1 \Phi^3 \left(-3\sqrt{2} e^{\frac{i\pi}{12}} Y_1 (Y_2)^2 \right) + g_2 \Phi^5 \left(\sqrt{2} e^{\frac{i\pi}{12}} (Y_1)^5 + 5e^{\frac{i\pi}{6}} (Y_1)^2 (Y_2)^3 \right) \right] \\ m_{13} &= g_3 \Phi^4 e^{\frac{i\pi}{6}} (Y_2)^2 \\ m_{21} &= g_1 \Phi^3 \left(2e^{\frac{i\pi}{6}} (Y_1)^3 - \sqrt{2} e^{\frac{i\pi}{12}} (Y_2)^3 \right) \\ m_{22} &= g_2 \Phi^5 \left[(1-i)\sqrt{2} e^{\frac{i\pi}{12}} (Y_2)^5 - 5\sqrt{2} e^{\frac{i\pi}{12}} (Y_1)^3 (Y_2)^2 \right] \\ m_{23} &= g_3 \Phi^4 \sqrt{2} e^{\frac{i\pi}{12}} Y_1 Y_2 \\ m_{31} &= \left[g_1 \Phi^3 (3e^{\frac{i\pi}{6}} Y_1 (Y_2)^2) - g_2 \Phi^5 \left(2e^{\frac{i\pi}{6}} (Y_1)^5 + 5\sqrt{2} e^{\frac{i\pi}{12}} (Y_1)^2 (Y_2)^3 \right) \right] \\ m_{32} &= g_1 \Phi^3 \left(e^{\frac{i\pi}{6}} (Y_2)^3 - \sqrt{2} e^{\frac{i\pi}{12}} (Y_1)^3 \right) \\ m_{33} &= g_3 \Phi^4 (Y_1)^2 \end{aligned} \quad (26)$$

where $\{g_1, g_2, g_3\}$ are free parameters and $\langle H_u \rangle = v_u$ is the VEV of Higgs superfield H_u .

The superpotential involving the Majorana mass term can be written as follows:

$$\mathcal{W}_R = \Lambda (N_{R_1, R_2}^c N_{R_1, R_2}^c)_3 Y_3^{(2)} \Phi^6 + \Lambda (N_{R_3}^c N_{R_1, R_2}^c)_2 Y_{2''}^{(3)} \Phi^9 + \Lambda (N_{R_3}^c N_{R_3}^c) \Phi^8 \quad (27)$$

where Λ is the mass scale.

This gives the following Majorana mass matrix:

$$M_R = \Lambda \begin{pmatrix} \sqrt{2} e^{\frac{i\pi}{12}} Y_1 Y_2 \Phi^6 & \frac{1}{\sqrt{2}} e^{\frac{i\pi}{12}} (Y_1)^2 \Phi^6 & -3(Y_1)^2 Y_2 \Phi^9 \\ \frac{1}{\sqrt{2}} e^{\frac{i\pi}{12}} (Y_1)^2 \Phi^6 & e^{\frac{i\pi}{3}} (Y_2)^2 \Phi^6 & -((Y_1)^3 + (1-i)(Y_2)^3) \Phi^9 \\ -3(Y_1)^2 Y_2 \Phi^9 & -((Y_1)^3 + (1-i)(Y_2)^3) \Phi^9 & \Phi^8 \end{pmatrix}. \quad (28)$$

Within the current model, which incorporates T' modular symmetry, the complete 6×6 neutral fermion mass matrix for the type I seesaw mechanism in the flavor basis (ν_L, N_R^c) is given by

$$\mathbb{M} = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}. \quad (29)$$

