Chapter 4

Low-energy CP phases and resonant leptogenesis in radiative seesaw model

This chapter focuses on the study of resonant leptogenesis in a minimal radiative seesaw model. We consider the case where two quasi-degenerate right-handed neutrinos realize resonant leptogenesis, and the CP violation necessary to achieve leptogenesis occurs through the CP phases present in the neutrino mixing matrix. A numerical analysis is performed by taking the best-fit values from the current global data for three neutrino mixing angles and two mass-squared differences. In our research, we have demonstrated that the predicted value of baryon asymmetry depends on the Dirac and Majorana CP phases. Additionally, our model favours a normal hierarchy of neutrino masses, based on the predicted value of baryon asymmetry. We use the constrained CP phases to evaluate the effective neutrino mass, which is relevant to the neutrinoless double beta decay.

4.1 Introduction

Evidence from experiments on neutrino oscillation [1] suggests that the Standard Model is incomplete as it cannot account for neutrino mass. An attractive possibility of physics beyond the SM to account for tiny neutrino mass is the seesaw mechanism [2–4]. The seesaw mechanism can explain the tiny mass of the neutrino, as well as the baryon asymmetry of the Universe (BAU) through leptogenesis [5]. Leptogenesis generates lepton asymmetry through the out-of-equilibrium and CP-violating decay of right-handed neutrinos. This asymmetry is then partly converted to baryon asymmetry by the electroweak sphaleron processes [6].

In standard thermal leptogenesis with hierarchical masses of the right-handed neutrinos, the observed value of BAU can be explained if their mass scale is $\mathcal{O}(10^9)$ GeV [7]. However, this mass scale may be lower in cases with nearly degenerate right-handed neutrinos. Such a scenario is known as resonant leptogenesis [8, 9]. In a resonant leptogenesis scenario, a sufficient amount of BAU may be achieved by assuming the mass degeneracy of the right-handed neutrinos to be $\leq 10^{-8}$. Such a strong degeneracy is unnatural and fine-tuned.

Resonant leptogenesis occurs at lower temperatures, and the CP phases present in the neutrino mixing matrix act as a source of CP violation required to successfully explain the observed BAU via leptogenesis. The value of CP phases in the neutrino mixing matrix is not as established as the mixing angles according to various neutrino oscillation experiments. Measurements from long-baseline experiments such as T2K [10] and NOνA [11] along with reactor experiments: Daya-Bay [12], RENO [13], and Double-Chooz [14] suggest a preference for Dirac phase, $\delta \sim 1.5\pi$. Future experiments such as DUNE [15] and T2HK [16] are expected to provide a more precise determination of the Dirac CP-violating phase. On the other hand, if neutrinos are of Majorana nature, the standard parameterization of the Pontecorvo-Maki-Naka-Sakata (PMNS) [17–19] mixing matrix will have two additional Majorana phases. The nature of massive neutrinos can be examined in experiments that study neutrinoless double beta decay. These experiments can also provide valuable information about the Majorana phases. This motivates us to consider the investigation of baryogenesis and explore its dependence on CP phases present in the PMNS matrix.

Even though the Yukawa coupling matrix, crucial to the generation of CP asymmetry through the decays of right-handed neutrinos, cannot be exclusively reconstructed by low-energy neutrino observables. However, bridging the connection between low-energy CP phases and leptogenesis is an interesting subject to explore. There have been many studies that investigate this relationship within various frameworks [20–27]. The authors of reference [20] show the connection between low-energy CP violation and leptogenesis in the minimal seesaw model with two right-handed neutrinos. In their study, they investigated the process of baryogenesis through resonant leptogenesis. They examined the possibility of a successful leptogenesis with the requirement of CP violation being satisfied by the CP phases present in the neutrino mixing matrix. Such a connection may be naturally realized in models where generalized CP symmetry is imposed [28, 29]. Our approach is to explore the parameter space for the low-energy CP phases such that a successful explanation of the observed BAU may be given within the framework of the radiative seesaw model with an inert Higgs doublet.

