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Leptogenesis in a neutrino mass model coupled with inflaton

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Abstract

We propose a scenario for the generation of baryon number asymmetry based on the inflaton decay in a radiative neutrino mass model extended with singlet scalars. In this scenario, lepton number asymmetry is produced through the decay of non-thermal right-handed neutrinos caused from the inflaton decay. Since the amount of non-thermal right-handed neutrinos could be much larger than the thermal ones, the scenario could work without any resonance effect for rather low reheating temperature. Sufficient baryon number asymmetry can be generated for much lighter right-handed neutrinos compared with the Davidson-Ibarra bound.

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1 Introduction

CMB observations suggest that there is an inflationary expansion era in the early Universe [1]. After inflation, the Universe should be thermalized enough to realize an initial stage of the hot Big-bang Universe. Since inflation is usually assumed to be induced by the potential energy of a slow-rolling scalar field [2], this energy should be converted to radiation through so called reheating processes after the end of inflation. In order to make the reheating possible, inflaton should have some interactions with field contents of the standard model (SM) or others. As a result, in the effective model which is obtained after the inflaton is integrated out, its remnant is expected to be kept as effective interactions among the SM contents or additional fields at low energy regions. Since such interactions could be constrained by weak scale experiments or also be detected as some new physics at that scale, their study is useful for the model building beyond the SM. In particular, they might have some connection to the origin of the baryon number asymmetry in the Universe, which is one of big mysteries beyond the SM [3].

In this paper, we study this issue assuming that inflaton is a singlet scalar of the SM gauge symmetry. In that case, only restricted couplings between the inflaton and ingredients of the model are allowed as renormalizable terms by the gauge symmetry. For example, we may consider a simple extension of the SM only with right-handed neutrinos N_i and an additional doublet scalar. In a supersymmetric case, it contains superpartners of the contents. In such a framework, a well-known example of the singlet inflaton is a sneutrino in the supersymmetric case. Sneutrino $\tilde{N}$ has a coupling $\tilde{N}\bar{\ell}\tilde{\phi}$, where ℓ and $\tilde{\phi}$ are the ordinary doublet lepton and a fermionic superpartner of the doublet Higgs scalar ϕ, respectively. In this model, reheating after the inflation and the associated generation of lepton number asymmetry due to this coupling has been studied in several articles [4].

In a non-supersymmetric case, gauge invariant renormalizable couplings of the singlet scalar S with the contents of the model can be limited to two types if an additional symmetry is imposed. These couplings are $S\bar{N}_iN_i^c$ and $S\eta^\dagger\phi$ where η is the additional doublet scalar. They are expected to bring about reheating and be relevant to the generation of the baryon number asymmetry if S plays a role of inflaton. A radiative neutrino mass model extended with singlet scalars is a typical example, which includes these couplings as phenomenologically important terms [5–7]. In this paper, we focus our study on such a model and propose a possible new scenario for the generation of the baryon number asymmetry through the reheating due to the above mentioned coupling.

2 A radiative seesaw model extended by singlet scalars

The radiative seesaw model [8] is a very simple but promising extension of the SM with an inert doublet scalar η and right-handed singlet fermions N_i. They are assumed to have odd parity for an imposed Z_2 symmetry, although others are assigned even parity. Lagrangian for these new fields contains the following terms,

$$\begin{aligned} -\mathcal{L} &= \sum_{i=1}^{3}\left[\sum_{\alpha=e,\mu,\tau}\Big(-h_{\alpha i}\bar{N}_i\eta^\dagger\ell_\alpha - h_{\alpha i}^*\bar{\ell}_\alpha\eta N_i\Big) + \frac{1}{2}M_i\bar{N}_i^c N_i + \frac{1}{2}M_i\bar{N}_i N_i^c\right] \\ &+ m_\phi^2\phi^\dagger\phi + m_\eta^2\eta^\dagger\eta + \lambda_1(\phi^\dagger\phi)^2 + \lambda_2(\eta^\dagger\eta)^2 + \lambda_3(\phi^\dagger\phi)(\eta^\dagger\eta) + \lambda_4(\eta^\dagger\phi)(\phi^\dagger\eta) \\ &+ \frac{\lambda_5}{2}\left[(\eta^\dagger\phi)^2 + (\phi^\dagger\eta)^2\right], \end{aligned} \tag{1}$$

where ℓ_α is a left-handed doublet lepton and ϕ is the ordinary doublet Higgs scalar. The coupling constants λ_i's are real. The model is known to give a simultaneous explanation for the existence of neutrino masses and dark matter (DM) [9, 10]. Neutrino masses are induced at one-loop level and DM is prepared as the lightest Z_2 odd field. Moreover, the model can also explain the baryon number asymmetry in the Universe through leptogenesis if the masses of N_i are finely degenerate [11].

