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Resonant leptogenesis at TeV-scale and neutrinoless double beta decay

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ABSTRACT: We investigate a resonant leptogenesis scenario by quasi-degenerate right-handed neutrinos which have TeV-scale masses. Especially, we consider the case when two right-handed neutrinos are responsible to leptogenesis and the seesaw mechanism for active neutrino masses, and assume that the CP violation occurs only in the mixing matrix of active neutrinos. In this case the sign of the baryon asymmetry depends on the Dirac and Majorana CP phases as well as the mixing angle of the right-handed neutrinos. It is shown how the yield of the baryon asymmetry correlates with these parameters. In addition, we find that the effective neutrino mass in the neutrinoless double beta decay receives an additional constraint in order to account for the observed baryon asymmetry depending on the masses and mixing angle of right-handed neutrinos.

KEYWORDS: Cosmology of Theories beyond the SM, Neutrino Physics

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1 Introduction

Leptogenesis [1] is an attractive mechanism accounting for the baryon asymmetry of the Universe (BAU). See, for example, reviews [2, 3]. In the canonical scenario the out-of-equilibrium decays of right-handed neutrinos, ν_R 's generate a lepton asymmetry, which is partially converted into the baryon asymmetry through the sphaleron effect at high temperatures [4]. When their masses are hierarchical, the observed BAU [5]

$$Y_B^{\text{OBS}} = \left. \frac{n_B}{s} \right|_{\text{obs}} = (0.870 \pm 0.006) \times 10^{-10}, \quad (1.1)$$

where Y_B is the ratio between the baryon number density n_B and entropy density s , can be explained if their masses are heavier than $\mathcal{O}(10^9)$ GeV [6].¹

It should be noted that such superheavy particles can also give a significant impact on neutrino masses. The various oscillation experiments have shown that neutrinos have very suppressed but non-zero masses. The smallness of the masses can be naturally explained by the seesaw mechanism with superheavy ν_R 's [10–15].

Leptogenesis can operate even if ν_R 's masses are much smaller than the above value, which is resonant leptogenesis [16]. The mass degeneracy of ν_R 's enhances the CP violating effects, which leads to the resonant production of lepton asymmetry by their decay.² The required mass degeneracy may be a consequence of the symmetry of the model.

In resonant leptogenesis scenario, since it can occur at relatively lower temperatures, the flavor effects of leptogenesis [21–28] can be essential. In such a case, the yield of the

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¹The lower bound on masses can be reduced as $\mathcal{O}(10^6)$ GeV if one considers the non-thermal production of right-handed neutrinos via the inflaton decays [7–9].

²A sufficient amount of the BAU can be generated by right-handed neutrinos even with masses $\mathcal{O}(1)$ MeV- $\mathcal{O}(10^2)$ GeV if one uses the flavor oscillations of ν_R 's [17–20].

BAU depends on the mixing matrix of active neutrinos U called as the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [29, 30], and hence the CP violation due to the Dirac and/or Majorana phases in U can be an origin of the BAU.

We consider here resonant leptogenesis by right-handed neutrinos with TeV-scale masses in the framework of the seesaw mechanism. Especially, it is investigated the case in which the CP violation occurs only in the mixing matrix U of active neutrinos. We will show that how the yield of the BAU depends on the Dirac and/or Majorana phases.

Majorana masses of ν_R 's break the lepton number by two units, which is necessary for leptogenesis. Then, various processes, which are absent in the Standard Model, are predicted by the models with the seesaw mechanism. One important example is the neutrinoless double beta ($0\nu\beta\beta$) decay $(Z, A) \rightarrow (Z+2, A) + 2e^-$ [31]. The rates of such decays are parameterized by the so-called effective mass of neutrinos m_{eff} , which depends on the CP violating parameters of active neutrinos. We then discuss the possible relation between the yield of BAU and m_{eff} .

The present article is organized as follows: In section 2 we explain the framework of the analysis in which the properties of right-handed neutrinos are specified. In section 3 we present the method of estimating the BAU through resonant leptogenesis including the flavor effects. We then show how Y_B depends on the CP violating parameters of active neutrinos. It is discussed in section 4 that how the conditions accounting for the observed BAU give the impacts on the $0\nu\beta\beta$ decay. We will show that the BAU provides the upper and/or lower bound of the effective mass m_{eff} in some cases, especially when the mass difference of ν_R 's becomes larger. The final section is devoted to conclusions. We add appendix A to present the Boltzmann equations used in the analysis.

