Large lepton asymmetry from Q-balls

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We propose a scenario which can explain large lepton asymmetry and small baryon asymmetry simultaneously. Large lepton asymmetry is generated through the Affleck-Dine (AD) mechanism and almost all the produced lepton numbers are absorbed into Q-balls (L-balls). If the lifetime of the L-balls is longer than the onset of electroweak phase transition but shorter than the epoch of big bang nucleosynthesis (BBN), the large lepton asymmetry in the L-balls is protected from sphaleron effects. On the other hand, small (negative) lepton numbers are evaporated from the L-balls due to thermal effects, which are converted into the observed small baryon asymmetry by virtue of sphaleron effects. Large and positive lepton asymmetry of electron type is often requested from BBN. In our scenario by choosing an appropriate flat direction in the minimal supersymmetric standard model, we can produce positive lepton asymmetry of the electron type but totally negative lepton asymmetry.

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I. INTRODUCTION

The success of big bang nucleosynthesis (BBN) is one of the most powerful pieces of evidence of standard big bang cosmology [1]. Roughly speaking, the predicted primordial abundances of light elements (D, ^{3}He, ^{4}He, and ^{7}Li) coincide with those inferred from observations for the baryon-to-photon ratio $\eta \sim 5\times 10^{-10}$. However, as observations are improved and their errors are reduced, a small discrepancy may appear [2]. Furthermore, η is also determined by observations of small scale anisotropies of the cosmic microwave background radiation (CMB) [3–6], which may also cause the small discrepancy. Of course, the discordance may be completely removed as observations are further improved. However, it is also probable that such small discrepancies are genuine and suggest additional physics in BBN.

These discrepancies are often eliminated if predicted primordial abundance of ^{4}He is decreased. Such a decrease is realized if there exists large and positive lepton asymmetry of electron type [7]. This is mainly because the excess of electron neutrinos shifts the chemical equilibrium between protons and neutrons toward protons, which reduces the predicted primordial abundance of ^{4}He. Note that this effect is much more effective than the corresponding speed-up effect, that is, an increase of the Hubble expansion due to the presence of the chemical potential, which makes the predicted primordial abundance of ^{4}He increase. However, large and positive lepton asymmetry of the electron type is incompatible with small baryon asymmetry if we take account of the sphaleron effects, which convert lepton asymmetry to baryon asymmetry of the same order with the opposite sign [8]. This problem is evaded if one of the following three conditions is satisfied, that is, (a) lepton asymmetry is generated after electroweak phase transition but before BBN, (b) sphaleron processes do not work, (c) positive lepton asymmetry of the electron type is generated but no total lepton asymmetry is generated.

The first condition was discussed in the context of neutrino oscillations [9]. In this case, large lepton asymmetry is generated through oscillations between active neutrinos and sterile neutrinos. In order to explore the second condition, one should note that the presence of large chemical potential prevents restoration of electroweak symmetry [10]. Based on this fact, large lepton asymmetry compatible with small baryon asymmetry was discussed [11]. The third condition is discussed by March-Russell *et al.* [12]. The Affleck-Dine mechanism produces positive lepton asymmetry of electron type but no total lepton asymmetry, that is, $L_e = -L_\mu > 0$ and $L_\tau = 0$ for some flat direction, which generates small baryon asymmetry due to thermal mass effects of sphaleron processes.

In this paper we consider another possibility, which is something like the combination of (a) and (b). The Affleck-Dine (AD) mechanism produces positive lepton asymmetry of electron type but totally negative lepton asymmetry by choosing an appropriate flat direction in the minimal supersymmetric standard model (MSSM) [13]. As an example, we identify the "$e_1^c L_2 L_3$" flat direction to be the AD field and consider the Affleck-Dine leptogenesis. Here subscripts represent the generations. Then, $L_e = -L_\mu = -L_\tau = -L_{\rm total} > 0$ is realized. The shift of the chemical equilibrium between neutrons and protons due to the positive chemical potential of electron neutrinos affects the results of BBN dominantly, while the speed-up effect caused by all the species of neutrinos is relatively negligible. After the Affleck-Dine leptogenesis, the AD field experiences spatial instabilities and deforms into nontopological solitons, Q-balls (L-balls) [14–16]. Then, almost all the produced lepton numbers are absorbed into the L-balls [16,17]. If the lifetime of such L-balls is longer than the onset of electroweak phase transition but shorter than the epoch of BBN, the large lepton asymmetry is protected from sphaleron effects and later released into the universe by the decay of the L-balls. On the other hand, small (negative) lepton numbers are evaporated from the L-balls due to thermal effects before the electroweak phase transition, which are transformed into small baryon asymmetry through the sphaleron effect.