First, we briefly overview these features. For the definite argument, we assume that the lightest Z_2 odd field is a lightest neutral component of η here. Its mass is expressed as $M_\eta^2 = m_\eta^2 + (\lambda_3+\lambda_4+\lambda_5)\langle\phi\rangle^2$ and it is taken to be of $O(1)$ TeV. Since the SM contents are assigned even parity, it is stable and then it can be a good DM candidate [13, 14]. In fact, it is known to realize the required DM relic abundance only by fixing the couplings $\lambda_{3,4}$ at suitable values [11]. The neutrino oscillation data could also be roughly explained by assuming a simple flavor structure such as [10]

$$h_{ei} = 0, \quad h_{\mu j} = h_{\tau j} \equiv h_j \quad (j=1,2); \qquad h_{e3} = h_{\mu 3} = -h_{\tau 3} \equiv h_3. \tag{2}$$

In this case, the neutrino mass matrix can be written as

$$\mathcal{M} = (h_1^2\Lambda_1 + h_2^2\Lambda_2)\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} + h_3^2\Lambda_3\begin{pmatrix} 1 & 1 & -1 \\ 1 & 1 & -1 \\ -1 & -1 & 1 \end{pmatrix}, \tag{3}$$

	λ_5	$\lvert h_1\rvert$	$\lvert h_2\rvert$	$\lvert h_3\rvert$	M_1	M_2	M_3	M_η
(a)	4×10^{-4}	10^{-4}	5.67×10^{-3}	2.63×10^{-3}	10^6	3×10^6	6×10^6	10^3
(b)	3×10^{-5}	10^{-4}	3.33×10^{-3}	1.45×10^{-3}	10^4	3×10^4	6×10^4	10^3

Table 1 Typical parameter sets for the neutrino mass generation, which explain the neutrino oscillation data. A GeV unit is used for the mass.

and Λ_i $(i = 1-3)$ is given by

$$\Lambda_i = \frac{\lambda_5\langle\phi\rangle^2}{8\pi^2}\frac{M_i}{M_\eta^2 - M_i^2}\left(1 + \frac{M_i^2}{M_\eta^2 - M_i^2}\ln\frac{M_i^2}{M_\eta^2}\right). \tag{4}$$

The mass eigenvalues of this matrix are obtained as

$$\begin{aligned} m_1 &= 0, \qquad m_2 = 3|h_3|^2\Lambda_3, \\ m_3 &= 2\Big[|h_1|^4\Lambda_1^2 + |h_2|^4\Lambda_2^2 + 2|h_1|^2|h_2|^2\Lambda_1\Lambda_2\cos 2(\theta_1-\theta_2)\Big]^{1/2}, \end{aligned} \tag{5}$$

where $\theta_j = \arg(h_j)$. If we apply the parameters shown in Table 1 to this mass matrix as examples, the neutrino oscillation parameters required for the normal hierarchy can be obtained except that the tri-bimaximal PMNS matrix is brought about [10].[a] Since we now know that θ_{13} has a non-zero value, we have to modify the flavor structure given in eq. (2) [11]. However, since the required modification is expected to cause no crucial effect to the leptogenesis scenario, the use of this simple flavor structure is enough for the present purpose. Although the resonant leptogenesis works in this model, unnatural fine degeneracy among the right-handed neutrino masses seems to be required [11].[b] We consider an extension of the model with singlet scalars, which could remedy this fault without spoiling the favorable features of the model mentioned above.