2 TeV-scale right-handed neutrinos

First of all, let us explain the framework of the present analysis. We consider the Standard Model (SM) extended by three right-handed neutrinos ν_{RI} ($I = 1, 2, 3$) with the Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + i \bar{\nu}_{RI} \gamma^\mu \partial_\mu \nu_{RI} - \left(F_{\alpha I} \bar{\ell}_\alpha H \nu_{RI} + \frac{[M_M]_{IJ}}{2} \bar{\nu}_{RI}^c \nu_{RJ} + \text{h.c.} \right), \quad (2.1)$$

where $\mathcal{L}_{\text{SM}}$ is the SM Lagrangian, and ℓ_α ($\alpha = e, \mu, \tau$) and H are lepton and Higgs doublets, respectively. $F_{\alpha I}$ are Yukawa coupling constants and M_M are Majorana mass matrix of right-handed neutrinos. We take the basis in which the charged lepton mass matrix and M_M are both diagonal, and we write $[M_M]_{II} = M_I$. (We take M_I is real and positive.)

We apply the seesaw mechanism for generating the suppressed masses of active neutrinos, and work in the parameter range $M_I \gg |[M_D]_{\alpha I}| = |F_{\alpha I}| \langle H \rangle$. In this case, the lighter mass eigenstates are active neutrinos ν_i ($i = 1, 2, 3$) and their masses m_i are found from the seesaw mass matrix $M_\nu = -M_D^T M_M^{-1} M_D$ which is diagonalized as $U^\dagger M_\nu U^* = D_\nu = \text{diag}(m_1, m_2, m_3)$. Here U is the PMNS matrix [29, 30], which is repre-

	θ_{12}	θ_{23}	θ_{13}	Δm_{21}^2 [eV ²]	$\Delta m_{3\ell}^2$ [eV ²]
NH	33.62°	47.2°	8.54°	7.40×10^{-5}	$+2.494 \times 10^{-3}$ ($\ell = 1$)
IH	33.62°	48.1°	8.58°	7.40×10^{-5}	-2.465×10^{-3} ($\ell = 2$)

Table 1. The mixing angles and the mass squared differences from the global analysis of three flavor neutrino oscillations [32].

sented as

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\text{CP}}} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta_{\text{CP}}} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta_{\text{CP}}} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta_{\text{CP}}} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta_{\text{CP}}} & c_{23}c_{13} \end{pmatrix} \\
 \times \text{diag}(1, e^{i\alpha_{21}/2}, e^{i\alpha_{31}/2}), \quad (2.2)$$

where $s_{ij} = \sin \theta_{ij}$ and $c_{ij} = \cos \theta_{ij}$ with mixing angles θ_{ij} of active neutrinos. δ_{CP} is the Dirac phase and $\alpha_{21,31}$ are the Majorana phases for CP violation. The global analysis of three flavor neutrino oscillations [32] provides the mixing angles and the mass squared differences $\Delta m_{ij}^2 = m_i^2 - m_j^2$ as shown in table 1. Notice that there are two possibilities of mass ordering, the normal hierarchy (NH) $m_3 > m_2 > m_1$ and the inverted hierarchy (IH) $m_2 > m_1 > m_3$.

On the other hand, the heavier ones are heavy neutral leptons N_I with masses M_I . Through the non-zero vacuum-expectation value of the Higgs field, they mix with active ones as $\nu_{L\alpha} = U_{\alpha i}\nu_i + \Theta_{\alpha I}N_I$ with $\Theta_{\alpha I} = [M_D]_{\alpha I}M_I^{-1}$. This mixing induces the weak interaction of heavy neutral leptons suppressed by $\Theta_{\alpha I}$. The properties of heavy neutral leptons are then determined by M_I and $F_{\alpha I}$. In order to induce the mixing angles and masses of neutrino oscillation observations, the Yukawa coupling can be expressed as [33]

$$F = \frac{i}{\langle H \rangle} U D_\nu^{1/2} \Omega M_M^{1/2}, \quad (2.3)$$

where Ω is the arbitrary 3×3 complex orthogonal matrix, which is parameterized as

$$\Omega = \begin{pmatrix} \cos \omega_{12} & \sin \omega_{12} & 0 \\ -\sin \omega_{12} & \cos \omega_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos \omega_{13} & 0 & \sin \omega_{13} \\ 0 & 1 & 0 \\ -\sin \omega_{13} & 0 & \cos \omega_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \omega_{23} & \sin \omega_{23} \\ 0 & -\sin \omega_{23} & \cos \omega_{23} \end{pmatrix}, \quad (2.4)$$

where ω_{IJ} are complex mixing parameters.