In our scenario we consider the Affleck-Dine mechanism and the subsequent Q-ball formation in the gauge-mediated supersymmetry (SUSY) breaking model. This is mainly because in the gravity-mediated SUSY breaking model, the energy per unit charge of Q-balls is large enough to produce the lightest supersymmetric particles (LSPs) so that they will overclose the universe. Therefore, we do not consider the gravity-mediated SUSY breaking model. Since we assume that the AD field starts oscillating from the gravitational scale to produce large lepton asymmetry, the produced Q-balls are "new" [18] or "delayed"-type [17], depending on the sign of the coefficient of the one-loop correction to the effective potential. However, since the decay processes of the new type Q-balls are not completed before BBN, our scenario does not apply for them. Thus, we concentrate on delayed-type Q-balls in gauge-mediated SUSY breaking models.

The rest of the paper is as follows. In Sec. II we briefly review the Affleck-Dine mechanism and properties of Q-balls. In Sec. III we discuss our mechanism to generate large lepton asymmetry compatible with small baryon asymmetry. Section IV is devoted to discussion and conclusions.

II. AFFLECK-DINE MECHANISM AND Q-BALL FORMATION

In this section we briefly review the Affleck-Dine mechanism and properties of Q-balls. In MSSM, there exist flat directions, along which there are no classical potentials in the supersymmetric limit. Since flat directions consist of squarks and/or sleptons, they carry baryon and/or lepton numbers, and can be identified as the Affleck-Dine (AD) field. In the following discussion, we adopt the "$e^c LL$" direction as the AD field. In this case the AD field carries only the lepton number.

These flat directions are lifted by supersymmetry (SUSY) breaking effects. In the gauge-mediated SUSY breaking model, the potential of a flat direction is parabolic at the origin, and almost flat beyond the messenger scale [14,17,19],

$$V_{gauge} \sim \begin{cases} m_\phi^2 |\Phi|^2 & (|\Phi| \ll M_S), \\ M_F^4 \left(\log \dfrac{|\Phi|^2}{M_S^2} \right)^2 & (|\Phi| \gg M_S), \end{cases} \tag{1}$$

where m_ϕ is a soft breaking mass $\sim O(1 \text{ TeV})$, M_F is the SUSY breaking scale, and M_S is the messenger mass scale.

Since gravity always exists, flat directions are also lifted by gravity-mediated SUSY breaking effects [20],

$$V_{grav} \simeq m_{3/2}^2 \left[1 + K \log \left(\frac{|\Phi|^2}{M^2} \right) \right] |\Phi|^2, \tag{2}$$

where K is the numerical coefficient of the one-loop corrections and M is the gravitational scale ($\simeq 2.4 \times 10^{18}$ GeV). This term can be dominant only at high energy scales because of small gravitino mass $\lesssim O(1 \text{ GeV})$.

There is also the thermal effect on the potential, which appears at two-loop order as pointed out in Ref. [21]. This effect comes from the fact that the running of the gauge coupling $g(T)$ is modified by integrating out heavy particles which directly couple with the AD field. This contribution to the effective potential is given by

$$V_T^{(2)} \sim c \quad \alpha_{\rm w}^2 T^4 \log \frac{|\Phi|^2}{T^2}, \tag{3}$$

where $|c| \sim 1$, and $\alpha_{\rm w} \equiv g_{\rm w}^2/4\pi$ represents the gauge coupling constant of the weak interaction since we consider $e^c LL$ direction. Though the sign of c depends on flat directions, it is irrelevant to our discussion since we assume that the zero-temperature potential dominates over the thermal effects. Note that $\alpha_{\rm w}$ should be replaced with α_s for those flat directions which contain squarks.

The lepton number is usually created just after the AD field starts coherent rotation in the potential, and its number density n_L is estimated as

$$n_L(t_{osc}) \simeq \varepsilon \omega \phi_{osc}^2, \tag{4}$$

where $\varepsilon (\lesssim 1)$ is the ellipticity parameter, which represents the strongness of the A term, and ω and ϕ_{osc} are the angular velocity and amplitude of the AD field at the beginning of the oscillation (rotation) in its effective potential.

Actually, however, the AD field experiences spatial instabilities during its coherent oscillation, and deforms into nontopological solitons called Q-balls [14–16]. When the zero-temperature potential V_{gauge} dominates at the onset of coherent oscillation of the AD field, the gauge-mediation type Q-balls are formed. Their mass M_Q and size R_Q are given by [22]

$$M_Q \sim M_F Q^{3/4}, \quad R_Q \sim M_F^{-1} Q^{1/4}. \tag{5}$$

From the numerical simulations [16,17], the produced Q-balls absorb almost all the charges carried by the AD field and the typical charge is estimated as [17]

$$Q \simeq \beta \left(\frac{\phi_{osc}}{M_F} \right)^4 \tag{6}$$

with $\beta \approx 6 \times 10^{-4}$.