In the model defined by eq. (1), we can suppose two types of lepton number assignment for the new fields such as (i) $L(N_i) = 0$ and $L(\eta) = 1$, in which the lepton number is violated through the λ_5 terms, and (ii) $L(N_i) = 1$ and $L(\eta) = 0$, in which the lepton number is violated through the mass terms of N_i. If these lepton number violating terms are supposed to have its origin at high energy regions and they are effectively induced from

[a] Although we can fix the parameters at the values required for the inverted hierarchy in the similar way, we confine the present study to the normal hierarchy.

[b] This mass degeneracy might be explained by assuming the pseudo-Dirac nature for N_i, which could be caused by symmetry breaking at a TeV scale [12].

it at low energy regions, some new fields might be introduced to give their origin. Along this idea, we consider an extension of the model with singlet scalars S_a. The addition of S_a allows to introduce gauge invariant terms such as $\mu_a S_a \eta^\dagger \phi$ and $y_i^{(a)} S_a \bar{N}_i N_i^c$. As is shown below, these could induce the above mentioned lepton number violating terms as the effective ones in the case (i) and (ii), respectively. Since we impose the lepton number conservation in these terms, S_a should be assigned the lepton number $+1$ and -2 in each case. In order to keep important features of the original model, the Z_2 symmetry should be an exact symmetry. Thus, in the former case, S_a should have odd Z_2 parity and $\langle S_a \rangle = 0$. If S_a is supposed to be heavy enough and it is integrated out to derive the low energy effective model, the λ_5 term in eq. (1) is induced as long as a lepton number violating term $m_a^2 S_a^2$ exists [5]. On the other hand, in the latter case, S_a should have even parity of Z_2 and then $\langle S_a \rangle \neq 0$ can be allowed at TeV or higher energy scales. In such a case, even if $M_i = 0$ is supposed in eq. (1), this vacuum expectation value generates Majorana masses for N_i without violating the Z_2 symmetry.

We identify the one of these singlet scalars S_a with inflaton. It is discussed that it could play a role of inflaton by assuming special potential for it or its non-minimal coupling with Ricci scalar [5–7]. In the model corresponding to the case (i), both the inflation and the non-thermal leptogenesis associated to the reheating due to the inflaton decay through the interaction $\mu_a S_a \phi^\dagger \eta$ has already been discussed in [7]. The model is found to work well under the appropriate conditions there. In this paper, we study another possibility in the case (ii), where the reheating is caused by the coupling $S_a \bar{N}_i N_i^c$. Leptogenesis is also supposed to be brought about through this reheating process. In this direction, different types of scenario for the leptogenesis might be considered depending on the way how the lepton number asymmetry is generated in the doublet lepton sector. Here, we consider that the lepton number asymmetry is produced through the decay of N_i which is non-thermally produced through the inflaton decay.[c]

[c]Another scenario might be constructed by assuming that the lepton number asymmetry is produced directly through the inflaton decay to the Dirac type right-handed neutrinos N_i under the condition $M_i = 0$. Such a possibility will be discussed elsewhere.

The model might contain terms relevant to the singlet scalars S_a as

$$\begin{aligned} -\mathcal{L} &= \tilde{m}_{S_a}^2 S_a^\dagger S_a + \kappa_S^{(a)}(S_a^\dagger S_a)^2 + \kappa_\phi^{(a)}(S_a^\dagger S_a)(\phi^\dagger\phi) + \kappa_\eta^{(a)}(S_a^\dagger S_a)(\eta^\dagger\eta) \\ &+ y_i^{(a)} S_a \bar{N}_i^c N_i + y_i^{(a)*} S_a^\dagger \bar{N}_i N_i^c \\ &+ \frac{1}{2} m_{S_a}^2 S_a^2 + \frac{1}{2} m_{S_a}^2 S_a^{\dagger 2}. \end{aligned} \tag{6}$$

The lepton number is explicitly broken through both the Majorana masses of N_i in eq. (1) and mass terms of S_a in the third line of eq. (6). The latter one makes the components of S_a split into mass eigenstates $S_{\pm a}$ with mass eigenvalues $m_{\pm a}^2 = m_{S_a}^2 \pm \tilde{m}_{S_a}^2$. As is easily found, S_{+a} and S_{-a} correspond to real and imaginary parts of S_a, respectively. This results in the lepton number violation in the Yukawa coupling $\frac{y_i^{(a)}}{\sqrt{2}} S_{\pm a} \bar{N}_i N_i^c$. We do not consider the spontaneous mass generation for N_i through the interaction given in the second line and then $\langle S_a \rangle = 0$ is supposed here. This extension could change phenomenology in the original Ma model. The $\kappa_\phi^{(a)}$ and $\kappa_\eta^{(a)}$ terms could affect the quartic couplings λ_1-λ_4 for ϕ and η through the radiative effects. As a result, they might be constrained by weak scale experiments. On the other hand, $\frac{y_i^{(a)}}{\sqrt{2}} S_{\pm a} \bar{N}_i N_i^c$ could be relevant to the leptogenesis. In the following parts, we focus our discussion on this latter point.