In this analysis we consider the case when only two right-handed neutrinos are responsible to the seesaw mechanism as well as leptogenesis for simplicity. The mass and Yukawa couplings of the rest right-handed neutrino are taken to be sufficiently heavy and small, respectively. For the NH case with $m_3 > m_2 > m_1 = 0$ we consider the two right-handed neutrinos ν_{R2} and ν_{R3} and mixing parameters are taken to be

$$\omega_{12} = \omega_{13} = 0, \quad \omega_{23} \neq 0. \quad (2.5)$$

On the other hand, for the IH case with $m_2 > m_1 > m_3 = 0$ we consider ν_{R1} and ν_{R2} and

$$\omega_{13} = \omega_{23} = 0, \quad \omega_{12} \neq 0. \quad (2.6)$$

There are three CP violating parameters which can be a source of the BAU under this situation. They are the Dirac phase δ_{CP} , one combination of Majorana phases, i.e., $(\alpha_{21} - \alpha_{31})$ or α_{21} for the NH or IH case, and the imaginary part of the mixing parameter, i.e., $\text{Im}\omega_{23}$ or $\text{Im}\omega_{12}$ for the NH or IH case. In the present analysis we assume that the CP violation occurs only in the PMNS matrix and all the mixing parameters ω_{IJ} are real. See, for example, refs. [25–27]. It is then discussed whether two right-handed neutrinos whose masses are TeV-scale can produce a sufficient amount of the BAU or not.

3 Baryon asymmetry and CP violations in leptonic sector

In this section we investigate the baryogenesis scenario by TeV-scale right-handed neutrinos through resonant leptogenesis [16]. The BAU in eq. (1.1) can be explained if their masses are quasi-degenerate. We thus take $M_3 = M_N + \Delta M/2$ and $M_2 = M_N - \Delta M/2$ for the NH case while $M_2 = M_N + \Delta M/2$ and $M_1 = M_N - \Delta M/2$ for the IH case, where $M_N \gg \Delta M > 0$. In this case the generation of the BAU is effective at TeV-scale temperatures and then the flavor effects of leptogenesis [21–28] must be taken into account. This is crucial to produce the baryon asymmetry by the CP violation in the PMNS matrix, since such an effect disappears for unflavored leptogenesis. From now on we will estimate the yield of the BAU by TeV-scale right-handed neutrinos and show how it depends on the low energy CP violating parameters in the PMNS matrix.

In this work, we use the Boltzmann equations for estimating the amount of the produced baryon asymmetry. In the N_I decay the interference between tree and one-loop diagrams of vertex and self-energy corrections induces the lepton asymmetry due to the CP violation in the neutrino Yukawa coupling constants. It is characterized by the CP asymmetry parameter $\varepsilon_{\alpha I}$ which is defined by

$$\varepsilon_{\alpha I} = \frac{\Gamma(N_I \rightarrow \ell_\alpha + \bar{\Phi}) - \Gamma(N_I \rightarrow \bar{\ell}_\alpha + \Phi)}{\sum_\alpha \Gamma(N_I \rightarrow \ell_\alpha + \bar{\Phi}) + \sum_\alpha \Gamma(N_I \rightarrow \bar{\ell}_\alpha + \Phi)}, \quad (3.1)$$

where $\Gamma(N_I \rightarrow \ell_\alpha + \bar{\Phi})$ is the partial decay width for $N_I \rightarrow \ell_\alpha + \bar{\Phi}$. Now we consider the case with $\Delta M \ll M_N$, and then the contribution from the self-energy correction dominates over that from the vertex correction. In this case $\varepsilon_{\alpha I}$ is given by [16]

$$\varepsilon_{\alpha I} \simeq \frac{1}{8\pi} \sum_{J \neq I} \frac{\text{Im}[F_{\alpha I}^* F_{\alpha J} (F^\dagger F)_{IJ}]}{(F^\dagger F)_{II}} \frac{M_I M_J (M_I^2 - M_J^2)}{(M_I^2 - M_J^2)^2 + A^2}. \quad (3.2)$$

In this equation A denotes a regulator for the degenerate mass. The estimation based on the Boltzmann equations becomes worse when the mass difference of right-handed neutrinos becomes very small. It has, however, been shown in refs. [34, 35] by using the more precise approach with the Kadanoff-Baym equations that the estimation with the regulator $A = M_I \Gamma_I + M_J \Gamma_J$ (where Γ_I is the total decay rate of N_I) is the good approximation

Figure 1. Contour plots of Y_B^{MAX} in the NH case. Y_B^{MAX} is positive or negative in the region with bright or dark color. In the left or right panel the plot is shown in the $\delta_{\text{CP}} - (\alpha_{21} - \alpha_{31})$ plane when $\text{Re}\omega_{23} = \pi/4$ or the $\text{Re}\omega_{23} - \delta_{\text{CP}}$ plane when $\alpha_{21} - \alpha_{31} = \pi$, respectively. The green lines show the central value of δ_{CP} from the global neutrino oscillation analysis.

to estimate the maximal value of the BAU. It is then found that $|\varepsilon_{\alpha I}|$ takes the maximal value when the condition $A = |M_I^2 - M_J^2|$ is satisfied. This means that the maximal value of $|\varepsilon_{\alpha I}|$ is achieved when the mass difference is $\Delta M = \Delta M_* \equiv A/(2M_N)$. From now on, we call the yield of the BAU with $\Delta M = \Delta M_*$ as Y_B^{MAX} .

