Thermal leptogenesis with triplet Higgs boson and mass varying neutrinos

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We study the thermal leptogenesis in the scenario where the standard model is extended to include one $SU(2)_L$ triplet Higgs boson, in addition to three generations of the right-handed neutrinos. In the model, we introduce the coupling between the quintessence and the right-handed neutrinos, the triplet Higgs boson, so that the light neutrino masses vary during the evolution of the Universe. Assuming that the lepton number asymmetry is generated by the decays of the lightest right-handed neutrino N_1, we find the thermal leptogenesis can be characterized by four model independent parameters. In the case where the contribution of the triplet Higgs to the lepton asymmetry is dominant, we give the relation between the minimal M_1 and the absolute mass scale $\bar{m}$ of the light neutrinos, by solving the Boltzmann equations numerically. We will also show that, with the varying neutrino masses, the reheating temperature can be lowered in comparison to the traditional thermal leptogenesis.

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The baryon number asymmetry of the Universe has been determined precisely [1]:

$$\eta_B \equiv \frac{n_B}{n_\gamma} = (6.3 \pm 0.3) \times 10^{-10}, \tag{1}$$

where $n_B = n_b - n_{\bar{b}}$ and n_γ are the baryon and photon number densities, respectively. As the confirmation of the neutrino oscillations by several experiments [2,3], leptogenesis [4] is now an attractive scenario to explain the observed baryon number asymmetry, where the lepton number asymmetry is first produced and then converted to the baryon number asymmetry via the $(B + L)$-violating sphaleron interactions [5].

The minimal thermal leptogenesis is quite economic and requires only three generations of the right-handed Majorana neutrinos beyond the standard model, which are also necessary to explain the small neutrino masses through the seesaw mechanism [6]. However, this scenario seems to require too high reheating temperature which may conflict with the upper bound of the reheating temperature set by the gravitino problem [7], and hierarchical neutrino spectrum with $m_i \lesssim 0.12\,\mathrm{eV}$ [8]. Furthermore, if the light neutrinos are degenerate, as indicated by the experimental signal of neutrinoless double beta decay [9], it is hard to imagine that the Dirac and the Majorana neutrino mass matrices, both naturally having hierarchical eigenvalues, conspire to produce the degenerate neutrino spectrum via the seesaw mechanism. The degenerate neutrino spectrum is naturally produced in the type II seesaw [10] model, where a triplet Higgs boson is introduced, whose vacuum expectation value (vev) gives the common neutrino mass scale and the type I seesaw produces the mass square differences required by the oscillation experiments.

A way to reconcile the minimal thermal leptogenesis and the gravitino problem is to consider that the neutrino masses are a cosmological variable [11,12]. In a recent work, we studied the scenario [13] where the interaction between the right-handed neutrinos and the quintessence [14–17], a dynamical scalar field as a candidate for the dark energy [18], which drives the accelerating of the Universe at the present time [19], makes the masses of the right-handed neutrinos vary during the evolution of the Universe. In this scenario, the reheating temperature is lowered and compatible with the limits set by the gravitino problem, and a degenerate light neutrino spectrum is also permitted. However, the two conditions, the low reheating temperature and degenerate neutrino spectrum, cannot be satisfied simultaneously yet.

In this paper, we study a scenario of the thermal leptogenesis where the light neutrinos are degenerate, to explain the neutrinoless double beta decay, and at the same time the reheating temperature is low. This scenario is realized in the type II seesaw model with variable neutrino masses. The type II seesaw model including one $SU(2)_L$ triplet Higgs boson [20], in addition to three generations of the right-handed neutrinos, is a general scenario derived from the left-right symmetric models [21].

