Neutrino Mixing and Leptogenesis with A_4 Modular Symmetry

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Abstract

- The aim of this work is to construct a model based on A_4 modular symmetry for explaining neutrino oscillation data along with leptogenesis within the framework of Linear seesaw.
- The SM is extended by three RH neutrinos (N_{Ri}), three LH sterile neutrinos (S_{Li}) and one weighton.
- An additional global $U(1)_X$ symmetry has been imposed to eliminate certain unwanted terms in the superpotential, which thus successfully explains the observed neutrino oscillation data and leptogenesis.

Introduction

- A_4 **Modular Symmetry:** Basically the modular group is the group of LFT acting on a complex variable τ.

$$\tau \longrightarrow \gamma\tau = \frac{a\tau + b}{c\tau + d}, \text{ where } a, b, c, d \in \mathbb{Z} \quad \text{and} \quad ad - bc = 1, \quad \text{Im}[\tau] > 0$$

- Imposition of A_4 modular symmetry minimizes the use of flavon fields, unlike the conventional A_4 group, since the Yukawa couplings have the non-trivial group transformation.
- The Yukawa couplings: $\mathbf{Y} = (y_1, y_2, y_3)$, transforming as a triplet under A_4 with modular weight $k_I = 2$ can be expressed in terms of Dedekind eta-function $\eta(\tau)$ and its derivative, given as

$$\eta(\tau) = e^{\frac{i\pi\tau}{12}} \prod_{n=1}^{\infty} (1 - e^{2in\tau\pi}). \tag{1}$$

- The neutrino mass matrix under the linear seesaw in the flavor basis of (ν_L, N_R, S_L^c) is expressed as

$$\mathbb{M} = \begin{pmatrix} 0 & M_D & M_{LS} \\ M_D^T & 0 & M_{RS} \\ M_{LS}^T & M_{RS}^T & 0 \end{pmatrix}$$

- The resulting light neutrino mass formula

$$m_\nu = M_D M_{RS}^{-1} M_{LS}^T + \text{transpose} \tag{2}$$

Model Framework

- The particle content of the model and their Quantum Nos. are given in Table 1.
- Thus, one can write the interaction Lagrangian for the **Charged Lepton, Dirac, Pseudo-Dirac, Mixing of Heavy fermions** N_R **&** S_L as given by Eqns. (3, 4, 5, 6) respectively

$$\mathcal{W}_{M_\ell} = y_\ell^{ee} \overline{L}_{e_L} H e_R + y_\ell^{\mu\mu} \overline{L}_{\mu_L} H_d \mu_R + y_\ell^{\tau\tau} \overline{L}_{\tau_L} H_d \tau_R, \tag{3}$$

$$\mathcal{W}_D = \alpha_D \overline{L}_{e_L} H_u (\mathbf{Y} N_R)_1 + \beta_D \overline{L}_{\mu_L} H_u (\mathbf{Y} N_R)_{1'} + \gamma_D \overline{L}_{\tau_L} H_u (\mathbf{Y} N_R)_{1''}, \tag{4}$$

$$\mathcal{W}_{LS} = \left[\alpha'_D \overline{L}_{e_L} H_u (\mathbf{Y} S_L^c)_1 + \beta'_D \overline{L}_{\mu_L} H_u (\mathbf{Y} S_L^c)_{1'} + \gamma'_D \overline{L}_{\tau_L} H_u (\mathbf{Y} S_L^c)_{1''}\right] \frac{\rho^3}{\Lambda^3}, \tag{5}$$

$$\mathcal{W}_{M_{RS}} = [\alpha_{SN} \mathbf{Y} (\overline{S_L} N_R)_{\text{symm}} + \beta_{SN} \mathbf{Y} (\overline{S_L} N_R)_{\text{Anti-symm}}]\rho \tag{6}$$

Fields	e_R^c	μ_R^c	τ_R^c	L_L	N_R	S_L^c	$H_{u,d}$	ρ
$SU(2)_L$	1	1	1	2	1	1	2	1
$U(1)_Y$	1	1	1	$-1/2$	0	0	$1/2, -1/2$	0
$U(1)_X$	1	1	1	-1	1	2	0	1
A_4	1	$1'$	$1''$	$1, 1'', 1'$	3	3	1	1
k_I	1	1	1	-1	-1	-1	0	0

Table 1: Particle content of the model and their charges under $SU(2)_L \times U(1)_Y \times U(1)_X \times A_4$ where k_I is the number of modular weight.