We estimate the yield of the BAU by using the Boltzmann equations for the yields of N_I (Y_{N_I}) and the charges ($X_\alpha = B/3 - L_\alpha$) associated with the baryon number B and the lepton flavor number L_α .³ The explicit equations are presented in appendix A. The initial conditions are $Y_{N_I} = Y_{N_I}^{\text{eq}}$ and $X_\alpha = 0$, where $Y_{N_I}^{\text{eq}}$ is the equilibrium value of Y_{N_I} . We then solve the equations from the initial temperature $T_i \gg M_N$,⁴ to the final temperature $T_f = T_{\text{sph}}$ and calculate the yield of the BAU. Here T_{sph} is the sphaleron freeze-out temperature and $T_{\text{sph}} = 131.7 \text{ GeV}$ [38] for the observed Higgs boson mass.

We take $M_N = 1 \text{ TeV}$ as a representative value and evaluate the maximal value Y_B^{MAX} by setting the mass difference as $\Delta M = \Delta M_*$. In addition, as explained in the previous section, we consider the case when the CP violation occurs only in the mixing matrix U of active neutrinos, i.e., we set $\text{Im}\omega_{IJ} = 0$. We take the central values of the mixing angles θ_{ij} and the mass squared differences Δm_{ij} shown in table 1 for the sake of simplicity. Under this situation we investigate how Y_B depends on the CP phases δ_{CP} and α_{ij} and the mixing angle $\text{Re}\omega_{IJ}$ of ν_R 's.

First, we show the results for the NH case in figure 1. We find that Y_B^{MAX} can be large as $\mathcal{O}(10^{-6})$, which is much larger than the observational BAU in eq. (1.1). The left panel represents the contour plot of Y_B^{MAX} in the Dirac and Majorana phase plane by taking

³The estimation based on the Kadanoff-Baym equation is found in refs. [36, 37].

⁴We take $T_i/M_N = 100$ for the numerical study.

Figure 2. Contour plots of Y_B^{MAX} in the IH case. Y_B^{MAX} is larger or smaller in the region with bright or dark color. In the left or right panel the plot is shown in the $\delta_{\text{CP}}-\alpha_{21}$ plane when $\text{Re}\omega_{12} = \pi/4$ or the $\text{Re}\omega_{12}-\delta_{\text{CP}}$ plane when $\alpha_{21} = \pi$, respectively. The green lines show the central value of δ_{CP} from the global neutrino oscillation analysis.

the mixing angle $\text{Re}\omega_{23} = \pi/4$. Notice that we have shown the results of Y_B^{MAX} by taking $\Delta M = \Delta M_*$. This means that the observed value Y_B^{OBS} in eq. (1.1) can be explained in the parameter region $Y_B^{\text{MAX}} \geq Y_B^{\text{OBS}}$ by taking $\Delta M \geq \Delta M_*$. The relevant Majorana phase is the combination, $\alpha_{21} - \alpha_{31}$, in the NH case. It can be seen that the yield of the BAU does depend on both phases significantly.⁵ Thus, the experimental information of Dirac phase, e.g., from accelerator neutrinos [40, 41] is crucial for determining the sign of the BAU. It should be noted that the dependence on the CP violating phases is approximately given by

$$Y_B \propto \sin \left(\frac{\alpha_{21} - \alpha_{31}}{2} + \delta_{\text{CP}} \right), \quad (3.3)$$

which is found from the parameter dependence in $\varepsilon_{\alpha I}$ as well as the strength of the wash-out effects, i.e., the structures in the partial decay rates $\Gamma(N_I \rightarrow \ell_\alpha + \bar{\Phi})$. On the other hand, the right panel in figure 1 shows the contour in the mixing angle $\text{Re}\omega_{23}$ and δ_{CP} plane when $\alpha_{21} - \alpha_{31} = \pi$. It is found that Y_B^{MAX} depends on $\text{Re}\omega_{23}$ and the observed BAU cannot be generated when the mixing of ν_R 's disappears at $\text{Re}\omega_{23} = 0, \pi/2$.