In this scenario, the lepton number asymmetry can be generated by the decays of the right-handed neutrinos and/or the $SU(2)_L$ triplet Higgs [22]. Assuming a hierarchical right-handed neutrino spectrum, $M_1 \ll M_2, M_3$, and M_1 is also much lighter than the mass of the triplet Higgs $M_1 \ll M_\Delta$, the lepton number asymmetry comes mainly from the decays of the lightest right-handed neutrino N_1. We find the thermal leptogenesis can be characterized by four model independent parameters: the CP asymmetry ε_1 of N_1 decays, the heavy neutrino mass M_1, the absolute mass scale $\bar{m}$ of the light neutrinos, and the effective light neutrino mass $\tilde{m}_1$, which is a similar result as in the minimal thermal leptogenesis [23].

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The Lagrangian relevant to leptogenesis reads

$$-\mathcal{L} = \frac{1}{2}M_i\bar{N}^C_{Ri}N_{Ri} + M^2_\Delta \,\mathrm{Tr}\,\Delta^\dagger_L\Delta_L + g^\nu_{ij}\bar{\psi}_{Li}N_{Rj}\phi + g^\Delta_{ij}\bar{\psi}^C_{Li}i\tau_2\Delta_L\psi_{Lj} - \mu\phi^T i\tau_2\Delta_L\phi + \text{H.c.}, \quad (2)$$

where $\psi_L = (\nu, l)^T$, $\phi = (\phi^0, \phi^-)^T$ are the lepton and the Higgs doublets, and

$$\Delta_L = \begin{pmatrix} \frac{1}{\sqrt{2}}\delta^\dagger & \delta^{\dagger\dagger} \\ \delta^0 & -\frac{1}{\sqrt{2}}\delta^\dagger \end{pmatrix}$$

is the Higgs triplet.

After the electroweak phase transition, the left-handed neutrino mass matrix can be written as

$$m_\nu = -g^{\nu*}\frac{1}{M}g^{\nu\dagger}v^2 + 2g^\Delta v_L = m^{\mathrm{I}}_\nu + m^{\mathrm{II}}_\nu, \quad (3)$$

where m^{I}_ν is the type I seesaw mass term, m^{II}_ν is the type II seesaw mass term, and $v = 174$ GeV, $v_L \simeq \mu^* v^2/M^2_\Delta$ are the vevs of ϕ and Δ_L, respectively.

The CP asymmetry ε_1 is generated by the interference of the loop diagrams, shown in Fig. 1, with the tree diagram of N_1 decay. Besides the two same diagrams as in the minimal seesaw scenario, diagrams (a) and (b) in Fig. 1, there is an additional diagram (c) with the exchange of the Higgs triplet. We then have

$$\varepsilon_1 = \varepsilon^N_1 + \varepsilon^\Delta_1, \quad (4)$$

with ε^N_1 and ε^Δ_1 the CP asymmetry of N_1 decays due to the exchange of the right-handed neutrinos and the Higgs triplet, respectively. For $M_1 \ll M_2, M_3, M_\Delta$, we have [24,25]

$$\varepsilon^N_1 \simeq \frac{3}{16\pi}\frac{M_1}{v^2}\frac{\sum_{ij}\mathrm{Im}[g^{\nu\dagger}_{1i}g^{\nu\dagger}_{1j}(m^{\mathrm{I}*}_\nu)_{ij}]}{(g^{\nu\dagger}g^\nu)_{11}}, \quad (5)$$

$$\varepsilon^\Delta_1 \simeq \frac{3}{16\pi}\frac{M_1}{v^2}\frac{\sum_{i,j}\mathrm{Im}[g^{\nu\dagger}_{1i}g^{\nu\dagger}_{1j}(m^{\mathrm{II}*}_\nu)_{ij}]}{(g^{\nu\dagger}g^\nu)_{11}}. \quad (6)$$

It is interesting to see that the triplet contribution will dominate the CP asymmetry ε_1 when it dominates the neutrino mass matrix m_ν [20]. In this case, there is an upper bound on the asymmetry [20,23,25,26],

$$|\varepsilon_1| \simeq |\varepsilon^\Delta_1| \leq \frac{3M_1m_3}{16\pi v^2} \simeq \varepsilon^{\max}_1. \quad (7)$$

In order to calculate the final baryon number asymmetry, we have calculated the washout effect by solving the Boltzmann equations numerically. All the relevant processes should be taken into account, which include N_1 decays and inverse decays; the $\Delta L = 1$ scatterings mediated by exchanging doublet Higgs; and $\Delta L = 2$ scatterings mediated by exchanging the right-handed neutrinos and the triplet Higgs. By solving the Boltzmann equations, we can get the baryon-to-photon ratio η_B.