In this chapter, we investigate a model of radiative neutrino masses having two right-handed neutrinos with TeV-scale masses. We have analyzed the scenario of resonant leptogenesis by considering a tiny splitting between the two right-handed neutrinos. An interesting feature of this model is that the observed BAU can be achieved even if the degeneracy is relaxed [30], making the model much more natural. We then carry out the study of resonant leptogenesis and how it relates to CP violation which is solely derived from the neutrino mixing matrix. Our focus will be on identifying the parameter space for the Dirac and Majorana phases that conform to the observed value of BAU. In simpler terms, we aim to understand how the low-energy CP phases impact resonant leptogenesis and how we can use this knowledge to better understand the universe.

This chapter is organized as follows: In Section 4.2, we have presented a brief description of the framework of the scotogenic model with two right-handed neutrinos. We have written the Yukawa coupling matrix in Casas-Ibarra type parameterization and established assumptions that the CP violation comes exclusively from the neutrino mixing matrix. In Section 4.3, we have introduced the terms relevant for evaluating baryon asymmetry. We explore the parameter space of our model using the constraints from the observed BAU in this section. We further show the results of our numerical evaluation of the coupled Boltzmann equation, which governs the evolution of the number density of various particles involved. Section 4.4 includes the results of neutrinoless double beta decay obtained using the constrained parameter space of Section 4.3. We finally conclude our work in Section 4.5.

4.2 Radiative neutrino mass model with an inert Higgs doublet

In this work, we have considered the study of a radiative seesaw model, first proposed by E. Ma [31]. We consider the minimal possible form of such a model. The model includes two right-handed neutrinos, N_i in the fermion sector, and an additional inert Higgs doublet, η in the scalar sector. The particle content of the model under $SU(2)_L \times U(1)_Y \times Z_2$ is summarized as follows.

$$\begin{aligned} &(\nu_L^\alpha,\ \alpha_L) \sim (2,\ -\frac{1}{2},\ +), \quad \alpha_R^\alpha \sim (1,\ 1,\ +), \quad (\Phi^+,\ \Phi^0) \sim (2,\ \frac{1}{2},\ +) \\ &N_i \sim (1,\ 0,\ -), \quad (\eta^+,\ \eta^0) \sim (2,\ \frac{1}{2},\ -) \end{aligned} \tag{4.1}$$

The SM fields are Z_2 even whereas the new fields are assumed to be odd under the Z_2 symmetry. The invariant Lagrangian of the new fields may be written as

$$\mathcal{L} \supset -h_{\alpha i}\bar{l}_L^\alpha \tilde{\eta} N_i \ + \ \frac{1}{2} M_i \bar{N}_i (N_i^c) \ + \ h.c., \tag{4.2}$$

where $h_{\alpha i}$ denote the Yukawa couplings, l_L^α (with $\alpha = e,\ \mu,\ \tau$) is the SM lepton doublets, $\tilde{\eta} = i\sigma_2\eta^*$, with σ_2 being the 2^{nd} Pauli matrices and M_i is the Majorana masses of the right-handed neutrinos. It is assumed that the inert Higgs doublet has no vacuum expectation value (vev), and we find that no Dirac mass term is generated after electroweak symmetry breaking (EWSB). The neutrino remains massless at the tree level and can be generated at the one-loop level. The potential of the model becomes

$$\begin{aligned} V =& - \mu^2 \Phi^\dagger \Phi + m_\eta^2 \eta^\dagger \eta + \frac{\lambda_1}{2}(\Phi^\dagger\Phi)^2 + \frac{\lambda_2}{2}(\eta^\dagger\eta)^2 + \lambda_3(\Phi^\dagger\Phi)(\eta^\dagger\eta) \\ &+ \lambda_4(\Phi^\dagger\eta)(\eta^\dagger\Phi) + \frac{\lambda_5}{2}\left[(\Phi^\dagger\eta)(\Phi^\dagger\eta) + (\eta^\dagger\Phi)(\eta^\dagger\Phi)\right], \end{aligned} \tag{4.3}$$