Using the appropriate mass hierarchy among the mass matrices as provided below

$$M_R \gg M_D, \quad (30)$$

The light neutrino mass in the type I seesaw is given by

$$m_\nu = M_D M_R^{-1} M_D^T. \quad (31)$$

IV. NUMERICAL ANALYSIS

A. Neutrino fit data

In general, the parameters $\{\alpha, \beta, \gamma\}$ taken in the charged lepton mass matrix in Eq. (23) are complex. However, they can be taken as real without the loss of generality by absorbing their phases into the right-handed lepton fields. Hence, their value can be completely determined by the charged lepton masses via the following relations:

$$\text{Tr}(M_l M_l^\dagger) = m_e^2 + m_\mu^2 + m_\tau^2$$

$$\text{Det}(M_l M_l^\dagger) = m_e^2 m_\mu^2 m_\tau^2$$

$$\frac{1}{2} [\text{Tr}(M_l M_l^\dagger)]^2 - \frac{1}{2} \text{Tr}[(M_l M_l^\dagger)^2] = m_e^2 m_\mu^2 + m_\mu^2 m_\tau^2 + m_\tau^2 m_e^2. \quad (32)$$

Also, the charged lepton mass matrix is nondiagonal in this study, and it is diagonalized by the unitary matrix U_l , with $U_l^\dagger M_l M_l^\dagger U = \text{diag}(m_e^2, m_\mu^2, m_\tau^2)$. The neutrino mass matrix obtain in Eq. (31) is diagonalized by using the relation: $U_\nu^\dagger \mathcal{M} U_\nu = \text{diag}(m_1^2, m_2^2, m_3^2)$, where $\mathcal{M} = m_\nu m_\nu^\dagger$ and U_ν is a unitary matrix. Hence, the well-known Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix is calculated using the relation $U = U_l^\dagger U_\nu$ [41]. This matrix is parametrized by three mixing angles ($\theta_{12}, \theta_{13}, \theta_{23}$), one Dirac phase (δ_{CP}) and two Majorana phases (α_{21}, α_{31}) as given below

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix} \quad (33)$$

where, $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$. Using the PMNS matrix, we can calculate the three neutrino mixing angles as follows:

$$\begin{aligned} \sin^2 \theta_{13} &= |U_{13}|^2, & \sin^2 \theta_{12} &= \frac{|U_{12}|^2}{1 - |U_{13}|^2}, \\ \sin^2 \theta_{23} &= \frac{|U_{23}|^2}{1 - |U_{13}|^2}. \end{aligned} \quad (34)$$

The Jarlskog invariant J_{CP} and the CP -violating phase δ_{CP} are calculated using the elements of the PMNS matrix as given below

$$J_{CP} = \text{Im}[U_{e1}U_{\mu 2}U_{e2}^*U_{\mu 1}^*] = s_{23}c_{23}s_{12}c_{12}s_{13}c_{13}^2 \sin \delta_{CP}. \quad (35)$$

In numerical analysis, we use the global fit neutrino oscillation data within a 3σ interval as given in Table III.

We have taken the following ranges for the model parameters to match the neutrino oscillation data:

$$\begin{aligned} \text{Re}[\tau] &\in [-0.5, 0.5], \quad \text{Im}[\tau] \in [0.8, 1.5], \quad \{g_1, g_2, g_3\} \in [0.1, 1], \\ \Lambda &\in [10^{11}, 10^{14}] \text{ GeV}, \quad \Phi \in [0.2, 0.6]. \end{aligned} \quad (36)$$

The VEV of the Higgs superfields, $\langle H_u \rangle = \frac{v_u}{\sqrt{2}}$ and $\langle H_d \rangle = \frac{v_d}{\sqrt{2}}$ are related to the Standard Model Higgs

VEV, v_H , through the relation $v_H = \sqrt{v_u^2 + v_d^2}$ and the ratio of their VEVs is expressed as $\tan \beta = \frac{v_u}{v_d} = 5$ [4,43]. The input parameters are randomly scanned within the specified parameter ranges. The allowed regions are selected by applying the 3σ constraints on the solar and atmospheric mass-squared differences and mixing angles as listed in the Table III. The relation between the real part of modulus $\text{Re}[\tau]$ and the imaginary part of modulus $\text{Im}[\tau]$ is shown in Fig. 1. The top panel of Fig. 2 illustrates the correlation between the Yukawa coupling components Y_1, Y_2 , and the real part of the modulus $\text{Re}[\tau]$, whereas the bottom panel presents their correlation with the imaginary part $\text{Im}[\tau]$.