Next, we turn to consider the IH case. It is found from figure 2 that Y_B^{MAX} is at most $\mathcal{O}(10^{-8})$, and hence resonant leptogenesis in the IH case is less effective compared with the NH case. Moreover, the dependence on the CP phases are different from the NH case. In the left panel of figure 2 the contour plot of Y_B^{MAX} is shown in the $\delta_{\text{CP}}-\alpha_{21}$ plane when $\text{Re}\omega_{21} = \pi/4$. We find that Y_B depends on the Majorana phase significantly as in the NH case, however the dependence on the Dirac phase is much milder than the NH case. This behavior can also be seen in the right panel, which shows the contour plot of Y_B^{MAX} in the

⁵The dependence on $\text{Im}\omega_{23}$ is discussed in ref. [39].

Figure 3. Contour plots of Y_B^{MAX} with the Dirac phase in eq. (3.5) for the NH (left panel) and IH (right panel) cases. Y_B is positive or negative in the region with bright or dark color.

$\text{Re}\omega_{12}-\delta_{\text{CP}}$ plane when $\alpha_{21} = \pi$. It is found that the dependence on the CP phases are approximately given by

$$Y_B \propto \sin\left(\frac{\alpha_{12}}{2}\right). \quad (3.4)$$

Note that the subleading effect which disturbs the above dependence is larger than that in the NH case. The observed BAU cannot be produced for the vanishing mixing between ν_R 's at $\text{Re}\omega_{12} = 0, \pi/2$ similar to the NH case. In addition, the sign of the BAU correlates with the sign of $\text{Re}\omega_{12}$.

As described above, Y_B^{MAX} depends on the Dirac and Majorana phases and the mixing angle of ν_R 's. We then discuss the case with the Dirac phase which is the central value from the global neutrino oscillation analysis in ref. [32]:

$$\delta_{\text{CP}} = \begin{cases} -0.700\pi & (234^\circ) & \text{for the NH case} \\ -0.456\pi & (278^\circ) & \text{for the IH case} \end{cases}. \quad (3.5)$$

In this case the sign of the BAU is determined by the Majorana phase and the mixing angle of ν_R 's, which is represented in figure 3. The left panel shows the contour plot of Y_B^{MAX} in the $\text{Re}\omega_{23}-(\alpha_{21} - \alpha_{31})$ plane for the NH case. Interestingly, we observe that the correct value of Y_B can be realized for all possible values of Majorana phase by choosing the appropriate angle $\text{Re}\omega_{23}$. On the other hand, for the IH case the contour plot of Y_B^{MAX} in the $\text{Re}\omega_{12}-\alpha_{21}$ plane is shown in the right panel of figure 3. It is seen that the successful baryogenesis is realized for both $\text{Re}\omega_{12} < 0$ and $\text{Re}\omega_{12} > 0$. When $\text{Re}\omega_{12} < 0$, $\alpha_{21} \simeq 2\pi$ is required and then the CP violation by δ_{CP} is essential.

As explained above, the Majorana phase plays an important role for determining the sign of the BAU through leptogenesis scenario under consideration. It is therefore expected

that the BAU may give an impact on the other phenomena in which the Majorana phase is essential. One such example is the $0\nu\beta\beta$ decay, which will be discussed in the next section.

Before closing this section, we should mention the dependence on the averaged Majorana mass M_N of ν_R 's. It is interesting to note that the CP asymmetry parameter with $\Delta M = \Delta M_*$ does not depend on M_N in the considering situation. This results in the fact that Y_B^{MAX} is almost insensitive to M_N as long as $M_N \lesssim 30 \text{ TeV}$. In such a mass region the small dependence on M_N arises from the relative size between M_N and the sphaleron's freeze-out temperature T_{sph} . When M_N in the TeV region, leptogenesis occurs at $T \sim M_N$ which is not far from the T_{sph} . This means that the conversion of the lepton asymmetry into the baryon asymmetry terminates in the course of the washout processes. Thus, the final BAU does depend on M_N . If M_N is sufficiently larger than T_{sph} , this effect vanishes because Y_B is frozen well before $T = T_{\text{sph}}$. In addition, Y_B^{MAX} suffers from the effects of the scattering processes, which induces a small dependence of M_N . On the other hand, when $M_N \gtrsim 30 \text{ TeV}$, our assumption that the processes by the Yukawa interactions for all quarks and leptons including electrons are in thermal equilibrium at the leptogenesis regime is broken [42]. In such cases, the treatment of the flavor effects must be changed, which leads to a considerable modification of the estimation of Y_B^{MAX} . Therefore, our results in the present analysis are also insensitive to the choice of M_N as long as M_N is sufficiently small.