where λ_i represents the quartic couplings and are assumed to be real without loss of generality. If we take $\Phi = (0,\ (v+h)/\sqrt{2})^T$ and $\eta = (\eta^+,\ (\eta_R + i\eta_I)/\sqrt{2})^T$, the masses of the physical scalar states can be written as

$$\begin{aligned} m_h^2 &= \lambda_1 v^2, \\ m_{\eta^\pm}^2 &= m_\eta^2 + \frac{v^2}{2}\lambda_3, \\ m_{\eta_R}^2 &= m_\eta^2 + \frac{v^2}{2}(\lambda_3 + \lambda_4 + \lambda_5), \\ m_{\eta_I}^2 &= m_\eta^2 + \frac{v^2}{2}(\lambda_3 + \lambda_4 - \lambda_5), \end{aligned} \tag{4.4}$$

where v is the *vev* of the SM Higgs doublet, m_h denotes the mass of the SM Higgs, m_{η_R} and m_{η_I} are the mass of the real scalar η_R and the real pseudoscalar η_I, respectively. It is assumed that both η_R and η_I are lighter than the complex scalar $\eta^\pm$, whose mass is represented by $m_{\eta^\pm}^2$ in equation (4.4). It is clear that the mass difference between η_R and η_I is $m_{\eta_R} - m_{\eta_I} = v^2\lambda_5$ and therefore, as $\lambda_5 \to 0$, η_R and η_I becomes degenerate. We note that in this model, Z_2 symmetry stabilizes the lightest Z_2 odd particle and this particle can play the role of the dark matter candidate [1].

The radiative neutrino mass model gives rise to a neutrino mass matrix of the form [31]

$$(M_\nu)_{\alpha\beta} = \sum_i \frac{M_i h_{\alpha i}^* h_{\beta i}^*}{32\pi^2}\left[L\left(m_{\eta_R}^2\right) - L\left(m_{\eta_I}^2\right)\right], \tag{4.5}$$

with $L(m^2)$ defined as

$$L(m^2) = \frac{m^2}{m^2 - M_i^2}\log\left(\frac{m^2}{M_i^2}\right). \tag{4.6}$$

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[1] Here, we have restricted our study to baryon asymmetry of the Universe. A systematic study of the dark matter problem in such a model is carried out in [30, 32–34].

Analogous to the type-I seesaw formula we write the neutrino mass matrix of equation (4.5) as

$$M_\nu = h^* \Lambda^{-1} h^\dagger \tag{4.7}$$

where Λ is a diagonal matrix of the form [32]

$$\Lambda_i = \frac{2\pi^2}{\lambda_5}\xi_i \frac{2M_i}{v^2} \tag{4.8}$$

and

$$\xi_i = \left(\frac{1}{8}\frac{M_i^2}{m_{\eta_R}^2 - m_{\eta_I}^2}\left[L\left(m_{\eta_R}^2\right) - L\left(m_{\eta_I}^2\right)\right]\right)^{-1}. \tag{4.9}$$

The active neutrino mass matrix given in equation (4.5) can be diagonalized as $U^\dagger M_\nu U^* = D_\nu = \mathrm{diag}(m_1,\ m_2,\ m_3)$, where m_i are the masses of the light neutrino eigenstate. Here, U is a unitary matrix also known as the PMNS matrix, and is represented as

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix} \cdot P, \tag{4.10}$$

where $P = \mathrm{diag}(1,\ e^{i\sigma},\ e^{i\rho})$, $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$, δ_{CP} is the Dirac CP phase and σ, ρ are the Majorana phases. Since, we have extended the fermion sector with two right-handed neutrinos, only two light neutrinos achieve non-zero mass eigenvalues i.e., either $m_1 = 0$ (Normal Hierarchy) or $m_3 = 0$ (Inverted Hierarchy). This also means that one of the Majorana phases in U becomes not well defined and only one combination of Majorana phases remains, namely, $(\sigma-\rho)$ in NH or σ in IH.