Figure 3 illustrates the relation between the sum of neutrino masses $\sum m_\nu$ and the neutrino mixing angles

TABLE III. The NuFIT 6.0 (2024) results [42].

	Normal ordering	
	bfp $\pm 1\sigma$	3σ range
$\sin^2 \theta_{12}$	$0.307^{+0.012}_{-0.011}$	0.275–0.345
$\sin^2 \theta_{13}$	$0.02195^{+0.00054}_{-0.00058}$	0.02023–0.02376
$\sin^2 \theta_{23}$	$0.561^{+0.012}_{-0.015}$	0.430–0.596
$\frac{\Delta m_{21}^2}{10^{-5}(\text{eV}^2)}$	$7.49^{+0.19}_{-0.19}$	6.92–8.05
$\frac{\Delta m_{31}^2}{10^{-3}(\text{eV}^2)}$	$2.534^{+0.025}_{-0.023}$	2.463–2.606

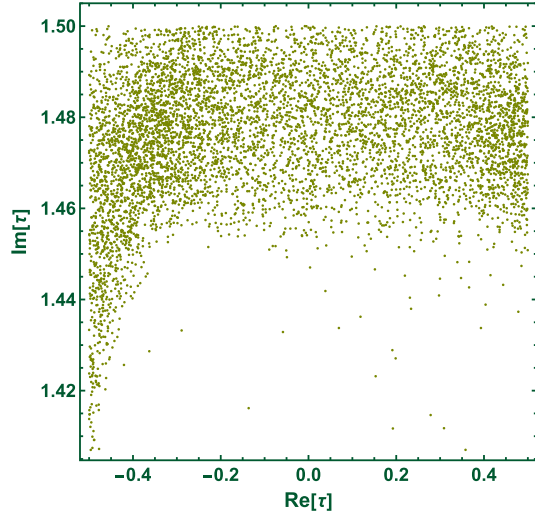
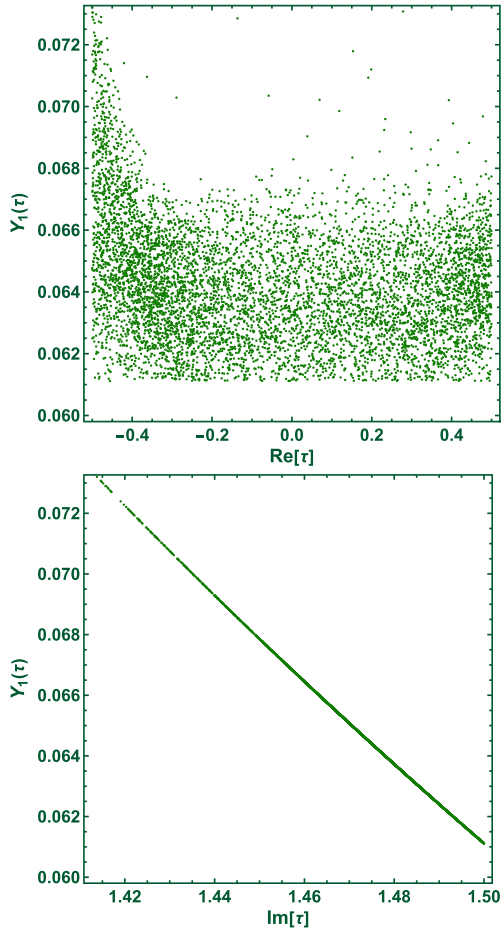


FIG. 1. Correlation between the real component and the imaginary component of τ .



$\{\sin^2 \theta_{13}, \sin^2 \theta_{12}, \sin^2 \theta_{23}\}$. The sum of the neutrino masses is found to be below the upper bound $\sum m_\nu < 0.12$ eV provided by Planck 2018 [44].

