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Neutrino Phenomenology and Leptogenesis in Type-III Seesaw under A_4 Modular Symmetry

Priya Mishra,[a,*] **Mitesh Kumar Behera,**[a] **Papia Panda**[a] **and Rukmani Mohanta**[a]

[a] *School of Physics, University of Hyderabad,*
Hyderabad - 500046, India
E-mail: mishpriya99@gmail.com, miteshbehera1304@gmail.com,
ppapia93@gmail.com, rukmani98@gmail.com

In this work, we implement A_4 modular invariance approach within the framework of type-III seesaw mechanism with $\mathrm{U}(1)_{\mathrm{B-L}}$ as an additional gauge symmetry to the standard model (SM). The model includes SM particle spectrum with extra $\mathrm{SU}(2)_{\mathrm{L}}$ triplet fermion Σ_R and a scalar singlet ρ, which breaks the $\mathrm{U}(1)_{\mathrm{B-L}}$ symmetry. Fermion triplet participates in the seesaw mechanism to give tiny mass to neutrinos. Hence, we are able to explain neutrino phenomenology, to name a few, sum of neutrino masses, reactor mixing angle etc. satisfying their present experimental 3σ bound respectively. Also, we discuss leptogenesis and effective electron neutrino mass parameter $\langle m_{ee} \rangle$ in neutrinoless double beta decay satisfying KamLAND-Zen bound.

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[*] Speaker

1. Introduction and Model Framework

Standard model (SM) is successful in explaining the interactions up to electroweak scale, however it fails to elucidate mixing patterns in quarks and lepton flavour sector, mass hierarchies amid leptons and quarks including non-zero mass of neutrinos. A symmetry-based approach is likely to be the most effective. We explore A$_4$ modular symmetry in type-III seesaw mechanism with U$(1)_{\rm B-L}$ gauged symmetry [2]. The advantage, of working in modular symmetry is that scalar fields are not needed anymore and the symmetry breaking is performed by the VeV of complex modulus field τ [1]. The role of modular forms is played by dimensionless Yukawa couplings which are holomorphic function of τ and hence they are transforming in a particular manner instead of being constant in case of discrete flavour symmetry approach. To fulfil the requirements of type-III seesaw we add three fermion triplets Σ_R, one singlet scalar to break the U$(1)_{\rm B-L}$ gauge symmetry and A$_4$ symmetry is broken by the complex modulus τ. The particle content of the model is mentioned in the following table,

Fields	$E^c_{R_1}$	$E^c_{R_2}$	$E^c_{R_3}$	L	Σ^c_{Ri}	$H_{u,d}$	ρ
$SU(2)_L$	1	1	1	2	3	2	1
$U(1)_Y$	1	1	1	$-\frac{1}{2}$	0	$\frac{1}{2}, -\frac{1}{2}$	0
$U(1)_{B-L}$	1	1	1	-1	1	0	-2
A_4	1	$1'$	$1''$	$1, 1'', 1'$	3	1	1
k_I	0	0	0	0	-2	0	2

Table 1: Particle content of the model and their charges under $SU(2)_L \times U(1)_Y \times U(1)_{B-L} \times A_4$, where, k_I is the modular weight.

The superpotential of the model is given as,

$$\begin{aligned}\mathcal{W}_{III} &= y_{ij} E^c_{R_i} H_d L_j - (G_D)_{ij} \left[H_u \Sigma^c_{R_i} \sqrt{2} \mathbf{Y} L_j \right] \\ &- \frac{M'_\Sigma}{2} \left(\beta_\Sigma \mathrm{Tr} \left[\mathbf{\Sigma^c_{R_i} Y \Sigma^c_{R_i}} \right]_{\rm sym} + \gamma_\Sigma \mathrm{Tr} \left[\mathbf{\Sigma^c_{R_i} Y \Sigma^c_{R_i}} \right]_{\rm asym} \right) \frac{\rho}{\Lambda},\end{aligned}$$

with G_D= diag$\{\alpha_1, \alpha_2, \alpha_3\}$, β_Σ = diag$\{\beta_1, \beta_2, \beta_3\}$ and γ_Σ = diag$\{\gamma_1, \gamma_2, \gamma_3\}$ being the model parameters, Λ is the cut-off parameter, M'_Σ is the mass parameter and the Yukawa couplings are function of complex modulus τ [2]. The neutrino mass takes the following form in type-III seesaw mechanism,