There are also other cases where V_{grav} dominates the potential at the onset of coherent oscillation of the AD field. If the coefficient of the one-loop correction K is negative, the gravity-mediation type Q-balls ("new" type) are produced [18]. On the other hand, if K is positive, Q-balls do not form until the AD field leaves the V_{grav} dominant region. Later it enters the V_{gauge} dominant region and experiences instabilities so that the gauge-mediation type Q-balls are produced (delayed-type Q-balls) [17].

In our scenario described in the next section, the AD field starts to oscillate from the gravitational scale, i.e., $\phi_{osc} = M$, which leads to the formation of new or "delayed"-type Q-balls. However, our scenario does not work for new type Q-balls because the produced Q-balls are large and do not decay before BBN. Hence, we concentrate on the delayed-type Q-balls below. Since the sign of K is in general indefinite and dependent on the model of the messenger sector in gauge-mediated SUSY breaking models, we assume that K is positive and delayed-type Q-balls are formed.

When the AD field starts to oscillate in the V_{grav} dominant region, where $H_{osc} \sim \omega \sim m_{3/2}$, the lepton number is produced as $n_L \simeq \varepsilon m_{3/2} \phi_{osc}^2$. Since the delayed-type Q-balls are formed only after the AD field enters the V_{gauge} dominant region for positive K, the charge of Q-ball is given by

$$Q \sim \beta \left(\frac{\phi_{eq}}{M_F} \right)^4 \sim \beta \left(\frac{M_F}{m_{3/2}} \right)^4 \tag{7}$$

with $\phi_{eq} \sim M_F^2/m_{3/2}$. Here the subscript "eq" denotes a value when the gauge- and the gravity-mediation potentials become equal. Thus the delayed-type Q-balls are formed at $H_{eq} \sim M_F^2/M$.

As we mentioned above, Q-balls absorb almost all the charges carried by the AD field. If we adopt the $e^c LL$ direction, all the lepton charges are confined in the Q-balls, namely, L-balls. Consequently, we must take out lepton charge from the L-balls through the evaporation, diffusion, and their decay. Part of the evaporated lepton charge is transformed into baryon charge by the sphaleron process, which accounts for the present baryon asymmetry.

In the case of L-balls, they decay into leptons such as neutrinos via gaugino exchanges. The decay rate of Q-balls is bounded as [23]

$$\left| \frac{dQ}{dt} \right| \lesssim \frac{\omega^3 A}{192\pi^2}, \tag{8}$$

where A is a surface area of the Q-ball. For L-balls, the decay rate is estimated as a value of the order of the upper limit.

According to Refs. [17,24,25], we evaluate the evaporation rate of L-balls, which is given by [24]

$$\zeta_{\rm evap} \equiv \frac{dQ}{dt} = -\kappa(\mu_Q - \mu_{\rm plasma}) T^2 4\pi R_Q^2,$$

$$\simeq -4\pi\kappa\mu_Q T^2 R_Q^2 \quad \text{for} \quad \mu_Q \gg \mu_{\rm plasma}, \tag{9}$$

where μ_Q and $\mu_{\rm plasma}$ are chemical potentials of the Q-ball and plasma, and the coefficient $\kappa \lesssim 1$ includes statistical and other numerical factors. The chemical potential of the Q-ball is given as $\mu_Q \simeq \omega$ since the energy of the ϕ particle inside the Q-ball is ω. At $T \gtrsim m_\phi$, large numbers of the scalar particles building up Q-balls are in the plasma, which implies $\kappa \sim 1$. On the other hand, at $T \lesssim m_\phi$, the evaporation from Q-balls is suppressed by the Boltzmann factor. In the case of L-balls, the main process of the evaporation is $\phi\phi \to ll$ through W-ino or B-ino exchange, which yields $\kappa \sim \alpha_{\rm w}^2 T^2/m_\phi^2$ at $T \lesssim m_\phi$.

However, if the charge transport is not effective enough, the evaporated lepton charges in the "atmosphere" of the L-ball will establish chemical equilibrium there. In this case, the dissipation of the charge is determined by the diffusion. The diffusion rate is estimated as [25],

$$\zeta_{\rm diff} \equiv \frac{dQ}{dt} = -4\pi D R_Q \mu_Q T^2$$

$$\simeq -4\pi D T^2, \tag{10}$$

where the diffusion constant D of relativistic sleptons and leptons in a hot plasma is given by $D \simeq a/T$ with $a \sim 20$ [26,27]. In short, the time scale of the charge transportation is determined by the evaporation rate when $|\zeta_{\rm evap}| < |\zeta_{\rm diff}|$, and by the diffusion rate when $|\zeta_{\rm evap}| > |\zeta_{\rm diff}|$.