3 Non-thermal leptogenesis associated to reheating

We assume that a real component of S_1 plays a role of inflaton. It is represented as $S_{\rm inf}(\equiv S_{+1})$ in the following part. When the inflation ends, $S_{\rm inf}$ is supposed to start damping oscillation around a potential minimum $\langle S_{\rm inf} \rangle = 0$. At the first stage of this oscillation, its amplitude is large and then preheating could occur through the quartic couplings $\frac{\kappa_\phi}{2} S_{\rm inf}^2 \phi^\dagger\phi$ and $\frac{\kappa_\eta}{2} S_{\rm inf}^2 \eta^\dagger\eta$ [15,16]. Although ϕ and η might be produced explosively through the resonance effect for suitable values of κ_ϕ and κ_η, the following decay of ϕ and η cannot produce any lepton and baryon number asymmetry. This situation is not changed even if η is heavier than N_i. Although η can decay into $\ell_\alpha N_i$, any lepton number asymmetry is not generated in the doublet lepton sector through this decay because of the cancellation of the asymmetry between the yields from η and $\eta^\dagger$.

At the later stage of this oscillation, the inflaton decay is expected to be induced by the coupling $\frac{y_i}{\sqrt{2}} S_{\rm inf} \bar{N}_i N_i^c$ where the coupling $y_i^{(1)}$ is abbreviated to y_i. The inflaton energy is expected to be converted dominantly to one of the right-handed neutrinos N_i, which has the mass satisfying $M_i < \frac{m_{S_{\rm inf}}}{2}$ and also the largest partial decay width

$$\Gamma_{S_{\rm inf}}^{(i)} = \frac{|y_i|^2}{8\pi} m_{S_{\rm inf}} \left(1 - \frac{4M_i^2}{m_{S_{\rm inf}}^2}\right)^{1/2}. \tag{7}$$

If we fix such a N_i at N_1 for the concreteness[d], the resulting number density of N_1 produced through this decay can be estimated as

$$n_{N_1}^{\rm nonth} = \frac{\rho_{S_{\rm inf}}}{M_1} = \frac{3|y_1|^4}{64\pi^2} \frac{M_{\rm pl}^2 m_{S_{\rm inf}}^2}{M_1} \left(1 - \frac{4M_1^2}{m_{S_{\rm inf}}^2}\right), \tag{8}$$

where we use a value of the inflaton energy density $\rho_{S_{\rm inf}}$. It is fixed through the condition $H \simeq \Gamma_{S_{\rm inf}}^{(1)}$ for the Hubble parameter $H^2 = \frac{\rho_{S_{\rm inf}}}{3M_{\rm pl}^2}$.

If the decay rate of N_1 is larger than the one of $S_{\rm inf}$, the produced N_1 is expected to decay to $\ell_\alpha \eta$ immediately since it is the lowest order process. In such a case, the decay of N_1 is considered to occur in a non-thermal situation before the completion of thermalization. Since the decay width of N_1 is estimated under the assumption (2) for the neutrino Yukawa couplings as

$$\Gamma_{N_1} = \frac{|h_1|^2}{4\pi} M_1 \left(1 - \frac{M_\eta^2}{M_1^2}\right), \tag{9}$$

the required condition $\Gamma_{S_{\rm inf}}^{(1)} < \Gamma_{N_1}$ might be roughly expressed as

$$\left(\frac{|y_1|}{10^{-8}}\right)\left(\frac{m_{S_{\rm inf}}}{10^7~{\rm GeV}}\right)^{\frac{1}{2}} < 10^3 \left(\frac{|h_1|}{10^{-3}}\right)\left(\frac{M_1}{10^3~{\rm GeV}}\right)^{\frac{1}{2}}\left(1 - \frac{M_\eta^2}{M_1^2}\right)^{\frac{1}{2}}\left(1 - \frac{4M_1^2}{m_{S_{\rm inf}}^2}\right)^{-\frac{1}{4}}. \tag{10}$$

Here we note that the inflaton mass $m_{S_{\rm inf}}$ is not constrained by the observational data of CMB as long as we assume the suitable inflation scenario such as the ones discussed in [6, 7].