In comparison to the minimal seesaw scenario [23,27–29], there new $\Delta L = 2$ scattering processes with the exchanges of the triplet Higgs should be considered. We give the reduced cross sections $\hat{\sigma}_N$ for the process $l\bar{\phi} \leftrightarrow \bar{l}\phi$, and $\hat{\sigma}_{N,t}$ for the process $ll(\bar{l}\,\bar{l}) \leftrightarrow \phi\phi(\bar{\phi}\,\bar{\phi})$ as

$$\begin{aligned}\hat{\sigma}_{N(N,t)}(s) = \frac{1}{2\pi}\Big\{&\sum_i (g^{\nu\dagger}g^\nu)^2_{ii}f^{N(N,t)}_{ii}(x) \\ &+ \sum_{i,j}\mathrm{Re}[(g^{\nu\dagger}g^\nu)^2_{ij}]f^{N(N,t)}_{ij}(x) \\ &+ \sum_{i,j,k}\mathrm{Re}\Big[g^{\Delta\dagger}_{ij}g^{\nu\dagger}_{ki}g^{\nu\dagger}_{kj}\frac{\mu}{M_1}\Big]f^{\Delta N(\Delta N,t)}_{ijk}(x) \\ &+ \sum_i (g^{\Delta\dagger}g^\Delta)_{ii}\frac{|\mu|^2}{M^2_1}f^{\Delta(\Delta,t)}_{ii}(x)\Big\}, \end{aligned} \quad (8)$$

with

$$f^N_{ii}(x) = 1 + \frac{a_i}{D_i(x)} + \frac{xa_i}{2D^2_i(x)} - \frac{a_i}{x}\Big[1 + \frac{x+a_i}{D_i(x)}\Big]\log\Big(1 + \frac{x}{a_i}\Big), \quad (9)$$

$$\begin{aligned}f^N_{ij}(x) = \frac{1}{2}\sqrt{a_ia_j}\Big[&\frac{1}{D_i(x)} + \frac{1}{D_j(x)} + \frac{x}{D_i(x)D_j(x)} + \Big(1 + \frac{a_i}{x}\Big) \\ &\times\Big(\frac{2}{a_j - a_i} - \frac{1}{D_j(x)}\Big)\log\Big(1 + \frac{x}{a_i}\Big) + \Big(1 + \frac{a_j}{x}\Big) \\ &\times\Big(\frac{2}{a_i - a_j} - \frac{1}{D_i(x)}\Big)\log\Big(1 + \frac{x}{a_j}\Big)\Big], \end{aligned} \quad (10)$$

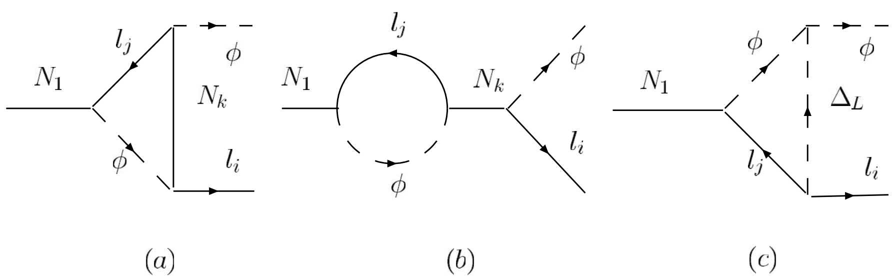

FIG. 1. The loop diagrams of N_1 decays.