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

where, M_D and M_R are the Dirac and Majorana matrices for neutral lepton sector. We scan the model parameters in the following range to get the oscillation parameters in their 3σ experimental bound:

$$\mathrm{Re}[\tau] \in [-0.5, 0.5], \ \ \mathrm{Im}[\tau] \in [0.75, 2], \quad M'_\Sigma \in [10^4, 10^5] \ \mathrm{TeV}, \quad v_\rho \in [10^3, 10^4] \ \mathrm{TeV}, \tag{2}$$

$$\Lambda \in [10^4, 10^5] \ \mathrm{TeV}, \ \ G_D \in [10^{-8}, 10^{-5}], \ \ \beta_\Sigma \in [10^{-5}, 10^{-1}], \ \ \gamma_\Sigma \in [10^{-9}, 10^{-10}]. \tag{3}$$

We use **chi square minimisation** technique to get the best fit of model parameters corresponding to the best fir of oscillation parameters.

Model Parameters	α_1	α_2	α_3	β_1	β_2	β_3
Best-fit values	3.83×10^{-7}	1.61×10^{-6}	5.73×10^{-7}	4.44×10^{-2}	0.824	1.05×10^{-3}

Table 2: Best-fit of model parameters by under constraint of experimentally observed data.

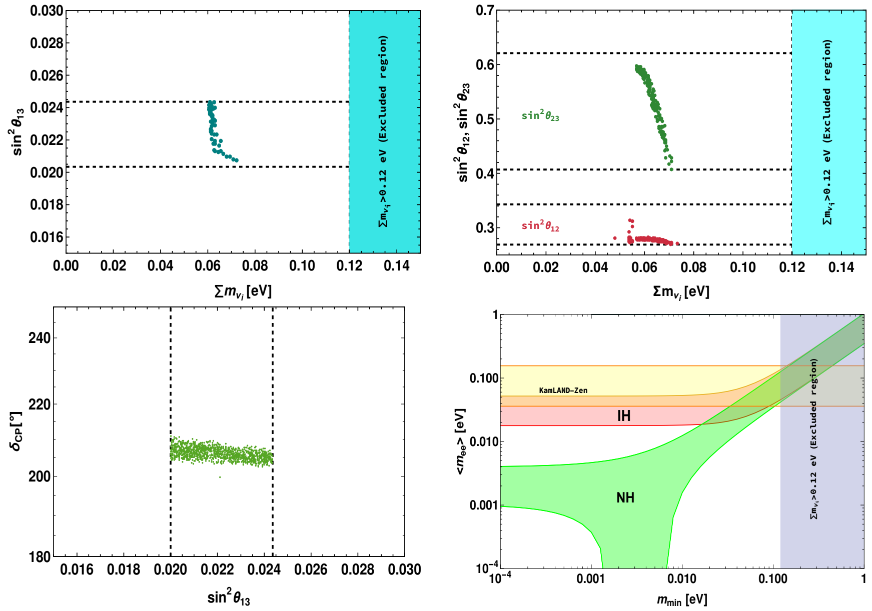

Figure 1: Upper left and right panel shows the plane of the mixing angles i.e., $\sin^2\theta_{13}$ $\sin^2\theta_{12}$ and $\sin^2\theta_{23}$ with sum of neutrino mass for the best fit values of model parameters while grid-lines represent the 3σ range of mixing angles. Lower left(right) pannel shows the $\sin^2\theta_{13}$ (mass of lightest neutrino) with respect to δ_{CP} (neutrinoless double beta decay mass parameter).