In order to study the scenario of resonant leptogenesis in this model it is convenient to write the Yukawa matrix h in Casas-Ibarra (CI) type parametrization [35]

$$h = U\sqrt{D_\nu}R^\dagger\sqrt{\Lambda}, \tag{4.11}$$

where R is a complex orthogonal matrix satisfying $RR^T = I$, which is of the form

$$R = R_1 \cdot R_2 \cdot R_3, \tag{4.12}$$

with

$$R_1 = \begin{pmatrix} \cos\omega_{12} & \sin\omega_{12} & 0 \\ -\sin\omega_{12} & \cos\omega_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

$$R_2 = \begin{pmatrix} \cos\omega_{13} & 0 & \sin\omega_{13} \\ 0 & 1 & 0 \\ -\sin\omega_{13} & 0 & \cos\omega_{13} \end{pmatrix},$$

$$R_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\omega_{23} & \sin\omega_{23} \\ 0 & -\sin\omega_{23} & \cos\omega_{23} \end{pmatrix},$$

where ω_{ij} are complex parameters. For two right-handed neutrino case, we have $\omega_{12} = \omega_{13} = 0$ in NH and $\omega_{13} = \omega_{23} = 0$ in IH case. In this work, we primarily focus on the possibility that the CP phases in the PMNS matrix of equation (4.10) act as a source of the BAU. Under such a scenario we are considering $\mathrm{Im}\omega_{23}$ or $\mathrm{Im}\omega_1 2$ to be zero for the NH or IH case, respectively i.e., the CP violating parameters responsible for successful baryogenesis are δ_{CP} and $(\sigma - \rho)$ or σ.

4.3 Resonant Leptogenesis

In this section, we discuss resonant leptogenesis within the scotogenic model, which is a radiative neutrino mass model with an inert Higgs doublet. In thermal leptogenesis, where the mass spectrum of the right-handed neutrino is hierarchical, the lower bound on the mass of the right-handed neutrino is $\mathcal{O}(10^9)$ GeV [7]. The high mass scale required for leptogenesis can be reduced in the case of resonant leptogenesis, where the masses of the right-handed neutrinos are almost equal. In the type-I seesaw model, the observed BAU can be explained by CP-violating, out-of-equilibrium decays of right-handed neutrinos with TeV-scale masses. However, this comes at the expense of a strong, fine-tuned degeneracy. This model of a radiative seesaw with an inert Higgs doublet relaxes such a strong degeneracy ($> 10^{-8}$).

The interference of the tree-level decay of right-handed neutrino with the one-loop self-energy and vertex diagrams gives CP violation and hence produces non-zero lepton asymmetry. In resonant leptogenesis, the self-energy correction is resonantly enhanced, and the flavour-dependent asymmetry parameter is given by [36, 37]

$$\varepsilon_{\alpha i} = \sum_{j\neq i} \frac{\mathrm{Im}\left[h^\dagger_{i\alpha} h_{\alpha j}(h^\dagger h)_{ij}\right] + \frac{M_i}{M_j}\mathrm{Im}\left[h^\dagger_{i\alpha} h_{\alpha j}(h^\dagger h)_{ji}\right]}{(h^\dagger h)_{ii}(h^\dagger h)_{jj}} \cdot \frac{(M_i^2 - M_j^2)M_i\Gamma_j}{(M_i^2 - M_j^2)^2 + M_i^2\Gamma_j^2}, \tag{4.13}$$

where the decay width Γ_i is defined as

$$\Gamma_i = \frac{M_i}{8\pi}(h^\dagger h)_{ii}(1-\eta_i)^2, \text{ with } \eta_i = \frac{m_\eta^2}{M_i^2}. \tag{4.14}$$

