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Neutrino mass and leptogenesis in a type I + II seesaw model with spontaneous CP violation

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We propose a hybrid scenario incorporating type I and type II seesaw models for neutrino mass where CP symmetry has been broken by the complex vacuum expectation value of a singlet scalar field. Applying appropriate symmetries we show that such a framework can simultaneously explain the neutrino oscillation data and measured baryon asymmetry via leptogenesis. Further, the natural choice of parameters leads to a mixed leptogenesis scenario driven by nearly degenerate right handed singlet neutrino and scalar triplet fields for which we show a detailed analysis.

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1. Introduction

Despite the tremendous success, Standard Model (SM) particle physics is not the complete one. Out of several pressing shortcomings of the SM, explanation of tiny mass of neutrinos as indicated by the oscillation data [1, 2] and the dominance of matter over antimatter as extracted from the studies of the Cosmic Ray Microwave Background [3] have been considered as very crucial. In order to resolve these issues simultaneously we propose a scenario where the SM is enhanced with an $\mathrm{SU}(2)_L$ triplet scalar with hypercharge $Y = 1$, an SM singlet Majorana fermion and a complex SM singlet scalar. This scenario naturally generates light neutrino mass by the combination of type I and type II seesaw mechanisms. Further, the scalar sector accommodates a softly broken Z_3 symmetry that generates CP violating complex vacuum expectation value (vev) for the singlet scalar field. It is not only providing the solution to *domain wall* problem but is also crucial for generating a nontrivial complex phase in the neutrino mass matrix. As a result, CP in leptonic sector is spontaneously broken as we restrict the model parameters to be real for which we exhibit an extensive numerical simulation of the model to identify the region of parameter space that satisfies the global fit of neutrino oscillation data [4]. Finally, we show that the model for spontaneous CP violation (SCPV) described here can simultaneously explain the neutrino mass and mixing while also generating a matter-antimatter asymmetry in consonance with observation [5].

2. The Singlet Doublet Triplet model

We augmented the SM with one $\mathrm{SU}(2)_L$ singlet (σ) and one complex triplet (Δ) with hypercharge $Y = 1$ and a singlet right handed Majorana neutrino (N_R). We describe this model as the *Singlet Doublet Triplet* (SDT) model that provides an economical setup which ensures SCPV by spontaneous breaking of a global discrete symmetry Z_3. In Table 1 we present the relevant field content and their corresponding charges under $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times Z_3$ symmetry.

	SM fields			BSM fields		
	H	L	e_R	σ	Δ	N_R
$\mathrm{SU}(2)_L$	2	2	1	1	3	1
$U(1)_Y$	$\frac{1}{2}$	$-\frac{1}{2}$	-1	0	1	0
$\mathbb{Z}_3$	1	ω	ω	ω	ω	ω

Table 1: Charge assignment and field content of the SDT model.

2.1 Lagrangian

The Lagrangian terms which are relevant for our analysis are given below

$$\mathcal{L} = V(\sigma, H, \Delta) - \mathcal{L}_Y, \tag{1}$$

where, the scalar potential $V(\sigma, H, \Delta)$ can be decomposed in three parts

$$V(\sigma, H, \Delta) = V_{\not{C}\not{P}}(\sigma) + V_{II}(\sigma, H, \Delta) + V_{\mathrm{soft}}(H, \Delta) . \tag{2}$$

In the above $V_{\not{C}\not{P}}$ involving only the singlet field generates a complex vev of the singlet driving the SCPV

$$V_{\not{C}\not{P}}(\sigma) \quad = \quad -m_\sigma^2\, \sigma^*\sigma + \lambda_\sigma\, (\sigma^*\sigma)^2 + \mu_{\sigma 3} \left[\sigma^3 + {\sigma^*}^3\right] . \tag{3}$$