The reheating temperature T_R is estimated from $H \simeq \Gamma_{S_{\rm inf}}^{(i)}$ as[e]

$$T_R \simeq 5.3 \times 10^3 \left(\frac{|y_1|}{10^{-8}}\right)\left(\frac{m_{S_{\rm inf}}}{10^7~{\rm GeV}}\right)^{\frac{1}{2}}\left(1 - \frac{4M_1^2}{m_{S_{\rm inf}}^2}\right)^{\frac{1}{4}}~{\rm GeV}. \tag{11}$$

[d]In this study, N_1 is assumed to be the lightest one as shown in Table 1, which is favored to suppress the washout of the generated lepton number asymmetry as discussed later.

[e]The reheating temperature should be estimated by using the $S_{\rm inf}$ decay rate to the final states composed of four particles $2(\bar{\ell}_\alpha \eta)$ instead of eq. (7). However, both of them give the same value for T_R as long as the condition (10) is imposed. As a result, no h_1 dependence appears in the expression of T_R.

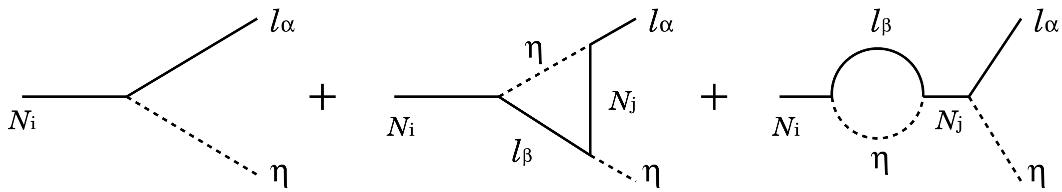

Fig. 1 Feynman diagrams contributing to the generation of the lepton number asymmetry.

The reheating temperature is found to take a fixed value for a constant value of $|y_1|^2 m_{S_{\rm inf}}$. Since we suppose that the DM abundance is realized by the thermal relic of the lightest neutral component of η in this model, $T_R > M_\eta$ should be fulfilled. This requires

$$\left(\frac{|y_1|}{10^{-8}}\right)\left(\frac{m_{S_{\rm inf}}}{10^7~{\rm GeV}}\right)^{\frac{1}{2}} > 0.2\left(\frac{M_\eta}{10^3~{\rm GeV}}\right). \tag{12}$$

An interesting thing is that the number density (8) could be much larger than the thermal equilibrium value even for the relativistic N_1 as

$$\frac{n_{N_1}^{\rm nonth}}{n_{N_1}^{\rm th}} \simeq 10^3\left(\frac{|y_1|}{10^{-8}}\right)\left(\frac{m_{S_{\rm inf}}}{10^7~{\rm GeV}}\right)^{\frac{1}{2}}\left(\frac{10^3~{\rm GeV}}{M_1}\right)\left(1-\frac{4M_1^2}{m_{S_{\rm inf}}^2}\right)^{\frac{1}{4}}, \tag{13}$$

where we use eqs. (8) and (11). If N_1 is non-relativistic and T_R is much smaller than M_1, this ratio is enhanced by a factor $e^{\frac{M_1}{T_R}}$.

