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.


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 $\tilde{N} \ell \tilde{\phi}$, where $\ell$ and $\phi$ are the ordinary doublet lepton and a fermionic superpartner of the doublet Higgs scalar $\phi$, 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 $SN_i N_i^c$ and $S\eta^\dagger \phi$ where $\eta$ 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 $\eta$ 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,

$$- \mathcal{L} = \sum_{i=1}^{3} \left[ \sum_{\alpha=e,\mu,\tau} \left( - h_{\alpha i} \bar{N}_i \eta^\dagger \ell_\alpha - h_{\alpha i}^* \bar{\ell}_\alpha \eta N_i \right) + \frac{1}{2} M_i \bar{N}_i N_i + \frac{1}{2} M_i \bar{N}_i N_i \right]$$

$$+ m_\phi^2 \phi \phi^\dagger + m_\eta^2 \eta \eta^\dagger + \lambda_1 (\phi^\dagger \phi)^2 + \lambda_2 (\eta^\dagger \eta)^2 + \lambda_3 (\phi^\dagger \phi)(\eta^\dagger \eta) + \lambda_4 (\eta^\dagger \phi)(\phi^\dagger \eta)$$

$$+ \frac{\lambda_5}{2} \left[ (\eta^\dagger \phi)^2 + (\phi^\dagger \eta)^2 \right],$$  

(1)

where $\ell_\alpha$ is a left-handed doublet lepton and $\phi$ is the ordinary doublet Higgs scalar. The coupling constants $\lambda_i$'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 $\eta$ here. Its mass is expressed as $M_\eta^2 = m_\eta^2 + (\lambda_3 + \lambda_4 + \lambda_5)(\phi)^2$ 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]

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

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

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

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and $\Lambda_i (i = 1 - 3)$ is given by

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

The mass eigenvalues of this matrix are obtained as

$$m_1 = 0, \quad m_2 = 3|h_3|^2 \Lambda_3, \quad m_3 = 2 \left[ |h_1|^2 \Lambda_1^2 + |h_2|^2 \Lambda_2^2 + 2|h_1|^2|h_2|^2 \Lambda_1 \Lambda_2 \cos(\theta_1 - \theta_2) \right]^{1/2}, \tag{5}$$

where $\theta_j = \text{arg}(h_j)$. 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 \[10\]. Since we now know that $\theta_{13}$ 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 \[11\]. 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 $\lambda_5$ 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

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

\[\text{This mass degeneracy might be explained by assuming the pseudo-Dirac nature for } N_i, \text{ 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 \( \lambda_5 \) term in eq. (11) 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. (11), 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.

\[ ^6 \text{Another scenario might be constructed by assuming that the lepton number asymmetry is produced directly through the inflaton decay to the Dirac type right-handed neutrinos } N_i \text{ under the condition } M_i = 0. \text{ Such a possibility will be discussed elsewhere.} \]
The model might contain terms relevant to the singlet scalars $S_a$ as

$$-\mathcal{L} = \bar{m}^2_{S_a} S^\dagger_a S_a + \kappa^a_S (S^\dagger_a S_a)^2 + \kappa^{(a)}_\phi (S^\dagger_a S_a)(\phi^\dagger \phi) + \kappa^{(a)}_\eta (S^\dagger_a S_a)(\eta^\dagger \eta)$$

$$+ \frac{y^a_i}{\sqrt{2}} S^\dagger_a \bar{N}_i^c N_i + \frac{y^{(a)*}_i}{\sqrt{2}} S^\dagger_a \bar{N}_i^c N_i^c$$