$$f_{ii}^{\Delta}(x) = 12\left[\frac{1}{x}\log\left(1+\frac{x}{y}\right) - \frac{1}{x+y}\right], \quad (11)$$

$$f_{ijk}^{\Delta N}(x) = 8\frac{\sqrt{a_k}(x-a_k)}{(x-a_k)^2 + a_k c_k}\left[1 - \frac{y}{x}\log\left(1+\frac{x}{y}\right)\right] + 4\frac{\sqrt{a_k}}{x+a_k+y}\left[\frac{y}{x}\log\left(1+\frac{x}{y}\right) - \left(1+\frac{a_k}{x}\right) \times \log\left(1+\frac{x}{a_k}\right)\right], \quad (12)$$

$$f_{ii}^{N,t}(x) = \frac{x}{x+a_i} + \frac{a_i}{x+2a_i}\log\left(1+\frac{x}{a_i}\right), \quad (13)$$

$$f_{ij}^{N,t}(x) = \frac{1}{2}\frac{\sqrt{a_i a_j}}{(a_i-a_j)(x+a_i+a_j)}\left[(2x+3a_i+a_j) \times \log\left(1+\frac{x}{a_j}\right) - (2x+3a_j+a_i)\log\left(1+\frac{x}{a_i}\right)\right], \quad (14)$$

$$f_{ii}^{\Delta,t}(x) = 6\frac{x(x-y)^2}{[(x-y)^2 + yc_\Delta]^2}, \quad (15)$$

$$f_{ijk}^{\Delta N,t}(x) = 6\sqrt{a_k}\frac{x-y}{(x-y)^2 + yc_\Delta}\log\left(1+\frac{x}{a_k}\right). \quad (16)$$

Here $x = s/M_1^2$, $a_i \equiv M_i^2/M_1^2$, and $1/D_i(x) \equiv (x-a_i)/[(x-a_i)^2 + a_i c_i]$ is the off-shell part of the N_i propagator with $c_i \equiv a_i(g^{\nu\dagger}g^{\nu})_{ii}^2/(8\pi)^2$, and $c_\Delta \equiv \Gamma_\Delta^2/M_1^2$. Similar to Ref. [23], the reaction density $\gamma_N + \gamma_{N,t}$ can be separated into two parts: the resonance contribution which is highly peaked around $x = 1$ and the contribution comes from the region $x \ll 1$ which corresponds to $z \gg 1$,

$$\gamma_N^{\rm res} = \frac{M_1^5}{64\pi^3 v^2}\tilde{m}_1\frac{1}{z}K_1(z), \quad (17)$$

$$\gamma_N(z \gg 1) \simeq \gamma_{N,t}(z \gg 1) \simeq \frac{3M_1^6}{8\pi^5 v^4}\bar{m}^2\frac{1}{z^6}, \quad (18)$$

where $\tilde{m}_1 \equiv [(g^{\nu\dagger}g^{\nu})_{11}v^2]/M_1$ and $\bar{m}^2 \equiv m_1^2 + m_2^2 + m_3^2 = {\rm tr}(m_\nu^\dagger m_\nu) = {\rm tr}[(m_\nu^{\rm I} + m_\nu^{\rm II})^\dagger(m_\nu^{\rm I} + m_\nu^{\rm II})]$. Analysis for $z < 1$ is also similar to Ref. [23]. The reaction densities γ_i [27] are defined as

$$\gamma_i(z) = \frac{M_1^4}{64\pi^4}\frac{1}{z}\int_{(m_a^2+m_b^2)/M_1^2}^{\infty} dx\,\hat{\sigma}_i(x)\sqrt{x}K_1(z\sqrt{x}), \quad (19)$$

where m_a and m_b are the masses of the two particles in the initial state. Since $\gamma_N + \gamma_{N,t}$ is not changed compared to the results of Ref. [23], the thermal leptogenesis can still be characterized by four parameters: ε_1, M_1, $\bar{m}$, $\tilde{m}_1$, even in the presence of the $SU(2)_L$ triplet Higgs.