Since the N_1 decay to $\ell_\alpha\eta$ can satisfy the Sakharov conditions, the lepton number asymmetry could be generated through this process. In could be estimated as[f]

$$Y_L = 2\varepsilon\frac{n_{N_1}}{s}, \tag{14}$$

where Y_L is defined as $Y_L = \sum_\alpha \frac{n_{\ell_\alpha}-n_{\bar\ell_\alpha}}{s}$ by using the entropy density s. The CP asymmetry in the decay $N_1 \to \sum_\alpha \ell_\alpha\eta$ is represented by ε. It is brought about by the interference between tree and one-loop diagrams shown in Fig. 1 and can be derived as [17]

$$\begin{aligned}\varepsilon &= \frac{\Gamma(N_1\to\sum_\alpha \ell_\alpha\eta^\dagger)-\Gamma(N_1\to\sum_\alpha\bar\ell_\alpha\eta)}{\Gamma(N_1\to\sum_\alpha \ell_\alpha\eta^\dagger)+\Gamma(N_1\to\sum_\alpha\bar\ell_\alpha\eta)} \\ &= \frac{1}{16\pi C}\frac{\sum_{j=2,3}{\rm Im}\left[\left(\sum_{\alpha=e,\mu,\tau}h_{\alpha 1}h_{\alpha j}^*\right)^2\right]}{\sum_{\alpha=e,\mu,\tau}h_{\alpha 1}h_{\alpha 1}^*}\,G\left(\frac{M_j^2}{M_1^2},\frac{M_\eta^2}{M_1^2}\right),\end{aligned} \tag{15}$$

[f]This Y_L should be understood as Y_{B-L} under the existence of sphaleron interaction.

where $C = \frac{3}{4} + \frac{1}{4}\left(1 - \frac{M_\eta^2}{M_1^2}\right)^2$ and $G(x,y)$ is defined by

$$\begin{aligned} G(x,y) &= \frac{5}{4}F(x,0) + \frac{1}{4}F(x,y) + \frac{1}{4}(1-y)^2\left[F(x,0)+F(x,y)\right], \\ F(x,y) &= \sqrt{x}\left[1 - y - (1+x)\ln\left(\frac{1-y+x}{x}\right)\right]. \end{aligned} \tag{16}$$

If we apply the flavor structure of neutrino Yukawa couplings given in eq. (2) to this formula, ε is expressed as

$$\varepsilon = \frac{|h_2|^2 \sin 2(\theta_1 - \theta_2)}{8\pi C}\, G\left(\frac{M_2^2}{M_1^2}, \frac{M_\eta^2}{M_1^2}\right). \tag{17}$$

We assume the maximum CP phase $\sin 2(\theta_1 - \theta_2) = 1$ in the following numerical study.

When the reheating completes through the inflaton decay, all fields could be considered to take the thermal distribution at the temperature T_R. However, the asymmetry produced through the decay of the non-thermal N_1 could exist as $Y_L = 2\varepsilon \frac{n_{N_1}^{\rm nonth}}{s}$ at this stage. If we take this view point, this asymmetry could be treated as its initial value at the reheating temperature T_R for the following evolution of Y_L. In the usual thermal leptogenesis scenario discussed in [11], N_1 is considered to be in the thermal equilibrium due to the assumption $T_R > M_1$. Thus, we find the relation at T_R, by comparing these two cases, such as

$$Y_L^{\rm nonth} = \frac{n_{N_1}^{\rm nonth}}{n_{N_1}^{\rm th}} Y_L^{\rm th}. \tag{18}$$

This suggests that $Y_L^{\rm nonth}$ could have a largely enhanced value compared with $Y_L^{\rm th}$ as long as the factor $\frac{n_{N_1}^{\rm nonth}}{n_{N_1}^{\rm th}}$ takes an enhanced value as suggested in eq. (13). However, we should note that this enhanced initial asymmetry can play a substantial role for the generation of the sufficient baryon number asymmetry only if the washout of the lepton number asymmetry is ineffective at a neighborhood of T_R. Such a situation could be realized owing to the Boltzmann suppression only for $M_1 > T_R$. By combing it with the requirement $\frac{n_{N_1}^{\rm nonth}}{n_{N_1}^{\rm th}} \gg 1$, the condition might be expressed as

$$10^{-3}\left(\frac{M_1}{10^3~{\rm GeV}}\right)\left(1 - \frac{4M_1^2}{m_{S_{\rm inf}}^2}\right)^{-\frac{1}{4}} \ll \left(\frac{|y_1|}{10^{-8}}\right)\left(\frac{m_{S_{\rm inf}}}{10^7~{\rm GeV}}\right)^{\frac{1}{2}} < 0.2\left(\frac{M_1}{10^3~{\rm GeV}}\right). \tag{19}$$

We note that it is easy for this condition to be consistent with eq. (10) as long as the Yukawa coupling h_1 is larger than 10^{-6}. Thus, we can expect that the lepton number asymmetry, which is enhanced from that in the thermal leptogenesis, could be obtained for the model parameters which are suitably fixed without any serious tuning.