$$+ \frac{1}{2} m^2_{S_a} S^2_a + \frac{1}{2} m^2_{S_a} S^\dagger_2 a.$$

(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 $m^2_{\pm a} = m^2_{S_a} \pm \bar{m}^2_{S_a}$. 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 $\frac{y^a_i}{\sqrt{2}} S^\pm_a \bar{N}_i^c N_i^c$. We do not consider the spontaneous mass generation for $N_i$ through the interaction given in the second line and then $\langle S^a_0 \rangle = 0$ is supposed here. This extension could change phenomenology in the original Ma model. The $\kappa^{(a)}_\phi$ and $\kappa^{(a)}_\eta$ terms could affect the quartic couplings $\lambda_1-\lambda_4$ for $\phi$ and $\eta$ through the radiative effects. As a result, they might be constrained by weak scale experiments. On the other hand, $\frac{y^a_i}{\sqrt{2}} S^\pm_a \bar{N}_i^c N_i^c$ 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 $S^\inf \equiv S^1_\pm$ in the following part. When the inflation ends, $S^\inf$ is supposed to start damping oscillation around a potential minimum $\langle S^\inf \rangle = 0$. At the first stage of this oscillation, its amplitude is large and then preheating could occur through the quartic couplings $\kappa^{2}_\phi S^2 \phi^\dagger \phi$ and $\kappa^{2}_\eta S^2 \eta^\dagger \eta$. Although $\phi$ and $\eta$ might be produced explosively through the resonance effect for suitable values of $\kappa^{(a)}_\phi$ and $\kappa^{(a)}_\eta$, the following decay of $\phi$ and $\eta$ cannot produce any lepton and baryon number asymmetry. This situation is not changed even if $\eta$ is heavier than $N_i$. Although $\eta$ can decay into $\ell_a N_i$, 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 $\eta$ and $\eta^\dagger$.

At the later stage of this oscillation, the inflaton decay is expected to be induced by the coupling $\frac{y^a_i}{\sqrt{2}} S^\inf \bar{N}_i^c N_i^c$ where the coupling $y^{(1)}_i$ 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 $M_i < \frac{m_{S_{\text{inf}}}}{2}$ and also the largest partial decay width

$$\Gamma^{(i)}_{S_{\text{inf}}} = \frac{|y_i|^2}{8\pi} m_{S_{\text{inf}}} \left(1 - \frac{4M_i^2}{m_{S_{\text{inf}}}^2}\right)^{1/2}. \quad (7)$$

If we fix such a $N_i$ at $N_1$ for the concretenessootnote{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.}, the resulting number density of $N_1$ produced through this decay can be estimated as

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

where we use a value of the inflaton energy density $\rho_{S_{\text{inf}}}$. It is fixed through the condition $H \simeq \Gamma^{(1)}_{S_{\text{inf}}}$ for the Hubble parameter $H^2 = \frac{\rho_{S_{\text{inf}}}}{3M_{\text{pl}}}$. If the decay rate of $N_1$ is larger than the one of $S_{\text{inf}}$, 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ootnote{The reheating temperature should be estimated by using the $S_{\text{inf}}$ 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 $T_R$.} for the neutrino Yukawa couplings as

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

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

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

Here we note that the inflaton mass $m_{S_{\text{inf}}}$ is not constrained by the observational data of CMB as long as we assume the suitable inflation scenario such as the ones discussed in \cite{6,7}. The reheating temperature $T_R$ is estimated from $H \simeq \Gamma^{(i)}_{S_{\text{inf}}}$ as

$$T_R \simeq 5.3 \times 10^3 \left(\frac{|y_1|}{10^{-8}}\right) \left(\frac{m_{S_{\text{inf}}}}{10^7 \text{ GeV}}\right)^{1/2} \left(1 - \frac{4M_1^2}{m_{S_{\text{inf}}}^2}\right)^{1/4} \text{ GeV}. \quad (11)$$
The reheating temperature is found to take a fixed value for a constant value of $|y_1|^2 m_{S_{\text{inf}}}$. Since we suppose that the DM abundance is realized by the thermal relic of the lightest neutral component of $\eta$ in this model, $T_R > M_\eta$ should be fulfilled. This requires

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

(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

$$
n^\text{nonth}_i \frac{n^\text{th}}{n^\text{th}}_i \simeq 10^3 \left( \frac{|y_1|}{10^{-8}} \right) \left( \frac{m_{S_{\text{inf}}}}{10^7 \text{ GeV}} \right)^{\frac{1}{2}} \left( \frac{10^3 \text{ GeV}}{M_1} \right) \left( 1 - \frac{4M_1^2}{m_{\eta}^2} \right)^{\frac{1}{4}},
$$

(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 $e^{M_1/T_R}$.