The CP asymmetry generated from the decay of nearly degenerate right-handed neutrinos generates the lepton asymmetry, whose value can be evaluated by analysis of the Boltzmann equation. Here, we solve the coupled Boltzmann equations (equation (4.15) and (4.16)) which describes the evolution of the right-handed neutrino density, n_{N_i} and lepton number density, $n_{N_{\alpha\alpha}}$ ($\alpha = e,\ \mu,\ \tau$) [38, 39].

$$\frac{dn_{N_i}}{dz} = -D_i\left(n_{N_i} - n_{N_i}^{eq}\right) \tag{4.15}$$

$$\frac{dn_{N_{\alpha\alpha}}}{dz} = -\sum_{i=1}^{2}\varphi_{\alpha i}D_i\left(n_{N_i} - n_{N_i}^{eq}\right) - \frac{1}{4}\left\{\sum_{i=1}^{2}(rz)^2 D_i\mathcal{K}_2(rz) + W_{\Delta L=2}\right\} n_{N_{\alpha\alpha}}. \tag{4.16}$$

The above Boltzmann equations are flavour-diagonal, and we have considered the decays, inverse decays of the right-handed neutrinos, and the $\Delta L = 2$ washout processes. The equilibrium number density of the right-handed neutrinos is given by

$$n_{N_i}^{eq} = \frac{45}{2\pi^2 g_*}z^2\mathcal{K}_2(z), \tag{4.17}$$

, where $\mathcal{K}_2$ and g_* are the modified Bessel function of the second kind and the number of relativistic degrees of freedom, respectively. The decay parameter, D_i

is defined as

$$D_i = \frac{z}{H(z=1)} \frac{\Gamma_{N_i}}{n^{eq}_{N_i}} \tag{4.18}$$

, with H being the Hubble parameter. The $\Delta L = 2$ washout processes consist of scattering such as $l\eta \leftrightarrow \bar{l}\eta^*$ and $ll \leftrightarrow \eta^*\eta^*$ and can be written as [32]

$$\Delta W = \frac{\Gamma_{\Delta L=2}}{Hz} = \frac{36\sqrt{5}M_{Pl}}{\pi^{\frac{1}{2}} g_l \sqrt{g_*} v^4} \frac{1}{z^2} \frac{1}{\lambda_5} M \bar{m}_\xi^2, \tag{4.19}$$

where $\bar{m}_\xi$ is the effective mass parameter and is defined as

$$\begin{aligned} \bar{m}_\xi^2 &= \sum_{i,j} \xi_i \xi_j \mathrm{Re}\left[(R D_\nu R^\dagger)^2_{ij}\right] \\ &\approx 4\xi_1^2 m_1^2 + \xi_2^2 m_2^2 + \xi_3^2 m_3^2. \end{aligned} \tag{4.20}$$

To examine the possibility of CP phases present in the PMNS matrix as the sole source of CP violation necessary to achieve successful leptogenesis, we take $\mathrm{Re}\omega_{23}$ or $\mathrm{Re}\omega_{12}$ to be $\frac{\pi}{4}$ for NH or IH cases, respectively. We have fixed the mass of right-handed neutrinos to be $M_1 = 5$ TeV, the mass splitting parameter to be $\Delta M = 10^{-7}$, $m_{\eta_R} = 1.5$ TeV, and $\lambda_5 = 10^{-3}$. We observe that with these parameter choices, the baryon asymmetry value, η_B is relatively small, $\mathcal{O}(10^{-20})$ for IH, and hence, we will confine our study to the NH case. Since the BAU is generated at the TeV scale, we take into consideration the flavour effects of leptogenesis. This makes the CP violation in the PMNS matrix relevant to the production of the BAU. Here, the primary focus is to show how the generated baryon asymmetry depends on the CP phases δ_{CP} and $\alpha = \sigma - \rho$. To estimate the baryon asymmetry, we solve the Boltzmann equations numerically using equations (4.15) and (4.16). The value of η_B depends on the initial condition of right-handed neutrinos and in this work, we have considered the vanishing initial abundance of right-handed neutrinos. To make the parameter scan in the $\delta_{CP} - \alpha$ plane, we take the entire range [0, 2π] for both δ_{CP} as well as α and evaluate η_B by taking the best-fit values for the three mixing angles and two mass-squared differences from the global results of latest neutrino oscillation experiments [40]. To compare the numerical results for η_B with the experimental results given by Planck [41],