2. Leptogenesis

In here, we explore leptogenesis in type-III seesaw model with fermion triplets, where, the lightest heavy fermion is in TeV scale. The general expression for CP asymmetry is mentioned below [3],

$$\epsilon_{CP} = -\sum_j \frac{3}{2}\frac{M_{\Sigma_{R_i}}}{M_{\Sigma_{R_j}}}\frac{\Gamma_{\Sigma_{R_i}}}{M_{\Sigma_{R_j}}}\left(\frac{V_j - 2S_j}{3}\right)\frac{\mathrm{Im}(\tilde{Y}_\Sigma \tilde{Y}_\Sigma^\dagger)_{ij}}{(\tilde{Y}_\Sigma \tilde{Y}_\Sigma^\dagger)_{ii}(\tilde{Y}_\Sigma \tilde{Y}_\Sigma^\dagger)_{jj}}, \quad \tilde{Y}_\Sigma = Y_\Sigma U_R \tag{4}$$

where, $Y_\Sigma = (M_D/v_u)$ is the Yukawa matrix of Dirac mass term and U_R being the eigenvector matrix of M_R. The Boltzmann equations associated with evolution of the number densities of right-handed fermion field and lepton can be articulated in terms of the yield parameters, i.e., the ratio of number densities to entropy density, and are expressed as [4],

$$\begin{aligned} \frac{dY_\Sigma}{dz} &= -\frac{z}{sH(M_\Sigma)}\left[\left(\frac{Y_\Sigma}{Y_\Sigma^{\mathrm{eq}}} - 1\right)\gamma_D + \left(\left(\frac{Y_\Sigma}{Y_\Sigma^{\mathrm{eq}}}\right)^2 - 1\right)\gamma_A\right], \\ \frac{dY_{B-L}}{dz} &= -\frac{z}{sH(M_\Sigma)}\left[\frac{Y_{B-L}}{Y_\ell^{\mathrm{eq}}}\gamma_D - \epsilon_{CP}\left(\frac{Y_\Sigma}{Y_\Sigma^{\mathrm{eq}}} - 1\right)\frac{\gamma_D}{2}\right]. \end{aligned} \tag{5}$$

We also include flavour approximations and the Boltzmann equation describing the generation of $(B-L)$ asymmetry for each lepton flavor is [5],

$$\frac{dY^{\alpha}_{B-L}}{dz} = -\frac{z}{sH(M_\Sigma)}\left[\epsilon^{\alpha}_{\Sigma}\left(\frac{Y_\Sigma}{Y^{eq}_{\Sigma}}-1\right)\gamma_D - \left(\frac{\gamma^{\alpha}_D}{2}\right)\frac{A_{\alpha\alpha}Y^{\alpha}_{\mathrm{B-L}_\alpha}}{Y^{eq}_{\ell}}\right], \tag{6}$$

where, $\epsilon^{\alpha}_{\Sigma}$ i.e., $(\alpha = e, \mu, \tau)$ represents the CP asymmetry in each lepton flavor.

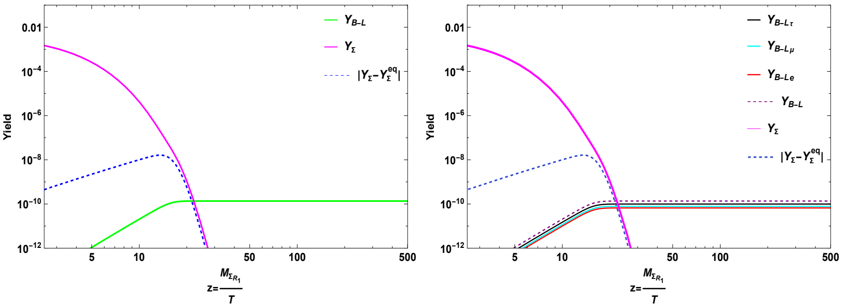

Figure 2: Left panel projects the evolution of Y_{B-L} (green solid line) as a function of $z = \frac{M_{\Sigma_{R_1}}}{T}$ for single flavour approximation, whereas, after including the flavor effects the yield is shown in right panel,

3. Conclusion

In our model, we have determined the range of model parameters for which the obtained neutrino oscillation parameters are in their 3σ range. We have also shown the neutrinoless double beta decay mass parameter satisfying the KamLAND-Zen bound. Additionally, we have incorporated leptogenesis to show the matter-antimatter asymmetry in the Universe.

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