The second part (V_{II}) originates an induced triplet vev while driving electroweak symmetry breaking as

$$\begin{aligned} V_{II}(\sigma, H, \Delta) \quad = \quad & -m_H^2(H^\dagger H) + \frac{\lambda}{4}(H^\dagger H)^2 + m_\Delta^2 \mathrm{Tr}(\Delta^\dagger \Delta) + \lambda_2 \left[\mathrm{Tr}(\Delta^\dagger \Delta)\right]^2 \\ & + \lambda_3 \mathrm{Tr}(\Delta^\dagger \Delta)^2 + \lambda_1 (H^\dagger H)\mathrm{Tr}(\Delta^\dagger \Delta) + \lambda_4 (H^\dagger \Delta \Delta^\dagger H) \\ & + (\sigma^* \sigma)[\lambda_{\sigma H}(H^\dagger H) + \lambda_{\sigma\Delta}\mathrm{Tr}(\Delta^\dagger \Delta)] \\ & + \lambda_{\sigma H \Delta}\left[\sigma H^\mathsf{T} i\tau_2 \Delta^\dagger H + \text{ h.c.}\right] , \end{aligned} \tag{4}$$

where the quartic coupling $\lambda_{\sigma H\Delta}$ propagates the complex phase from the singlet vev to the triplet vev. The final term in the potential softly breaks the discrete global symmetry Z_3 as given by

$$V_{\text{soft}}(H, \Delta) \quad = \quad \mu\left[H^\mathsf{T} i\tau_2 \Delta^\dagger H + \text{ h.c.}\right] . \tag{5}$$

The above term not only rescue from the formation of domain wall due to the spontaneous breaking of discrete global symmetry but also is essential for the generation of CP phase in the neutrino mass matrix. The scalar fields in terms of their components and vev configurations are given as

$$\sigma = \frac{1}{\sqrt{2}}\left(\sigma_R + i\sigma_I + v_\sigma e^{i\theta_\sigma}\right); \; H = \begin{pmatrix} \phi^+ \\ \phi^0 + v_H/\sqrt{2} \end{pmatrix}; \; \Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 + v_\Delta e^{i\theta_\Delta}/\sqrt{2} & -\delta^+/\sqrt{2} \end{pmatrix} . \tag{6}$$

The Yukawa interactions can be written as

$$-\mathcal{L}_Y = \frac{1}{2}\mathcal{Y}_{\Delta ij} L_i^\mathsf{T} C i\tau_2 \Delta L_j + \mathcal{Y}_{\nu i}\overline{L}_i \widetilde{H} N_R + \frac{1}{2} y_R \sigma^* \overline{N_R} N_R^c + \mathcal{Y}_{lij}\overline{L}_i H e_{Rj} + \text{ h.c.} , \tag{7}$$

where $\mathcal{Y}_\Delta, \mathcal{Y}_\nu$ and $\mathcal{Y}_l$ are denoted as the Yukawa coupling matrices with the triplet, right handed neutrino (RHN) and the lepton doublet respectively. The Yukawa coupling y_R is responsible for generating the mass of the RHN after the singlet obtains a vev. From the Eq. 7 the neutrino mass term can be expressed using type I+II mechanism as

$$M_\nu = \frac{v_\Delta}{\sqrt{2}}\begin{pmatrix} y_1 & y_2 & y_3 \\ y_2 & y_4 & y_5 \\ y_3 & y_5 & y_6 \end{pmatrix} e^{i\theta_{\text{eff}}} - \frac{v_H^2}{2|M_R|}\begin{pmatrix} x_1^2 & x_1 x_2 & x_1 x_3 \\ x_1 x_2 & x_2^2 & x_2 x_3 \\ x_1 x_3 & x_2 x_3 & x_3^2 \end{pmatrix} , \tag{8}$$

where $\mathcal{Y}_\nu = (x_1 \quad x_2 \quad x_3)^\mathsf{T}$ and we have redefined $\mathcal{Y}_{\Delta 11} = y_1$, $\mathcal{Y}_{\Delta 12} = y_2$, $\mathcal{Y}_{\Delta 13} = y_3$, $\mathcal{Y}_{\Delta 22} = y_4$, $\mathcal{Y}_{\Delta 23} = y_5$ and $\mathcal{Y}_{\Delta 33} = y_6$ for simplicity. It is important to note that in the presence of the trilinear μ term, a non zero phase $\theta_{\text{eff}} = (\theta_\Delta - \theta_\sigma)$ gives rise to the CP violating phase δ_{CP} appearing in the neutrino mass matrix.