In Fig. 4, we have shown the correlation of Jarlskog invariant J_{CP} with the sum of neutrino mass (left panel) and with the Dirac CP phase δ_{CP} (right panel). The value of J_{CP} is found to be in the range $-0.08 \lesssim J_{CP} \lesssim 0.08$. The value of Delta CP phase δ_{CP} is found in the range $\delta_{CP}^o \in [0^\circ, 89^\circ]$ and $\delta_{CP}^o \in [270^\circ, 359^\circ]$.

B. Neutrinoless double beta decay ($0\nu\beta\beta$)

Neutrinoless double beta decay is a hypothetical nuclear reaction that violates conservation of lepton number by $\Delta L = 2$

$$(Z, A) \longrightarrow (Z + 2, A) + 2e^-. \quad (37)$$

In this reaction, the nucleus undergoes double beta decay without emission of neutrinos. Its detection would confirm

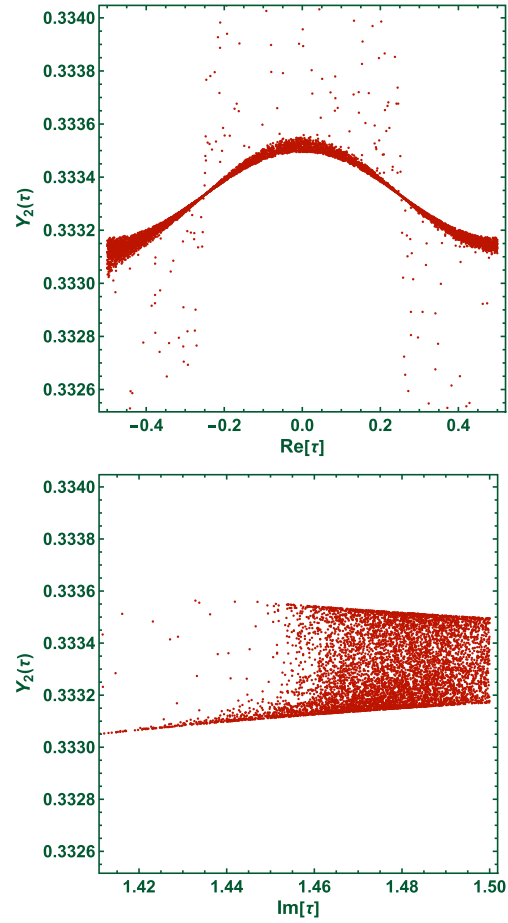


FIG. 2. Top: correlation of Yukawa couplings $Y_1(\tau)$ and $Y_2(\tau)$ with the real part of modulus, i.e., $\text{Re}[\tau]$. Bottom: relationship of Yukawa couplings $Y_1(\tau)$ and $Y_2(\tau)$ with the imaginary part of modulus, i.e., $\text{Im}[\tau]$.