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

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

(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 $N_1 \rightarrow \sum_\alpha \ell_\alpha \eta$ is represented by $\varepsilon$. It is brought about by the interference between tree and one-loop diagrams shown in Fig. 1 and can be derived as

$$
\varepsilon = \frac{\Gamma(N_1 \rightarrow \sum_\alpha \ell_\alpha \eta^\dagger) - \Gamma(N_1 \rightarrow \sum_\alpha \bar{\ell}_\alpha \eta)}{\Gamma(N_1 \rightarrow \sum_\alpha \ell_\alpha \eta^\dagger) + \Gamma(N_1 \rightarrow \sum_\alpha \bar{\ell}_\alpha \eta)}
= \frac{1}{16\pi C} \sum_{j=2,3} \text{Im} \left[ \left( \sum_{\alpha=e,\mu,\tau} h_{\alpha 1}^* h_{\alpha j} \right)^2 \right] G \left( \frac{M_j^2}{M_i^2}, M_\eta^2, M_\ell^2 \right),
$$

(15)

$^4$This $Y_L$ should be understood as $Y_{B-L}$ under the existence of sphaleron interaction.
where $C = \frac{3}{4} + \frac{1}{4} \left(1 - \frac{M_2^2}{M_1^2}\right)^2$ and $G(x, y)$ is defined by

$$G(x, y) = \frac{5}{4} F(x, 0) + \frac{1}{4} F(x, y) + \frac{1}{4} (1 - y)^2 [F(x, 0) + F(x, y)],$$

$$F(x, y) = \sqrt{x} \left[1 - y - (1 + x) \ln \left(\frac{1 - y + x}{x}\right)\right].$$

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

$$\varepsilon = \frac{|h_2|^2 \sin 2(\theta_1 - \theta_2)}{8\pi C} G \left(\frac{M_2^2}{M_1^2}, \frac{M_0^2}{M_1^2}\right).$$

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 $Y_{L_{n\text{on}}} = 2\varepsilon \frac{n_{N_1}^{\text{non}}}{s}$ at this stage. If we take this viewpoint, 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

$$Y_{L_{n\text{on}}} = \frac{n_{N_1}^{\text{non}}}{n_{N_1}^{\text{th}}} Y_{L_{\text{th}}}.$$  \(18\)

This suggests that $Y_{L_{n\text{on}}}$ could have a largely enhanced value compared with $Y_{L_{\text{th}}}$ as long as the factor $\frac{n_{N_1}^{\text{non}}}{n_{N_1}^{\text{th}}}$ 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 $\frac{n_{N_1}^{\text{non}}}{n_{N_1}^{\text{th}}} \gg 1$, the condition might be expressed as

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

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 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

$$
\frac{dY_{N_1}}{dz} = -\frac{z}{sH(M_1)} \left( \frac{Y_{N_1}}{Y_{N_1}^{\text{eq}}} - 1 \right) \left\{ \gamma^{N_1}_{D} + \sum_{j=1,2} \left( \gamma^{(2)}_{N_1 N_j} + \gamma^{(3)}_{N_1 N_i} \right) \right\},
$$
$$
\frac{dY_L}{dz} = \frac{z}{sH(M_1)} \left\{ \varepsilon \left( \frac{Y_{N_1}}{Y_{N_1}^{\text{eq}}} - 1 \right) \gamma^{N_1}_{D} - \frac{2Y_L}{Y_{\ell}^{\text{eq}}} \left( \gamma^{(2)}_{N} + \gamma^{(13)}_{N} \right) \right\},
$$

where $z$ is defined as $z = \frac{M_1}{T}$. The relevant reaction density $\gamma$ used in these equations can be found in [11]. 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 $Y_B = -\frac{8}{23} Y_L(z_{\text{EW}})$, where the sphaleron decoupling temperature $T_{\text{EW}}$ 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 $\theta_{13}$ 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

\^{8}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 $m_{S_{inf}}$ 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 $m_{S_{inf}} = 10^9$ GeV in (a), and $10^{-8.6}$, $10^{-8.7}$, $10^{-8.8}$, $10^{-8.9}$, $10^{-9}$ for $m_{S_{inf}} = 10^7$ GeV in (b).

the analysis are shown in Fig. 2. Although $z_{EW}$ 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 $z_{EW}$. 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 $\lambda_5$ 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 $\lambda_5$ might be determined from a viewpoint of leptogenesis. Since $\lambda_5$ 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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