Given the measured neutrino masses are $\sim 10^{-11}$ GeV and assuming democratic contribution from the type I and type II seesaws we see that $v_\Delta \sim 10^{-11}$ GeV and $v_\sigma \sim 10^{15}$ GeV with

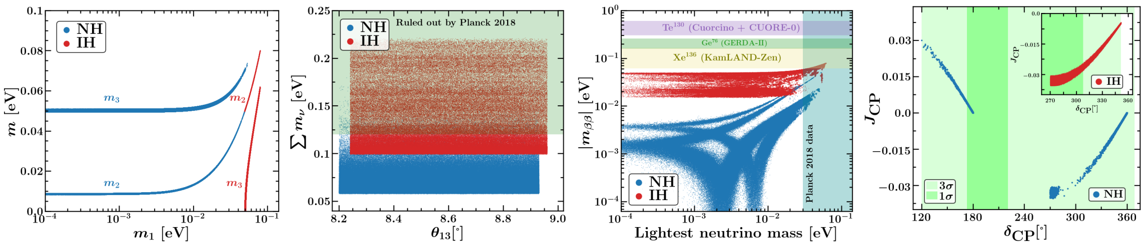
$$v_\Delta v_\sigma \sim v_H^2 \times \frac{O(\mathcal{Y}_\nu)^2}{O(\mathcal{Y}_\Delta)} . \tag{9}$$

This sets the scale associated with V_{CP} to be at 10^{15} GeV that is well separated from the weak scale justifying using the decoupling limits to analyse the scalar potential and consequently we can have the two doubly charged, two singly charged and three neutral scalar particles. One of the neutral scalar is 125 GeV SM like Higgs. Further, the effective SCPV term of this proposed model can be defined by $\widetilde{\mu} e^{i\widetilde{\theta}}$ for which there are no physical scalar particles with definite parity.

3. Evaluation of neutrino oscillation parameters

The mass matrix M_ν can be diagonalised by an unitary matrix U in the following way

$$U^\dagger h U = \mathrm{diag}(m_1^2, m_2^2, m_3^2) , \tag{10}$$



(a) (b) (c) (d)

Figure 1: 1a: Absolute mass of neutrino mass eigenstates allowed by neutrino oscillation data. 1b: Total mass of active neutrinos with respect to the reactor mixing angle θ_{13}. The blue (red) points are allowed by neutrino oscillation data for NH (IH) and the shaded region (green) is the excluded from Planck data. 1c: Effective Majorana mass variation with respect to the lightest neutrino mass. 1d: Jarlskog invariant as a function of the CP violating phase.

with $h \equiv M_\nu M_\nu^\dagger$. Further, m_1^2, m_2^2 and m_3^2 are the squared eigenvalues of the M_ν matrix. The mixing matrix U can be parameterized by three angles $\theta_{12}, \theta_{23}, \theta_{13}$ and one CP phase δ following the PDG convention [6]. The explicit CP violation in the neutrino sector implies a non zero value for the rephasing invariant quantity defined through $J_{\rm CP}$ which is proportional to the complex phase δ. We use the six global fit parameters (two mass squared differences, three angles and one phase) extracted from neutrino oscillation data [4] to put constraints on the parameter space of our model. We have varied the free parameters of our model to reproduce the neutrino oscillation data for normal hierarchy (NH) and inverted hierarchy (IH). We construct the neutrino mass matrix and extract various neutrino oscillation parameters following the algorithm described in [7] and compare with various experimental constraints listed in [5].