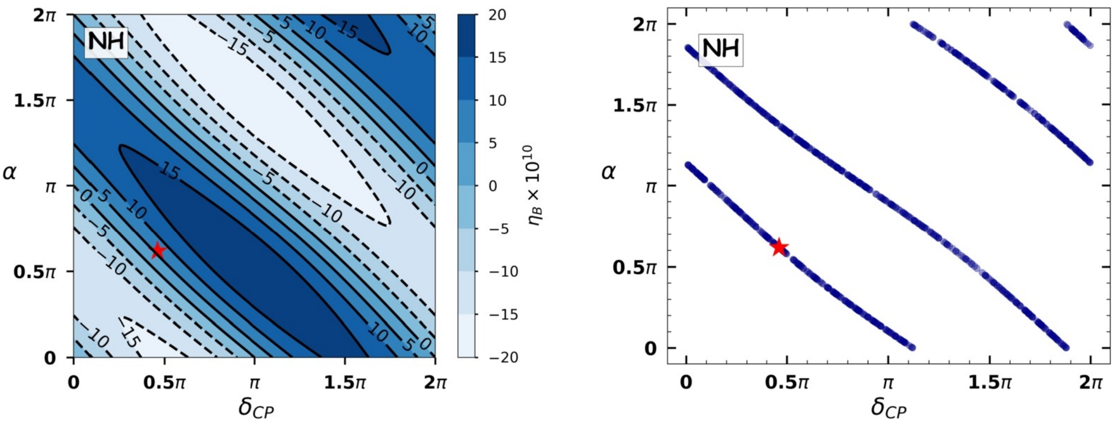

Figure 4.1: The left panel shows the contour plot of η_B in the $\delta_{CP} - \alpha$ plane. The red cross mark indicates the χ^2-minimum value for $(\delta_{CP},\ \alpha)$. η_B has negative values in regions with dotted lines. The right panel shows the allowed region of parameter space constrained by the Planck bound, $\eta_B = (6.10 \pm 0.04) \times 10^{-10}$.

we make a χ^2 analysis and minimize the function

$$\chi^2 = \sum \frac{(\lambda^{model} - \lambda^{expt})^2}{\Delta\lambda^2} \tag{4.21}$$

where λ^{model} represents the η_B predicted by the model, λ^{expt} is the experimentally measured value of η_B, and $\Delta\lambda$ denote the 1σ range. Figure 4.1 shows the results of the parameter scan. The contour plot of η_B in the $\delta_{CP} - \alpha$ plane is shown in the left panel. The value of η_B calculated in this scenario depends on both the CP phases. The right panel of Figure 4.1 represents the region in $\delta_{CP} - \alpha$ space that is constrained by the observed value of BAU from the Planck data, $\eta_B = (6.10 \pm 0.04) \times 10^{-10}$. The best-fit value in the parameter space of our model is evaluated using equation (4.21), which is denoted by a red star mark and corresponds to $\delta_{CP} = 0.46\pi$ and $\alpha = 0.62\pi$. For the best-fit point, we show in Figure 4.2 the evolution of lepton number density for three flavours and baryon asymmetry as a function of z. For the mass of right-handed neutrinos, $M_1 = 5$ TeV ($< 10^9$ GeV) we get a fully flavoured leptogenesis. In this scenario, the muon lepton Yukawa interaction is thermalized and there is complete flavour decoherence. We now have separate asymmetries along e, μ, and τ directions. As is seen in Figure 4.2 the lepton number density $N_{\mu\mu}$ vanishes as z increases.