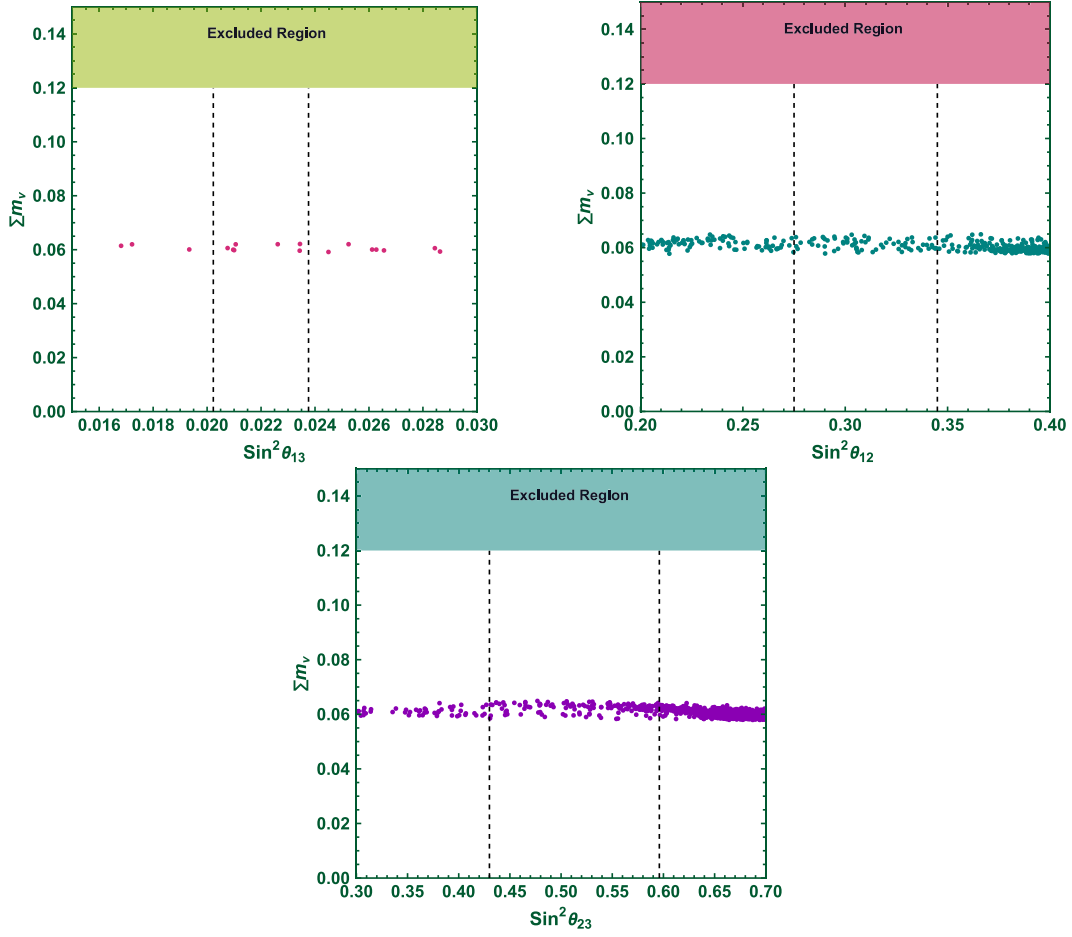


FIG. 3. Correlation of the mixing angles $\sin^2 \theta_{13}$, $\sin^2 \theta_{12}$ and $\sin^2 \theta_{23}$ with the sum of neutrino mass $\sum m_\nu$.

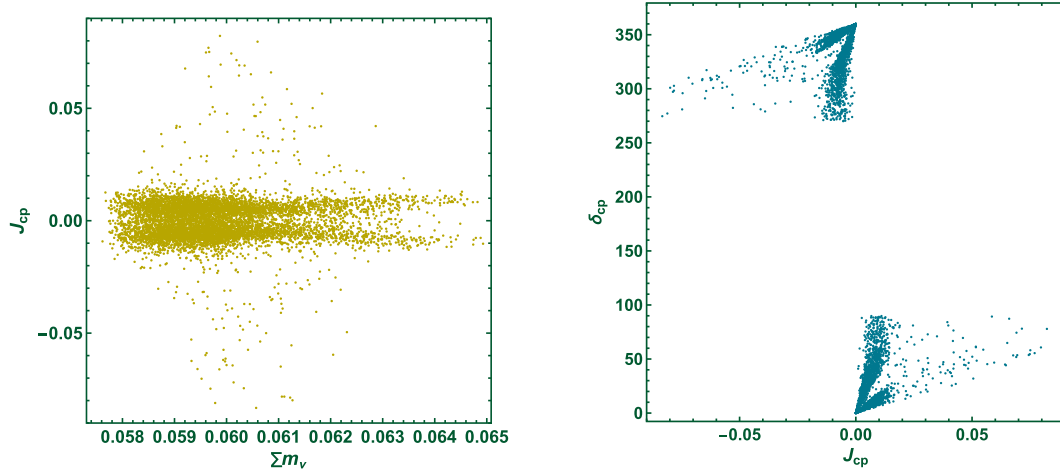


FIG. 4. Left: correlation between J_{CP} and sum of neutrino masses ($\sum m_\nu$). Right: variation of J_{CP} with the Dirac CP phase δ_{CP} .