Mass Matrix and Mixing Angle Expressions

$$M_\ell = \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix}, \quad M_D = \frac{v}{\sqrt{2}} \begin{pmatrix} y_1\alpha_d & y_3 & y_2 \\ y_2 & y_1\beta_d & y_3 \\ y_3 & y_2 & y_1\gamma_d \end{pmatrix}, \quad M_{LS} = \frac{v v_\rho^3}{\sqrt{2}\Lambda^3} \begin{pmatrix} y_1\alpha_d & y_3 & y_2 \\ y_2 & y_1\beta_d & y_3 \\ y_3 & y_2 & y_1\gamma_d \end{pmatrix},$$

$$M_{RS} = \frac{v_\rho}{\sqrt{2}} \left[\alpha_{NS} \begin{pmatrix} 2y_1 & -y_3 & -y_2 \\ -y_3 & 2y_2 & -y_1 \\ -y_2 & -y_1 & 2y_3 \end{pmatrix} + \beta_{NS} \begin{pmatrix} 0 & y_3 & -y_2 \\ -y_3 & 0 & y_1 \\ y_2 & -y_1 & 0 \end{pmatrix}\right].$$

$$\sin^2\theta_{13} = |U_{13}|^2, \quad \sin^2\theta_{23} = \frac{|U_{23}|^2}{1 - |U_{13}|^2}, \quad \sin^2\theta_{12} = \frac{|U_{12}|^2}{1 - |U_{13}|^2}. \quad [U \text{ diagonalizes matrix (2)}]$$

Results

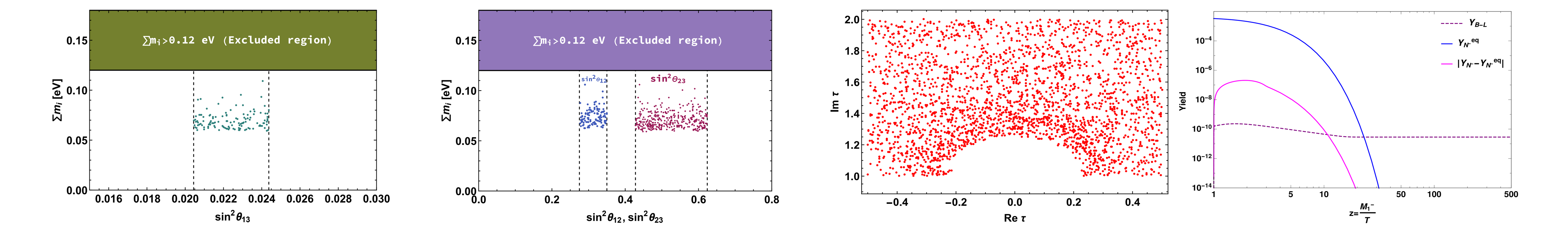

Figure 1: These plots express mixing angles $\sin^2\theta_{13}$, ($\sin^2\theta_{12}$ and $\sin^2\theta_{12}$) (middle) versus Σm_i[eV], right middle plot shows relation of Reτ and Imτ, and extreme right plot shows evolution of Y_{B-L} (dashed) as a function of $z = M_1^-/T$.

Leptogenesis

- To incorporate leptogenesis, a higher dimensional mass term is introduced for the Majorana fermion (N_R) as in eqn.(7), prompting a small mass splitting between the heavy fermions, where α_R is the coupling.

$$\mathcal{W}_M = -\alpha_R Y \overline{N_R^c} N_R \frac{\rho^2}{\Lambda} \tag{7}$$

Boltzmann equations

$$\begin{aligned} \frac{dY_{N^-}}{dz} &= -\frac{z}{sH(M_1^-)} \left[\left(\frac{Y_{N^-}}{Y_{N^-}^{\text{eq}}} - 1\right)\gamma_D + \left(\left(\frac{Y_{N^-}}{Y_{N^-}^{\text{eq}}}\right)^2 - 1\right)\gamma_S\right], \\ \frac{dY_{B-L}}{dz} &= -\frac{z}{sH(M_1^-)} \left[\epsilon_{N^-}\left(\frac{Y_{N^-}}{Y_{N^-}^{\text{eq}}} - 1\right)\gamma_D - \frac{Y_{B-L}}{Y_\ell^{\text{eq}}}\frac{\gamma_D}{2}\right], \end{aligned} \tag{8}$$

where s denotes the entropy density, $z = M_1^-/T$ and the equilibrium number densities are given by

$$Y_{N^-}^{\text{eq}} = \frac{135 g_{N^-}}{16\pi^4 g_\star} z^2 K_2(z), \quad Y_\ell^{\text{eq}} = \frac{135\zeta(3) g_\ell}{8\pi^4 g_\star}. \tag{9}$$

Here, $K_{1,2}$ denote modified Bessel functions, $g_\ell = 2$ and $g_{N^-} = 2$ denote the d.o.f. of lepton and right-handed superfields respectively. Further, γ_D and γ_S denote decay rate and scattering rate of the decaying particle.

Conclusion

- We have studied the implications of A_4 modular symmetry on neutrino masses and mixing along with leptogenesis in the framework of linear seesaw and successfully explained the observed neutrino oscillation data as well as the cosmological bound on neutrino masses i.e., $\Sigma m_i < 0.12$ eV. We also investigated leptogenesis from the decay of the lightest heavy fermion and showed that it can explain the observed BAU.