4 Neutrinoless double beta decay

In the seesaw mechanism active neutrinos are Majorana fermions, and the lepton number is broken in contrast to the SM. One interesting example of the lepton number violating processes is the $0\nu\beta\beta$ decay: $(A, Z) \rightarrow (A, Z+2) + 2e^-$ [31]. The decay rate is proportional to m_{eff}^2 where the effective neutrino mass is given by

$$m_{\text{eff}} = \left| \sum_i m_i U_{ei}^2 \right|. \quad (4.1)$$

Here we take into account the contribution only from active neutrinos, because that from heavy neutral leptons is negligible in the considered situation.

We have assumed that only two right-handed neutrinos are responsible to the seesaw mechanism of neutrino masses, and then the lightest active neutrino is massless. In this case the effective mass is written as

$$m_{\text{eff}}^2 = m_2^2 c_{13}^4 s_{12}^4 + m_3^2 s_{13}^4 + 2 m_2 m_3 c_{13}^2 s_{12}^2 s_{13}^2 \cos(\alpha_{21} - \alpha_{31} + 2\delta_{\text{CP}}), \quad (4.2)$$

for the NH case and

$$m_{\text{eff}}^2 = c_{13}^4 \left[m_1^2 c_{12}^4 + m_2^2 s_{12}^4 + 2 m_1 m_2 c_{12}^2 s_{12}^2 \cos \alpha_{21} \right], \quad (4.3)$$

for the IH case. It is seen that m_{eff} depends on mixing angles and masses of active neutrinos as well as the CP violating phases. The effective mass when we use the central value of

Figure 4. Effective neutrino mass m_{eff} of neutrinoless double beta decay in terms of the Majorana phase $(\alpha_{21} - \alpha_{31})$ for the NH case (left panel) and α_{21} for the IH case (right panel), respectively.

δ_{CP} in eq. (3.5) can be determined by the Majorana phase as shown in figure 4. It is found that the possible range is

$$m_{\text{eff}} = \begin{cases} (1.5 - 3.7) \text{ meV} & \text{for the NH case} \\ (18 - 48) \text{ meV} & \text{for the IH case} \end{cases} . \quad (4.4)$$

where the minimal and maximal values of m_{eff} are achieved if $\alpha_{21} - \alpha_{31} = 0.4\pi$ and 1.4π for the NH case, and $\alpha_{21} = \pi$ and 0 for the IH case, respectively.

We have shown in the previous section that the successful scenario for resonant leptogenesis requires a certain range of the Majorana phase (i.e., $\alpha_{21} - \alpha_{31}$ or α_{21} for the NH or IH case) as well as the mixing angles of ν_R 's (i.e., $\text{Re}\omega_{23}$ or $\text{Re}\omega_{12}$ for the NH or IH case). It is, therefore, expected that the predicted range of m_{eff} is restricted for generating the sufficient amount of the BAU by leptogenesis.

It is important to note that Y_B^{MAX} and m_{eff} depend on an unique unknown parameter, i.e., the Majorana phase, for a given the mixing angle $\text{Re}\omega_{23}$ or $\text{Re}\omega_{12}$, and hence we can obtain the nontrivial relation between these parameters. This point is illustrated in figure 5. Namely, by changing the value of the mixing angle, a locus can be described in the $m_{\text{eff}}\text{-}Y_B^{\text{MAX}}$ plane.

In figure 6 we show the predicted region of m_{eff} in terms of the mixing angle in order to account for the observed BAU. For the NH case the impact on the $0\nu\beta\beta$ decay is different depending on values of $\text{Re}\omega_{23}$. When $\text{Re}\omega_{23} < 0$, the prediction of m_{eff} is unaffected by the BAU. On the other hand, when $\text{Re}\omega_{23} > 0$, m_{eff} receives the lower bound from the BAU. Thus, although the absolute upper and lower bounds are not changed by the BAU without knowing $\text{Re}\omega_{23}$, the range of m_{eff} may become smaller substantially if the positive value of $\text{Re}\omega_{23}$ would be realized. Note that the BAU gives the upper bound on m_{eff} when ΔM becomes sufficiently large, and the allowed region disappears for $\Delta M \geq \mathcal{O}(10^5)\Delta M_*$.