that neutrinos are Majorana particles. The decay rate for neutrinoless double beta decay is proportional to the effective neutrino mass $|m_{ee}|$

$$|m_{ee}| = \left| m_1 \cos^2 \theta_{12} \cos^2 \theta_{13} + m_2 \sin^2 \theta_{12} \cos^2 \theta_{13} e^{i\alpha_{21}} + m_3 \sin^2 \theta_{13} e^{i(\alpha_{31} - 2\delta_{CP})} \right|. \quad (38)$$

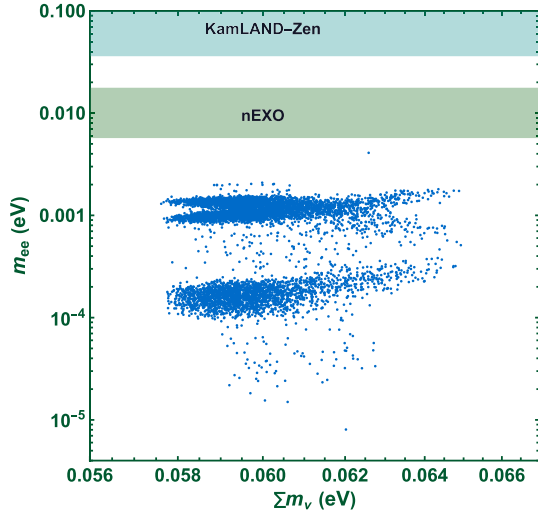


FIG. 5. Effective neutrino mass $|m_{ee}|$ as a function of sum of neutrino mass ($\sum m_\nu$). The shaded region represents the current experimental limit on effective neutrino mass.

In Fig. 5, we have presented our model prediction for $|m_{ee}|$ as a function of the sum of the neutrino mass $\sum m_\nu$. The current experimental limit from KamLAND-Zen [45] experiment for $|m_{ee}|$ is in the range (36 – 156) meV. The sensitivity limits on $|m_{ee}|$ projected for future experiment nEXO [46] lie within (5.7 – 17.7) meV at 90% CL. Our prediction cannot be explored in the current experiments, as evident from Fig. 5.

C. Baryogenesis via thermal leptogenesis

In this study, we have obtained a hierarchical mass pattern for heavy right-handed neutrinos: $M_1 < M_2 < M_3$. The relation between heavy neutrino masses is illustrated in Fig. 6. The heavy neutrinos are not stable and they decay into SM lepton and Higgs doublet via Yukawa couplings [8,47]. The decay of right-handed neutrinos violates lepton number as they can decay into both leptons and antileptons due to their Majorana nature. The out of equilibrium decay of right handed neutrinos produces the lepton asymmetry, which can be transferred into baryon asymmetry via the SM *sphaleron process*. This is known as the leptogenesis mechanism [48–55] for the production of matter-antimatter asymmetry in our universe. In our work, we have used the ULYSSES [56,57] software package to study thermal leptogenesis¹ [61–63]. The semiclassical Boltzmann equation for one decaying right handed neutrino

¹For degenerate mass splitting with $|M_i - M_j| \sim \Gamma_i$, one has to consider the resonant leptogenesis scenario [8,58–60]. Here Γ_i is the decay rate of right handed neutrinos.

N_1 with number density N_{N_1} in the single flavor approximation is given by [64]

$$\begin{aligned} \frac{dN_{N_1}}{dz} &= -D_1(N_{N_1} - N_{N_1}^{eq}) \\ \frac{dN_{B-L}}{dz} &= \epsilon^{(1)}D_1(N_{N_1} - N_{N_1}^{eq}) - W_1N_{B-L} \end{aligned} \quad (39)$$

where N_{B-L} , D_1 , and W_1 are the lepton asymmetry number density, decay, and washout, respectively. The evolution parameter $z = \frac{M_1}{T}$ where M_1 is the mass of lightest right handed neutrino and T is the plasma temperature.