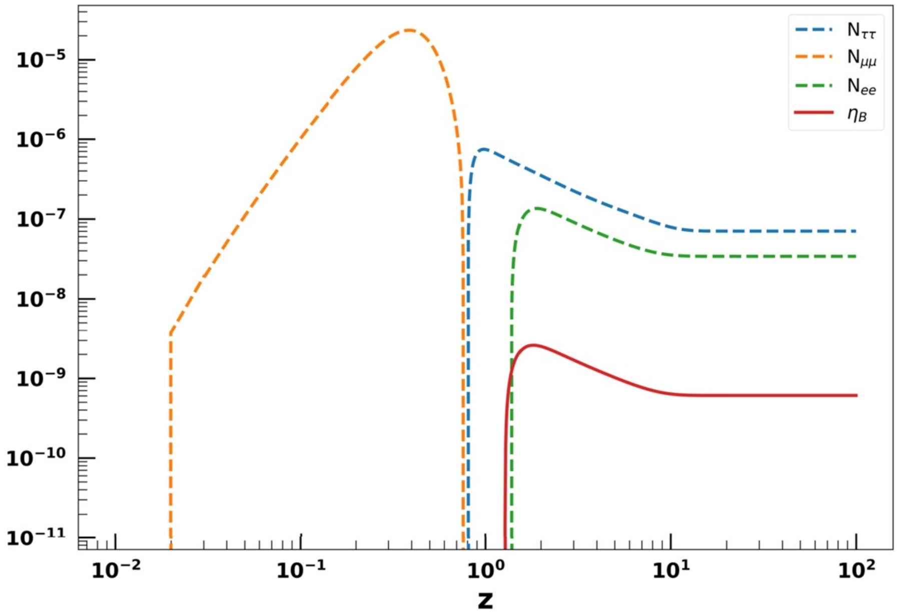

Figure 4.2: Variation of lepton number density $N_{\alpha\alpha}$ and η_B as a function of z.

This shows relatively strong wash-out along the μ direction and only $e,\ \mu$ flavours give significant contributions to the baryon asymmetry. The final value of baryon asymmetry is observed at a high value of z and is found to be $\eta_B \approx 6.1 \times 10^{-10}$.

In this section, we demonstrate how BAU could be explained via resonant leptogenesis within the scotogenic model such that the required CP violation comes exclusively from the PMNS matrix. By confronting the predictions of our model with experimentally measured η_B, we obtained the allowed region for the CP phases. In the following section, we will examine the process of neutrinoless double beta decay and evaluate the effective light neutrino mass that determines the amplitude of the decay.

4.4 Neutrinoless Double Beta Decay

If the neutrinos are of Majorana nature it can mediate the lepton number violating neutrinoless double beta decay: $(A,\ Z) \rightarrow (A,\ Z+2) + 2e^-$ [42–44]. The decay rate of such a process is proportional to the effective light neutrino mass, $|\langle m_{ee} \rangle|$