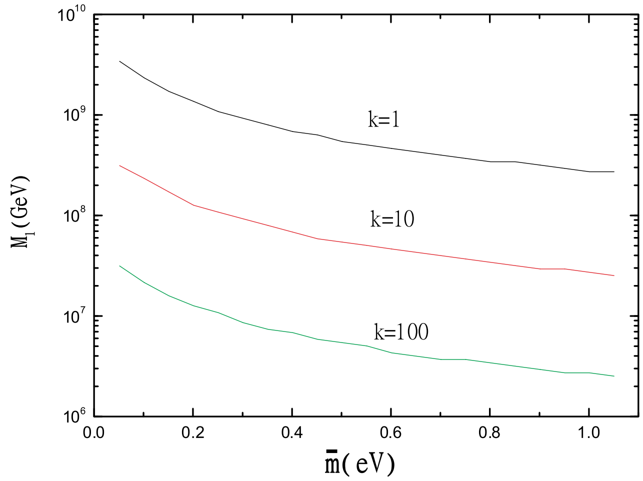

FIG. 2 (color online). The minimal M_1 as a function of $\bar{m}$ for $\eta_B = 5.4 \times 10^{-10}$. M_1 is the value of the right-handed neutrino mass at the leptogenesis epoch, and $\bar{m}$ is the absolute mass scale of the light neutrino at the present epoch. The curve with $k = 1$ stands for the case without the variation of the light neutrino masses.

The washout effect mainly depends on the effective neutrino mass $\tilde{m}_1$. Since $m_1 \leq \tilde{m}_1 \lesssim m_3$ [23,26] should not be satisfied when the triplet contribution is dominant, we can always adjust $\tilde{m}_1$ to avoid the large washout effect. Therefore the neutrino mass spectrum can be degenerate, even above the cosmological bound [20,30,31]. The numerical result is shown in Fig. 2. For $\bar{m} \simeq 0.051$ eV, the low limit of the neutrino mass scale from the oscillation experiments constraint [2,3,32], we get $M_1 \simeq 3.4 \times 10^9$ GeV. We can get $M_1 \simeq 2.7 \times 10^8$ GeV for $\bar{m} \simeq 1.0$ eV, which is the upper bound from the cosmological constraint $\sum_i m_i < 1.7$ eV [1].

We notice that these values of M_1 are only marginally consistent with the bound set by the gravitino problem [7]. In order to solve the problem, we consider the light neutrino masses are varying during the evolution of the Universe [11]. We introduce a parameter k which indicates the ratio of the light neutrino masses at the leptogenesis epoch and the present epoch. When solving the Boltzmann equations, the M_1, $\bar{m}$, and $\tilde{m}_1$ should all take the values at the leptogenesis epoch. If $\bar{m}$ takes the value at the present epoch, we should replace $\bar{m}$ by $k\bar{m}$ in the Boltzmann equations. By solving the Boltzmann equations numerically, we can see the reheating temperature is lowered with the increasing k. For $k = 10$, we can get $M_1 \simeq 3.1 \times 10^8$ GeV for $\bar{m} \simeq 0.051$ eV, and $M_1 \simeq 2.7 \times 10^7$ GeV for $\bar{m} \simeq 1.0$ eV. M_1 is lowered to $M_1 \simeq 3.1 \times 10^7$ GeV with $\bar{m} \simeq 0.051$ eV and $M_1 \simeq 2.5 \times 10^6$ GeV with $\bar{m} \simeq 1.0$ eV for $k = 100$. In this paper, the values of M_1 are all at the leptogenesis epoch, and $\bar{m}$ takes the value at the present epoch.

In this paper, we get the varying neutrino masses by introducing the interaction between the quintessence and the right-handed neutrinos, the triplet Higgs in Eq. (2). Assume these interactions take simple forms as

$$M_i \to M_i(Q) = \bar{M}_i e^{\beta(Q/M_{pl})}, \quad (20)$$

$$M_\Delta \to M_\Delta(Q) = \bar{M}_\Delta e^{(\beta/2)(Q/M_{pl})}, \quad (21)$$

where β is a $\mathcal{O}(1)$ coefficient. Then we get

$$m_\nu \propto e^{-\beta(Q/M_{pl})}, \quad (22)$$

and

$$k = e^{\beta[(Q_0 - Q_D)/M_{pl}]}. \quad (23)$$

Q_0, Q_D are the values of the quintessence field at the present epoch and the leptogenesis epoch, respectively.