The generated lepton asymmetry N_{B-L} is converted into the baryon to photon ratio via the following relation:

$$\eta_B = a_{\text{sph}} \frac{N_{B-L}}{N_\gamma^{\text{rec}}} = \frac{28}{79} \frac{1}{27} N_{B-L} = 0.013 N_{B-L} \quad (40)$$

where $a_{\text{sph}} = \frac{8}{23}$, as in our case, we assumed that both Higgs doublets survive at sphaleron freeze-out temperature.² The $\frac{1}{27}$ factor comes from the dilution of the baryon asymmetry by photons. This quantity can be measured using two independent probes: big-bang nucleosynthesis (BBN) and microwave background radiation (CMB) data. The measured value of η_B by this two method is given as follows:

$$\begin{aligned} \eta_B(\text{BBN}) &= (5.80 - 6.60) \times 10^{-10} \\ \eta_B(\text{CMB}) &= (6.02 - 6.18) \times 10^{-10} \end{aligned} \quad (41)$$

at 95% CL.

The CP asymmetry $\epsilon_{\alpha\alpha}$ is generated through the out of equilibrium decay of the lightest right handed neutrino N_1 . In the kinetic equations off diagonal flavor oscillation is being excluded. Hence, the total lepton asymmetry $\epsilon^{(1)}$ mentioned in Eq. (39) is calculated by summing over the flavor indices and is given by the following relation [48,61,62]:

$$\epsilon = \sum_\alpha \epsilon_{\alpha\alpha} = \frac{1}{8\pi(Y_D^\dagger Y_D)_{11}} \sum_j \text{Im}\{[(Y_D^\dagger Y_D)_{1j}]^2\} g(x_j) \quad (42)$$

where $x_j = \frac{M_j^2}{M_1^2}$ and

$$g(x) = \sqrt{x} \left[\frac{1}{1-x} + 1 - (1+x) \ln\left(\frac{1+x}{x}\right) \right] \quad (43)$$

²For one Higgs doublet $a_{\text{sph}} = \frac{28}{79}$, and is called the standard model sphaleron factor.

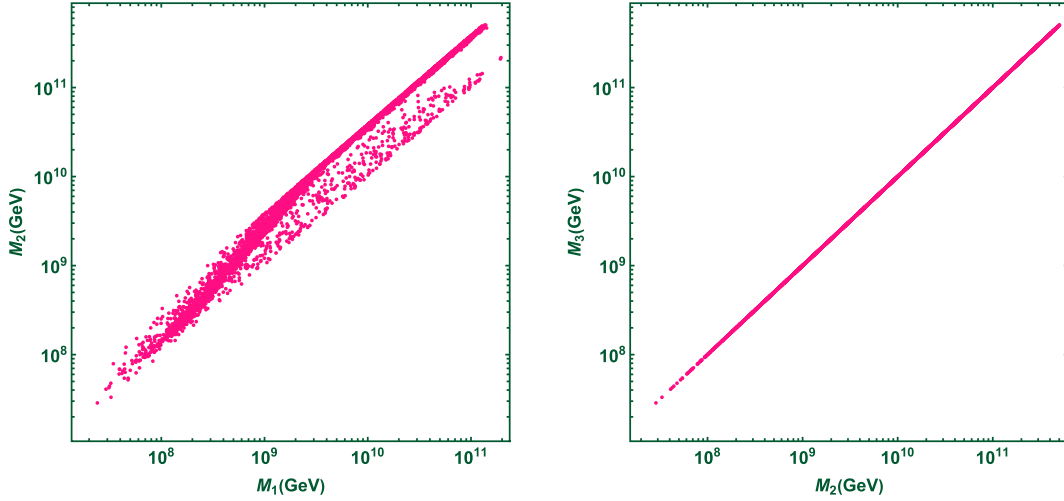


FIG. 6. Left: correlation between heavy neutrino mass M_1 and M_2 and right: between M_2 and M_3 .