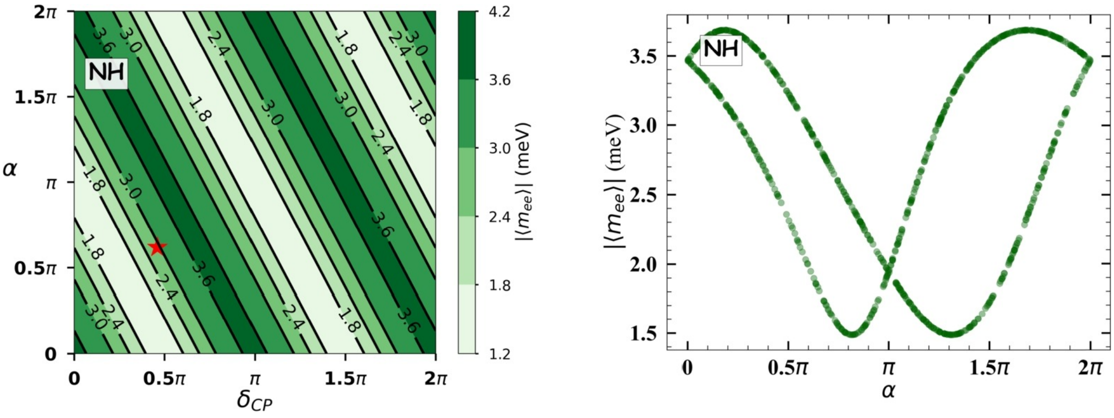

Figure 4.3: The left panel shows the contour plot of $|\langle m_{ee}\rangle|$ in $\delta_{CP}-\alpha$ plane. The red star mark indicates the best-fit point corresponding to χ^2-minimum value. The right panel shows the variation of effective light neutrino mass with the Majorana phase, α, constrained by the requirement of successful resonant leptogenesis.

and is given by[2]

$$|\langle m_{ee}\rangle| = |\sum_i m_i U_{ei}^2|. \tag{4.22}$$

We analyze the parameter space allowed by successful resonant leptogenesis and determine its effect on the predicted $|\langle m_{ee}\rangle|$. The left panel of Figure 4.3 shows the calculated value of effective light neutrino mass, $|\langle m_{ee}\rangle|$ by scanning δ_{CP} and α over the range $[0,\ 2\pi]$. The value of $|\langle m_{ee}\rangle|$ depends significantly on δ_{CP} as well. In the right panel of Figure 4.3, we show the predicted values of $|\langle m_{ee}\rangle|$ constrained by the successful generation of BAU via resonant leptogenesis. The predicted values range from 1.49 meV to 3.69 meV. The minimal value of $|\langle m_{ee}\rangle|$ is obtained when $\alpha = 0.8\pi$ and the maximal value is observed at $\alpha = 1.7\pi$.

4.5 Conclusions

We have conducted a study on a radiative seesaw model that can explain the origin of neutrino masses, BAU (Baryon Asymmetry of the Universe), and Dark

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[2] The contribution from heavy right-handed leptons is negligible, and hence we take into consideration the effect of only the light neutrinos.

Matter. This model is particularly interesting because it involves an additional inert Higgs doublet. Our research focuses on the extension of the fermion sector, where we introduced two right-handed neutrinos with nearly degenerate masses at the TeV scale. We are exploring the idea of generating the baryon asymmetry of the universe (BAU) by using resonant leptogenesis. This approach involves the decay of the Z_2 odd right-handed neutrinos into Z_2 even Standard Model (SM) leptons and an inert Higgs doublet, which is out-of-equilibrium and CP violating. The quasi-degenerate nature of the right-handed neutrinos is taken into account, and it is expected that leptogenesis will occur at TeV-scale temperature.

We have considered that the BAU can be generated with the CP violation, which may be measured at neutrino oscillation and neutrinoless double beta decay experiments. In other words, we have assumed that the CP violation necessary for successful leptogenesis comes from the phases present in the neutrino mixing matrix (PMNS matrix). Furthermore, we found that the model prefers NH of neutrino masses for the choices of mass parameters and the quartic coupling presented in this work. Thus, the parameters upon which the estimation of BAU depends are the Dirac phase, δ_{CP}, and the Majorana phase, $\alpha = \sigma - \rho$.

We numerically solved the coupled Boltzmann equations and found that this model can explain the observed BAU even when the source of CP violation are the CP phases, δ_{CP} and $\alpha = \sigma - \rho$. Thus, we found the region of parameter space that successfully produces the observed baryon asymmetry. The best-fit values for the parameters corresponding to χ^2-minimum value are $\delta_{CP} = 0.46\pi$ and $\alpha = 0.62\pi$. Next, we discussed how the requirement of successful resonant leptogenesis constrains the effective light neutrino mass, which is relevant for neutrinoless double beta decay. Using the constrained parameter space of the model, we calculated the $|\langle m_{ee}\rangle|$. We found that significantly, the $|\langle m_{ee}\rangle|$ depends on both the CP phases. Experiments that investigate neutrinoless double beta decay in future generations have the potential to explore this model.

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