A typical situation is that the non-relativistic N_1 is produced in such a circumstance that lepton number violating processes freeze out. In that case, the initial lepton asymmetry could be kept until the weak scale. On the other hand, if the washout effects are in thermal equilibrium, the initial lepton asymmetry is immediately erased and the scenario reduces to the case similar to the usual thermal leptogenesis. This feature makes a rather low reheating temperature favorable in this scenario. If this favorable situation is realized, the sufficient lepton number asymmetry is expected to be generated from the right-handed neutrino whose mass is much smaller than the Davidson-Ibarra bound [18] without any resonance effect [19]. It might give an another interesting possibility for the leptogenesis in the radiative neutrino mass model.

For a quantitative check of the above discussion, the analysis of the Boltzmann equations is required to estimate the washout effect of the generated lepton number asymmetry, especially, in a marginal situation. The lepton number asymmetry given in eq. (14) could be affected by the washout through lepton number violating scattering and the inverse decay at a neighborhood of T_R. The asymmetry Y_L at a certain temperature T is estimated by solving the Boltzmann equations

$$\begin{aligned} \frac{dY_{N_1}}{dz} &= -\frac{z}{sH(M_1)}\left(\frac{Y_{N_1}}{Y_{N_1}^{\rm eq}}-1\right)\left\{\gamma_D^{N_1}+\sum_{j=1,2}\left(\gamma_{N_1N_j}^{(2)}+\gamma_{N_1N_i}^{(3)}\right)\right\}, \\ \frac{dY_L}{dz} &= \frac{z}{sH(M_1)}\left\{\varepsilon\left(\frac{Y_{N_1}}{Y_{N_1}^{\rm eq}}-1\right)\gamma_D^{N_1}-\frac{2Y_L}{Y_\ell^{\rm eq}}\left(\gamma_N^{(2)}+\gamma_N^{(13)}\right)\right\}, \end{aligned} \tag{20}$$

where z is defined as $z=\frac{M_1}{T}$. The relevant reaction density γ used in these equations can be found in [11].[g] The baryon number asymmetry in the present Universe is converted from this lepton number asymmetry Y_L by the sphaleron interaction. It can be estimated as $Y_B=-\frac{8}{23}Y_L(z_{\rm EW})$, where the sphaleron decoupling temperature $T_{\rm EW}$ is taken to be 100 GeV.

The model parameters used in the numerical analysis are given in Table 1. They can explain well the neutrino oscillation data except for the nonzero mixing angle θ_{13} as addressed before. In this study, we fix the initial values of Y_{N_1} and Y_L to be the thermal one at T_R and the value fixed by eq. (14), respectively. Typical numerical results of

[g] Since the lepton number violating effect due to sphaleron is not contained in eq. (20), Y_L in eq. (20) should be understood as $-Y_{B-L}$. Non-degenerate right-handed neutrinos assumed here make the inverse decay to $N_{2,3}$ irrelevant in this analysis.