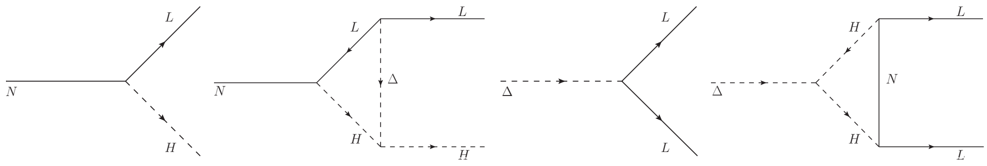
The absolute mass of the neutrinos allowed by the neutrino oscillation data [4] is shown in Fig. 1a. In Fig. 1b the total mass of all the active neutrinos $\sum m_\nu$ is depicted with respect to the reactor mixing angle θ_{13}. The bound on relativistic degrees of freedom from the Planck data [3] translates to a upper bound on the sum over neutrino masses. The effective Majorana mass parameter defined as $m_{\beta\beta} = \left| \sum_i m_i U_{ei}^2 \right|$ that is directly sensitive to neutrinoless double beta decay experiments have been plotted against the lowest neutrino mass in Fig. 1c. Similarly the allowed region in the parameter space of the Jarlskog invariant $J_{\rm CP}$ and the CP violating phase $\delta_{\rm CP}$ is displayed in Fig. 1d as can be read off from these two figures a large number of data points remains in agreement with the neutrinoless double beta decay experiments and measurements of the CP phase at neutrino factories. We conclude that the SDT model is capable surviving the present neutrino constraints. Armed with this we will now explore the possibility of leptogenesis within the framework of SDT model.

4. Leptogenesis within the SDT framework

The observed baryon asymmetry of the Universe as extracted from the studies of the Cosmic Ray Microwave Background at present stand at $Y_B = 8.718 \pm 0.04 \times 10^{-11}$ [3]. Within the SDT framework there are two different sources of CP asymmetry: (i) decay of right handed neutrino (N_R) to lepton and Higgs pair and (ii) decay of scalar triplet (Δ) to lepton pair.

4.1 CP asymmetry parameter

In the present scenario CP asymmetry is generated due to decay of the N_R and Δ to a pair of leptons and Higgs (Fig. 2a and 2b) and same sign di-leptons (Fig. 2c and 2d) respectively and is given by,



(a) **(b)** **(c)** **(d)**

Figure 2: Tree level (2a) and one loop (2b) diagrams giving rise to CP asymmetry from the N_R decay. Tree level (2c) and one loop (2d) diagrams contributing to CP asymmetry from the Δ decay.

$$\epsilon_N^\Delta = -\frac{1}{16\pi^2\Gamma_N}\sum_{il}\mathcal{I}m[\mathcal{Y}_{\nu i}\mathcal{Y}_{\nu l}(\mathcal{Y}_{\Delta il}e^{i\theta_{\text{eff}}})^*\mu^{\text{eff}*}]\left(1-\frac{M_\Delta^2}{|M_R|^2}\log(1+|M_R|^2/M_\Delta^2)\right), \tag{11}$$

$$\epsilon_\Delta^N = \frac{|M_R|}{64\pi^2 M_\Delta\Gamma_\Delta}\sum_{il}\mathcal{I}m[\mathcal{Y}_{\nu i}^*\mathcal{Y}_{\nu l}^*(\mathcal{Y}_{\Delta il}e^{i\theta_{\text{eff}}})\mu^{\text{eff}}]\log(1+M_\Delta^2/|M_R|^2)\ , \tag{12}$$

where Γ_N and Γ_Δ is the tree level decay width of N_R and Δ respectively.