For a numerical calculation of k, we consider a model of the quintessence with the double exponential potential [33]

$$V = V_0(e^{\lambda Q} + e^{\alpha Q}). \quad (24)$$

The equations of motion of the quintessence, for a flat universe, are given by

$$H^2 = \frac{8\pi G}{3}\left[\rho_B + \frac{\dot{Q}^2}{2} + V(Q)\right], \quad (25)$$

$$\ddot{Q} + 3H\dot{Q} + \frac{dV(Q)}{dQ} = 0, \quad (26)$$

where ρ_B represent the energy densities of the background fluid. This model has the tracking property for suitable parameters. Here, we choose $\lambda = 100M_{pl}^{-1}$, $\alpha = -100M_{pl}^{-1}$, the initial value of quintessence field $Q_i = 1.374M_{pl}$, and for the equation of state, which is defined as

$$w_Q = \frac{\dot{Q}^2/2 - V(Q)}{\dot{Q}^2/2 + V(Q)}, \quad (27)$$

the initial value is $w_{Q_i} = -1$. We find that $\Omega_{Q_0} \simeq 0.72$ and the present equation of state of the quintessence is $w_{Q_0} \simeq -1$ which are consistent with the observational data. In Fig. 3, we show the evolution of w_Q and Q with the temperature T.

Taking into account the interaction with the right-handed neutrinos and the triplet Higgs, we get the equation of motion of the quintessence as

$$\ddot{Q} + 3H\dot{Q} + \frac{dV(Q)}{dQ} + \frac{dV_I(Q)}{dQ} = 0. \quad (28)$$

The source term in the equation above is given by [34]

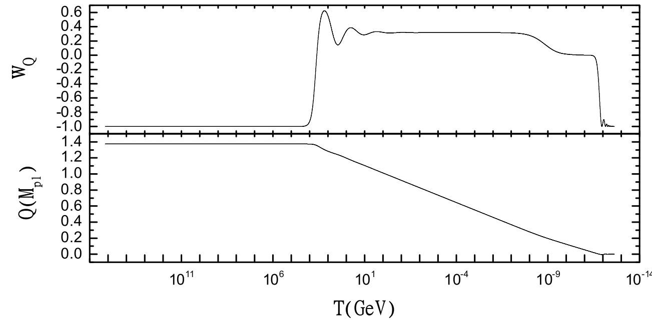

FIG. 3. The evolution of w_Q and Q as a function of the temperature T for the double exponential quintessence model.

$$\begin{aligned}\frac{dV_I(Q)}{dQ} &= \sum_i n_i \frac{dM_i}{dQ}\left\langle\frac{M_i}{E_i}\right\rangle + n_\Delta \frac{dM_\Delta}{dQ}\left\langle\frac{M_\Delta}{E_\Delta}\right\rangle \\ &= \frac{\beta}{M_{pl}}\frac{1}{\pi^2}T\sum_i M_i^3 K_1(M_i/T) + \frac{3}{4}\frac{\beta}{M_{pl}} \\ &\quad \times \frac{1}{\pi^2}TM_\Delta^3 K_1(M_\Delta/T),\end{aligned} \quad (29)$$

where n_i and E_i are the number density and the energy of the right-handed neutrinos, respectively, n_Δ and E_Δ belong to the triplet Higgs, $\langle\ \rangle$ indicates thermal average, and K_1 is the modified Bessel function. For simplicity, we have taken the Maxwell-Boltzmann distribution of the right-handed neutrinos and the triplet Higgs in the last step of the equation.