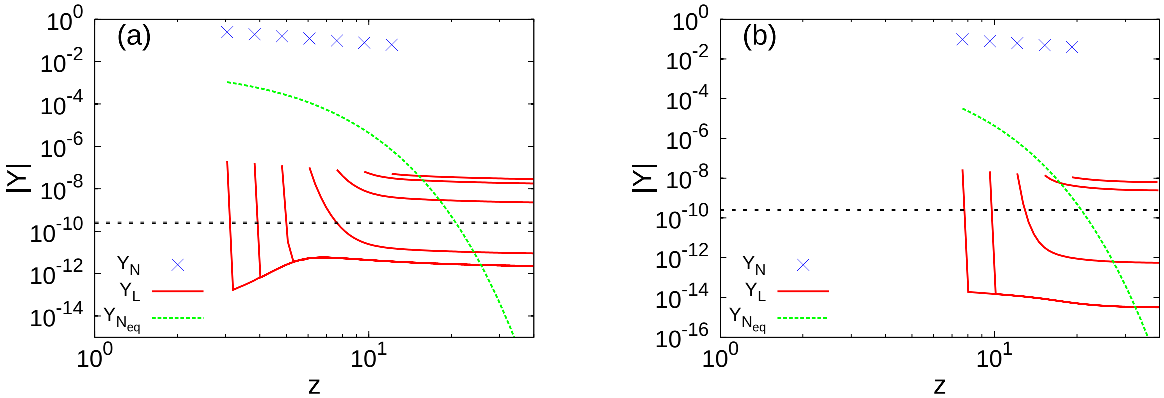

Fig. 2 The lepton number asymmetry Y_L generated for the parameter sets (a) and (b) in the neutrino sector shown in Table 1. Crosses represent the initial value of Y_{N_1} generated from the inflaton decay. Horizontal dotted lines correspond to the lepton asymmetry required to explain the amount of the baryon number in the Universe. Both y_1 and $m_{S_{\rm inf}}$ are taken so as to satisfy the conditions (10) and (19). For each lines and crosses for Y_L and Y_{N_1}, the value of y_1 is taken from left to right as $10^{-7.2}$, $10^{-7.3}, 10^{-7.4}$, $10^{-7.5}$, $10^{-7.6}$, $10^{-7.7}$, $10^{-7.8}$ for $m_{S_{\rm inf}} = 10^9$ GeV in (a), and $10^{-8.6}$, $10^{-8.7}, 10^{-8.8}$, $10^{-8.9}$, 10^{-9} for $m_{S_{\rm inf}} = 10^7$ GeV in (b).

the analysis are shown in Fig. 2. Although $z_{\rm EW}$ is much larger than 20 in the assumed value of M_1, Y_L converges to a constant value at $z = 20$ sufficiently, and then we can identify $Y_L(20)$ with the one at $z_{\rm EW}$. The steep decrease of Y_L at the initial stage of the evolution for a larger y_1 is considered to be caused by the washout. It is effective for the larger y_1, which results in the higher reheating temperature as $T_R \gtrsim M_1$. As the temperature decreases from T_R, the washout process is suppressed and Y_L converges to a constant value as in case of the ordinary thermal leptogenesis. For the smaller y_1, T_R becomes sufficiently lower and the washout process is frozen. In that case, the required Y_L can be obtained as long as its initial value is large enough. This result confirms that the reheating temperature and the decoupling of the washout effect are essential for the present scenario.

Since the initial value of Y_L is determined by the neutrino Yukawa couplings $h_{1,2}$ which are constrained by the neutrino oscillation data, the scenario is closely related to the neutrino mass generation as in the ordinary leptogenesis. However, we should also note that the model has an additional parameter λ_5 related to the neutrino mass. It makes the weak scale leptogenesis feasible also. If $|\lambda_5|$ takes a smaller value for fixed values of

M_i, the neutrino oscillation data require the larger neutrino Yukawa couplings $|h_i|$. In that case, the initial lepton number asymmetry becomes larger but the washout effects become also stronger. This suggests that a favorable value of λ_5 might be determined from a viewpoint of leptogenesis. Since λ_5 is also related to the DM physics in this model [11], further study in this direction may give us a useful hint for the model.

4 Summary

We have proposed a scenario for the generation of the baryon number asymmetry in a one-loop radiative neutrino mass model extended by the singlet scalars. In this model, singlet scalars are related to both the inflation and the neutrino mass generation. Leptogenesis is caused by the decay of non-thermal right-handed neutrinos which is produced through the decay of inflaton. If the right-handed neutrinos could decay immediately before they are thermalized, the lepton number asymmetry could be generated effectively through this decay. The number density of the non-thermal right-handed neutrino could be much larger than the thermal one so that the generated lepton asymmetry could be enhanced compared with the one which is generated from the decay of the thermal right-handed neutrinos. Based on this lepton asymmetry, sphaleron could generate a sufficient amount of the baryon number asymmetry. We discussed the condition for which the non-thermal right-handed neutrinos could be the mother field of the lepton number asymmetry. Numerical analysis for the evolution of the lepton number asymmetry shows that the sufficient baryon number asymmetry can be obtained from the decay of the right-handed neutrino, which is much lighter than the Davidson-Ibarra bound. Rather low reheating temperature could be sufficient for the generation of the required amount of the baryon number asymmetry in this scenario.

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