Figure 5. Yield of the BAU Y_B^{MAX} in terms of effective neutrino mass m_{eff} . In the left panel we consider the NH case and take $\text{Re}\omega_{23} = -\pi/4$ and $(\alpha_{21} - \alpha_{31}) = 0$ to π (red cross marks), $\text{Re}\omega_{23} = +\pi/4$ and $(\alpha_{21} - \alpha_{31}) = 0$ to π (red dot marks), $\text{Re}\omega_{23} = -\pi/4$ and $(\alpha_{21} - \alpha_{31}) = \pi$ to 2π (blue cross mark), and $\text{Re}\omega_{23} = +\pi/4$ and $(\alpha_{21} - \alpha_{31}) = \pi$ to 2π (blue dot marks). In the right panel we consider the IH case and take $\text{Re}\omega_{12} = -\pi/4$ and $\alpha_{21} = 0$ to π (red cross marks), $\text{Re}\omega_{12} = +\pi/4$ and $\alpha_{21} = 0$ to π (red dot marks), $\text{Re}\omega_{12} = -\pi/4$ and $\alpha_{21} = \pi$ to 2π (blue cross mark), and $\text{Re}\omega_{12} = +\pi/4$ and $\alpha_{21} = \pi$ to 2π (blue dot marks). The horizontal lines are the observed value of Y_B^{OBS} .

Figure 6. Range of effective neutrino mass m_{eff} in order to account for the observed BAU for the NH (left panel) and IH (right panel) cases. The colored region is allowed. In the NH case, the upper bounds for $\Delta M = 1.0 \times 10^4 \Delta M_*$ and $\Delta M = 6.0 \times 10^4 \Delta M_*$ are shown by red and blue lines, respectively. In the IH case, the upper bounds for $\Delta M = 1.0 \times 10^2 \Delta M_*$ and $\Delta M = 2.5 \times 10^2 \Delta M_*$ are shown by red and blue lines, respectively.

On the other hand, the successful baryogenesis is realized for $\text{Re}\omega_{12} \neq 0$ and $\pi/2$ for the IH case. When $\text{Re}\omega_{12} < 0$, the BAU suggests $\alpha_{21} \simeq 2\pi$, which leads to the maximal value of m_{eff} . Moreover, as mentioned above, m_{eff} receives an additional upper bound from the BAU. As shown in figure 6, the possible region vanishes for $\Delta M \gtrsim 300 \Delta M_*$.

We have so far taken the Dirac phase in eq. (3.5). The allowed region in figure 6 changes by the value of δ_{CP} for the NH case, while it remains almost the same for the IH case. When $\text{Re}\omega_{23} > 0$, the lower bound on the effective mass becomes severer as δ_{CP} becomes close to 200° , while weaker as δ_{CP} becomes close to 270° . On the other hand, when $\text{Re}\omega_{23} < 0$, the allowed range of the effective mass remains unchanged in the considering 1σ range ($\delta_{\text{CP}} = 203^\circ - 277^\circ$ [32]). This difference comes from the δ_{CP} dependence of Y_B . The experimental determination of δ_{CP} is thus important for the predictions of the BAU as well as the $0\nu\beta\beta$ decay for the NH case.

5 Conclusions

We have investigated the Standard Model extended by right-handed neutrinos, in which two ν_R 's are quasi-degenerate with TeV-scale masses. We have studied the origins of the neutrino masses and the BAU in this setup. By assuming that the neutrino masses are generated by the seesaw mechanism, the production of the BAU through resonant leptogenesis has been studied by using the Boltzmann equations with the flavor effects.

We have considered the case when the CP violation occurs only in the active neutrino sector. Since leptogenesis by TeV-scale right-handed neutrinos is considered, the flavor effects are essential to obtain the non-zero BAU. For the two right-handed neutrino case, the parameters relevant for the sign of the BAU are the Dirac phase δ_{CP} , the Majorana phase $\alpha_{21} - \alpha_{31}$ or α_{21} for the NH or IH case, and the mixing parameter $\text{Re}\omega_{23}$ or $\text{Re}\omega_{12}$ for the NH or IH case. We have shown how the BAU depends on these parameters and identified the possible range of these parameters to account for the observed BAU.

Furthermore, we have discussed the impact on the $0\nu\beta\beta$ decay. It has been found that the predicted range of the effective neutrino mass m_{eff} depends significantly on the mixing parameter and mass difference of ν_R 's as well as the mass hierarchy of active neutrinos. Especially, when ΔM becomes sufficiently larger than ΔM_* , m_{eff} receives the stringent upper bound in order to account for the BAU.