4.2 $B - L$ evolution

The lepton asymmetry originated via leptogenesis at the seesaw scale $\sim 10^{15}$ GeV (required to satisfy neutrino oscillation data assuming the Yukawa couplings $\mathcal{O}(1)$ in our case), can be connected to the present day value by solving Boltzmann equations (BEs) which govern the out-of-equilibrium dynamics of RHN and scalar triplet involving processes (particularly in our case). The interaction terms given in Eqs. 4, 5 and 7 violate lepton number by one or two units whenever N_R decays to (l, H) pair or Δ decays to (l_i, l_j), respectively keeping the baryon number conserved. We will estimate the evolution of $(B - L)$ abundance with the understanding that the lepton asymmetry is translated to a baryon asymmetry through SM interaction possibly via the non perturbative sphaleron processes. As the seesaw scale $\sim 10^{15}$ GeV consequently different lepton flavours are indistinguishable. Therefore, the relevant BEs do not contain lepton flavour indices leading to unflavoured leptogenesis [8, 9]. The corrected BEs are listed in [5] where we denote the abundance of $N_R, \Sigma = \Delta + \Delta^\dagger, \Delta_\Delta = \Delta - \Delta^\dagger$ and $B - L$ as $Y_N, Y_\Sigma, Y_{\Delta_\Delta}$ and $Y_{\Delta_{B-L}}$ respectively. The abundance of $(Y_{\Delta_{B-L}})$ saturates at large value of z. Eventually the baryon asymmetry can be obtained via sphaleron processes as given by [8, 9]

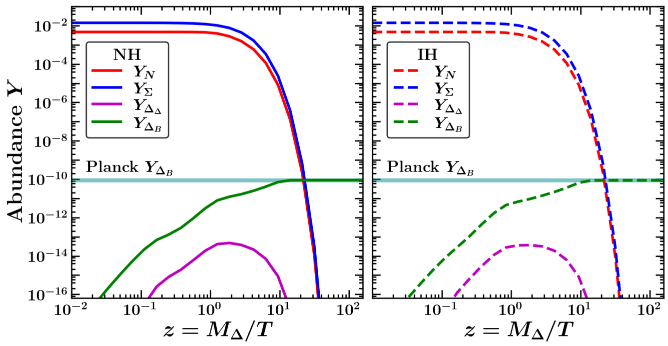
$$Y_{\Delta_B} = 3\times\frac{12}{37}\sum_i Y_{\Delta_{B-L}}\ , \tag{13}$$

where the factor 3 indicates the degrees of freedom of Δ.

In Fig. 3 we demonstrate the evolution of the comoving number densities. As for example, for the two particular benchmark points for NH (IH) the absolute values of CP asymmetry parameters ϵ_N and ϵ_Δ are 6.934×10^{-6} and 1.787×10^{-7} (9.729×10^{-6} and 6.363×10^{-8}) respectively. For the purpose of the illustration we take the NH block. The red line stands for the evolutions of N_R, the blue line shows the evolution of $\Sigma(= \Delta + \Delta^\dagger)$, the magenta line indicates the abundance of $\Delta_\Delta(= \Delta - \Delta^\dagger)$ and the green line represents the evolution of the baryon asymmetry Δ_B which asymptotically overlaps with the dark cyan horizontal line representing the measured value of BAU at the present epoch. Due to out-of-equilibrium decays of N_R and $\Delta(\Delta^\dagger)$ to probable channels, the red and the blue lines begin to fall around $z = 1$. As a consequence the baryon asymmetry increases and around $z = 10$ it begins to saturate. The dependence of the same quantities are represented by the same colours for the IH but with dashed lines.

5. Conclusion

We present a model of neutrino mass that combine the type I and type II seesaw scenarios. An extended scalar sector that include a SM singlet, a triplet in addition to the Higgs doublet is responsible for breaking



(a)

Figure 3: One representative point satisfying NH and IH along with Planck data for sum over neutrino masses has been chosen to demonstrate the evolution of the comoving number density for each component of lepton asymmetry including the final baryon asymmetry with respect to z.

CP spontaneously and generating a seesaw mass for the neutrinos. We utilise a Z_3 symmetry to organise the scalar sector accommodating a complex vacuum expectation value of the singlet that translates to a complex seesaw vev of the scalar triplet. Introduction of a soft Z_3 breaking term necessitated by the domain wall problem is also crucial for generating a relative phase between the type I and type II neutrino mass. This relative phase is the only source of CP violation which satisfy the neutrino oscillation data and the observed baryon asymmetry simultaneously

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