We then solve Eq. (28) numerically, assuming $\bar{M}_3 = 10\bar{M}_2 = 10^4\bar{M}_1$ and $\bar{M}_\Delta = 10^3\bar{M}_1$. The numerical results are shown in Figs. 4–7, where we have taken the same definition of w_Q as in Eq. (27). In Figs. 4 and 5, we take $\beta = -1.68$, $\bar{M}_1 = 3.1 \times 10^9$ GeV, and $\beta = -3.35$, $\bar{M}_1 = 3.1 \times 10^9$ GeV, respectively, which give rise to $Q_0 \simeq 0$ and $Q_D \simeq 1.374M_{pl}$. We then have $M_1 \simeq 3.1 \times 10^8$ GeV for $k = 10$, and $M_1 \simeq 3.1 \times 10^7$ GeV for $k = 100$, corresponding to the case we considered in the hierarchical neutrino spectrum with $\bar{m} \simeq 0.051$ eV. In Figs. 6 and 7, we choose the parameters $\beta = -1.68$, $\bar{M}_1 = 2.7 \times 10^8$ GeV and $\beta = -3.35$, $\bar{M}_1 = 2.5 \times 10^8$ GeV, respectively. We find the values of Q_0 and Q_D are almost the same as the above case. We then have $M_1 \simeq 2.7 \times 10^7$ GeV for $k = 10$ and $M_1 \simeq 2.5 \times 10^6$ GeV for $k = 100$, corresponding to the case that satisfies the cosmic limit $\bar{m} \simeq 1.0$ eV for the degenerate neutrinos.

Comparing Fig. 3 with Figs. 4–7, one can see that the interaction of the quintessence with the right-handed neutrinos and the triplet Higgs does change the equation of state of the quintessence field; however, it does not change the tracking properties of this model. Furthermore, the value of the quintessence field Q changes very little in this model until $T \sim 10^4$ GeV which

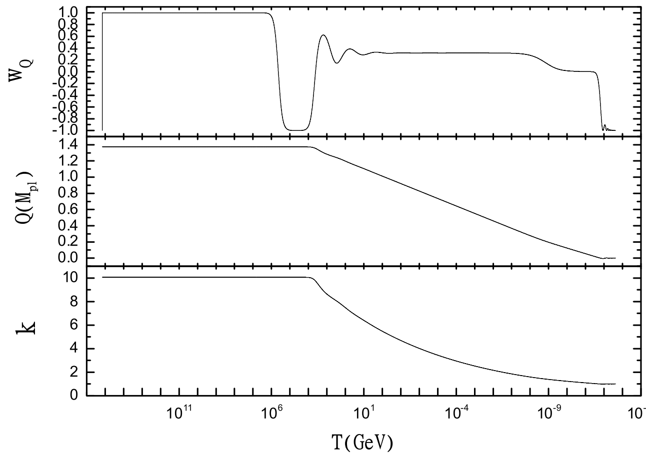

FIG. 4. The evolution of w_Q, Q, and k as a function of the temperature T for the double exponential quintessence model including the coupling with the right-handed neutrinos and the triplet Higgs. We take $\beta = -1.68$ and $\bar{M}_1 = 3.1 \times 10^9$ GeV.

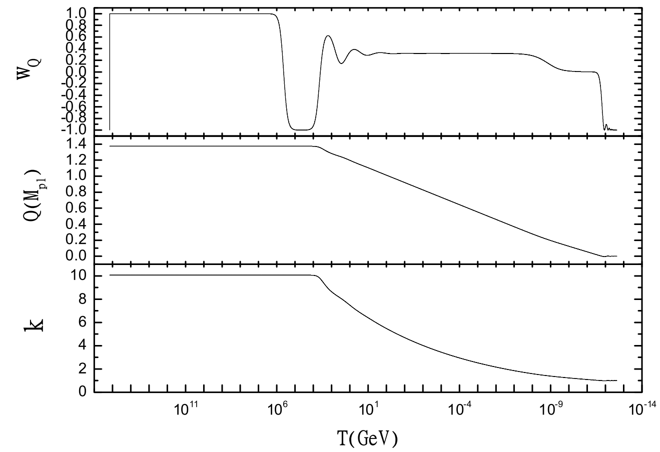

FIG. 6. The evolution of w_Q, Q, and k as a function of the temperature T for the double exponential quintessence model including the coupling with the right-handed neutrinos and the triplet Higgs. We take $\beta = -1.68$ and $\bar{M}_1 = 2.7 \times 10^8$ GeV.

satisfies our assumption for a constant k during the period of leptogenesis.