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A Boltzmann equations

In this appendix we present the formulae to estimate the yield of the BAU by using the Boltzmann equations. The yield of the right-handed neutrino N_I , Y_{N_I} , is given by

$$Y_{N_I} = \frac{n_{N_I}}{s}, \quad (\text{A.1})$$

where n_{N_I} is the number density of N_I . The entropy density of the universe is $s = (2\pi^2/45)g_{*s}T^3$ with the cosmic temperature T . The effective degrees of freedom is taken as $g_{*s} = 106.75$ throughout this analysis. When N_I is in equilibrium, the yield is estimated as

$$Y_{N_I}^{\text{eq}} = \frac{45}{2\pi^4 g_{*s}} (M_I^2/M^2) z^2 K_2((M_I/M)z), \quad (\text{A.2})$$

where the variable z is defined by $z = M/T$, in which M is the mass of lighter right-handed neutrinos, i.e., $M = M_2$ or M_1 for the NH or IH case, respectively. $K_2(z)$ is the modified Bessel function of the second kind. When the sphaleron processes are in thermal equilibrium, there are three conserved charges $X_\alpha = B/3 - L_\alpha$ ($\alpha = e, \mu, \tau$) associated with baryon number B and lepton flavors L_α . The yield of X_α is denoted by $Y_{X_\alpha} = n_{X_\alpha}/s$. The Boltzmann equations for Y_{N_I} and Y_{X_α} used in this analysis are given by [43, 44]

$$\begin{aligned} \frac{dY_{N_I}}{dz} = & -\frac{z}{sH(M)} \left\{ \left(\frac{Y_{N_I}}{Y_{N_I}^{\text{eq}}} - 1 \right) (\gamma_{N_I} + 2\gamma_{N_I t}^{(1)} + 4\gamma_{N_I t}^{(2)}) \right. \\ & \left. + \sum_{J \neq I} \left(\frac{Y_{N_I} Y_{N_J}}{Y_{N_I}^{\text{eq}} Y_{N_J}^{\text{eq}}} - 1 \right) (\gamma_{N_I N_J}^{(1)} + \gamma_{N_I N_J}^{(2)}) \right\}, \end{aligned} \quad (\text{A.3})$$

$$\begin{aligned} \frac{dY_{X_\alpha}}{dz} = & -\frac{z}{sH(M)} \left\{ \sum_I \left(\frac{Y_{N_I}}{Y_{N_I}^{\text{eq}}} - 1 \right) \varepsilon_{\alpha I} \gamma_{N_I} - \sum_\beta \left[\sum_I \left(\frac{1}{2} (C_{\alpha\beta}^\ell - C_\beta^\Phi) \gamma_{N_I}^\alpha \right. \right. \right. \\ & \left. \left. + \left(C_{\alpha\beta}^\ell \frac{Y_{N_I}}{Y_{N_I}^{\text{eq}}} - \frac{C_\beta^\Phi}{2} \right) \gamma_{N_I t}^{(1)} + \left(2C_{\alpha\beta}^\ell - \frac{C_\beta^\Phi}{2} \left(1 + \frac{Y_{N_I}}{Y_{N_I}^{\text{eq}}} \right) \right) \gamma_{N_I t}^{(2)} \right. \right. \\ & \left. \left. + \sum_\gamma \left((C_{\alpha\beta}^\ell + C_{\gamma\beta}^\ell - 2C_\beta^\Phi) (\gamma_N^{(1)\alpha\gamma} + \gamma_N^{(2)\alpha\gamma}) + \sum_{I,J} (C_{\alpha\beta}^\ell - C_{\gamma\beta}^\ell) \gamma_{N_I N_J}^{(1)\alpha\gamma} \right) \right] \frac{Y_{X_\beta}}{Y^{\text{eq}}} \right\}, \end{aligned} \quad (\text{A.4})$$

where $H(M)$ is the Hubble expansion rate for $T = M$ and $Y^{\text{eq}} = 45/(2\pi^4 g_{*s})$.⁶ C^ℓ and C^Φ are given by [22, 23]

$$C^\ell = \frac{1}{711} \begin{pmatrix} -211 & 16 & 16 \\ 16 & -211 & 16 \\ 16 & 16 & -211 \end{pmatrix}, \quad C^\Phi = \frac{8}{79} (1, 1, 1). \quad (\text{A.5})$$

The reaction densities γ 's are found in refs. [43, 44]. We have considered the non-supersymmetric case and taken into account the flavor effects of leptogenesis. Our notations

⁶We have applied the Boltzmann approximation.

of the reaction densities correspond to those in refs. [43, 44] as $\gamma_N^{(1)} = \gamma_N^{(2)}$, $\gamma_N^{(2)} = \gamma_N^{(13)}$, $\gamma_{N_I t}^{(1)} = \gamma_{N_I t}^{(3)}$, $\gamma_{N_I t}^{(2)} = \gamma_{N_I t}^{(4)}$, $\gamma_{N_I N_J}^{(1)} = \gamma_{N_I N_J}^{(2)}$, and $\gamma_{N_I N_J}^{(2)} = \gamma_{N_I N_J}^{(3)}$. The yield of the BAU is then given by

$$Y_B = \frac{28}{79} \sum_{\alpha} Y_{X_{\alpha}} \Big|_{T=T_{\text{sph}}} . \quad (\text{A.6})$$

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