The input Yukawa matrix for the calculation of baryon asymmetry in the ULYSSES package is given below

$$Y_D = \begin{pmatrix} -9.4 \times 10^{-5} + i2.7 \times 10^{-5} & -5.9 \times 10^{-4} + i3 \times 10^{-3} & 4.02 \times 10^{-3} + i2.3 \times 10^{-3} \\ 1.5 \times 10^{-3} - i6.05 \times 10^{-3} & 2.4 \times 10^{-6} + i1.3 \times 10^{-4} & -4.2 \times 10^{-4} - i1.1 \times 10^{-3} \\ -2.5 \times 10^{-3} + i2.04 \times 10^{-4} & 3.8 \times 10^{-3} + i2.2 \times 10^{-3} & 5.5 \times 10^{-5} - i1.5 \times 10^{-4} \end{pmatrix} \quad (44)$$

The mass of heavy right handed neutrinos taken as $M_1 = 1.8 \times 10^{10}$ GeV, $M_2 = 6.7 \times 10^{10}$ GeV, $M_3 = 1.2 \times 10^{11}$ GeV. The right-handed neutrino mass and Yukawa couplings also satisfy the neutrino oscillation data, as discussed earlier. We have taken only one set of these values to study the baryon asymmetry using the ULYSSES software package. From Fig. 7, we can see the evolution of single flavor lepton number density

(cyan line) and baryon asymmetry (purple line) with $z = \frac{M_1}{T}$. The observed value of η_B given in Eq. (41) is found to be in close agreement with the value predicted by our model.

V. CONCLUSION

In this work, we have developed a model to study neutrino phenomenology using FN-like modular symmetry. We have implemented T' modular symmetry, and neutrino mass is generated via the type I seesaw framework. FN-like modular symmetry work has been done recently for the quark sector [34]. In this work, we have implemented the same mechanism for the neutrino sector. The advantage of using FN-like modular symmetry is that we do not need additional symmetry $U(1)_{\text{FN}}$, unlike the other FN mechanism without modular symmetry. Here, the modular weights play the role of $U(1)_{\text{FN}}$ charge. A scalar field with a negative modular weight has been introduced, and the allowed Yukawa couplings are then suppressed by powers of the scalar VEV ($\langle \phi \rangle / \Lambda$). Our model produces the mass-squared difference of neutrino mass within the allowed region. All the mixing angles are also found within the 3σ bound. The sum of the light neutrino mass is found within $\sum m_\nu \in [0.0576 - 0.0646]$ eV in NO, which is consistent with the constraint provided by the combination

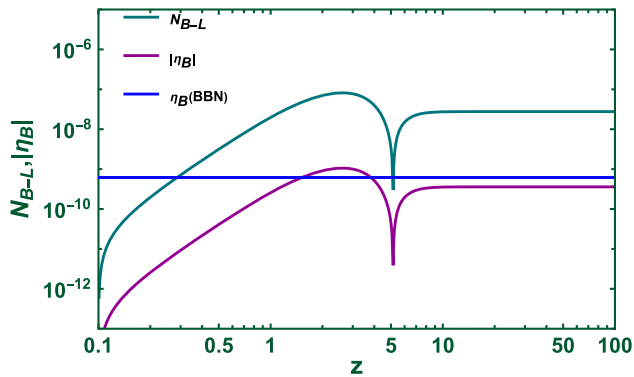


FIG. 7. Variation of lepton number density for single flavor and baryon asymmetry parameter with $z = \frac{M_1}{T}$. The cyan, purple, and blue lines corresponding to N_{B-L} , η_B and $\eta_B(\text{BBN})$, respectively.

of CMB and BAO data by DESI, $\sum m_\nu < 0.0642$ eV [65]. We have also carried out a study of neutrinoless double beta decay, and the m_{ee} value is obtained below the current experiment sensitivity limit for our model. We have also investigated the baryon asymmetry of our universe for the model. We studied baryogenesis via the thermal leptogenesis mechanism for the single flavor case in our work, and it is found to be consistent with the current observed value. It will be interesting to see if this mechanism can be realized in other neutrino mass models also.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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