In summary, we study the thermal leptogenesis in the scenario where the standard model is extended to include one $SU(2)_L$ triplet Higgs boson, in addition to three generations of the right-handed neutrinos. In the model, we introduce the coupling between the quintessence and the right-handed neutrinos, the triplet Higgs boson, so that the light neutrino masses vary during the evolution of the Universe. Assuming that the lepton number asymmetry is generated by the decays of the lightest right-handed neutrino N_1, we find the thermal leptogenesis can be characterized by four model independent parameters: ε_1, M_1, $\bar{m}$, $\tilde{m}$. With the dominant contribution of the triplet Higgs to the lepton asymmetry and the varying neutrino masses, we find the degenerate spectrum of the light neutrino masses and the lower reheating temperature can be gotten simultaneously, by solving the Boltzmann equations numerically.

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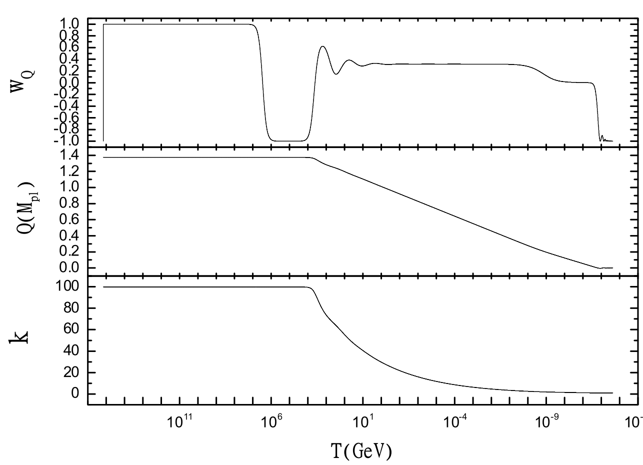

FIG. 5. The evolution of w_Q, Q, and k as a function of the temperature T for the double exponential quintessence model including the coupling with the right-handed neutrinos and the triplet Higgs. We take $\beta = -3.35$ and $\bar{M}_1 = 3.1 \times 10^9$ GeV.

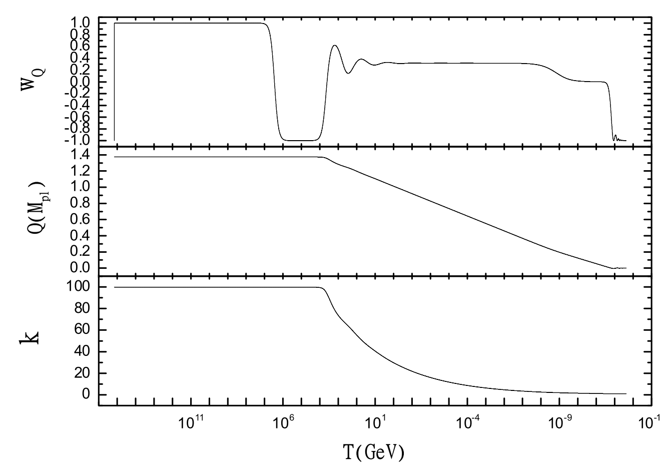

FIG. 7. The evolution of w_Q, Q, and k as a function of the temperature T for the double exponential quintessence model including the coupling with the right-handed neutrinos and the triplet Higgs. We take $\beta = -3.35$ and $\bar{M}_1 = 2.5 \times 10^8$ GeV.

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