The amount of the evaporated charges can be estimated by integrating Eqs. (9) and (10) in the course of the evolution of the universe. When the AD field starts to oscillate at the gravitational scale, its oscillation energy is comparable to the total energy of the universe. Therefore, the energy of the universe will be dominated by the AD condensate or Q-balls soon after the reheating and the universe continues to be matter dominated. The thermal history of the universe is rather involved because radiation comes from both decays of an inflaton and Q-balls. However, in fact, we have only to consider two cases where the cosmic temperature decreases monotonically.

III. LARGE LEPTON ASYMMETRY FROM L-BALL

In this section we give a detailed explanation of our scenario. Our goal is to generate small baryon asymmetry and positive large lepton asymmetry of the electron type simultaneously. In general, however, this is difficult to accomplish because the chemical equilibrium induced by the sphaleron transition forces the baryon and the lepton asymmetries to be of the same order with opposite sign [8]. Hence we must get over two problems: (i) how to protect large lepton asymmetry from being converted to baryon asymmetry by the sphaleron process, and (ii) how to reconcile the opposite sign of baryon and lepton asymmetries.

We show that these two obstacles can be evaded by considering the Affleck-Dine leptogenesis and the subsequent L-ball formation using the $e^c LL$ direction. First of all, we give the outline of our scenario and the solution to the problem (i). Large lepton asymmetry can be generated if the A terms, which make the AD field rotate in the effective potential, originate from some Kähler potential with vanishing superpotential. Then the AD field starts to oscillate with large initial amplitude $\phi_{osc} \simeq M$ and ellipticity $\varepsilon \simeq 1$. As spatial instabilities grow, delayed-type L-balls are formed and absorb almost all charges carried by the AD field. It is essential to our scenario that the lepton asymmetry confined in the L-balls is kept from the sphaleron process. However, a small part of lepton charges confined in the L-balls are evaporated due to thermal effects. Thus, lepton charges evaporated until the electroweak phase transition ($T \gtrsim T_C \sim 300$ GeV) ΔQ_{ew} are partly converted to baryon asymmetry through the sphaleron process, which explains the present small baryon asymmetry. On the other hand, large lepton asymmetry comes out through the decay of the remnant L-balls after the electroweak phase transition, which must be completed before BBN. Thus the small ratio $\Delta Q_{ew}/Q$ is the source of hierarchy between the baryon and the lepton asymmetries.

Next we give a solution to the problem (ii), that is, the sign of the lepton asymmetry. What we want to generate is positive baryon asymmetry and positive lepton asymmetry of electron type. However, the sphaleron process converts positive lepton asymmetry into negative baryon asymmetry. To surmount this problem, we adopt the $e_1^c L_2 L_3$ direction as the AD field, which leads $L_e = -L_\mu = -L_\tau = -L_{\rm total} > 0$. Thus the positive lepton asymmetry of the electron type is generated, whilst total lepton asymmetry is necessarily negative in order to have positive baryon asymmetry through the sphaleron transition. At the epoch of BBN, charged leptons except electrons have already disappeared through decay and annihilation processes. Also, because of the charge neutrality of the universe, lepton asymmetry stored in electrons are comparable to baryon asymmetry, which is rather small. Thus, there can exist large lepton asymmetry only in the neutrino sector. For later use, we define the degeneracy parameter ξ_l as the ratio of the chemical potential to the neutrino temperature. The presence of chemical potentials speed up the universe, which leads to an increase in the n/p ratio. However, its effect is negligible in comparison with the effect of the shift of chemical equilibrium between protons and neutrons due to the chemical potential of the electron neutrino in the case of $|\xi_{\nu_e}| = |\xi_{\nu_\mu}| = |\xi_{\nu_\tau}|$.

Now we give a quantitative estimate for our scenario. We assume that the zero-temperature potential dominates, i.e., $V_{gauge} \gg V_T^{(2)}$, at the formation of the delayed-type L-balls with $H \sim H_{eq}$:

$$\alpha_{\rm w}^2 T_{eq}^4 < M_F^4, \tag{11}$$

where T_{eq} is the temperature of the universe just before the delayed type L-balls are formed. As shown below, this constraint is automatically satisfied for the cases we consider.

The delayed-type L-balls must decay before BBN,

$$\tau_Q = \left(\frac{1}{Q} \left| \frac{dQ}{dt} \right| \right)^{-1} \lesssim 1 \ \ \text{sec}, \tag{12}$$

which leads to the constraint

$$\frac{m_{3/2}}{10 \ \ \text{MeV}} \gtrsim \left(\frac{M_F}{10 \ \ \text{TeV}} \right)^{4/5}. \tag{13}$$

Here Eq. (8) is used. In order to estimate the baryon and the lepton to entropy ratio, it is necessary to evaluate the entropy production by the decay of the L-balls. The decay temperature of the L-balls, T_d, is given by

$$T_d = \left(\frac{90}{\pi^2 g_*} \right)^{1/4} \sqrt{M \frac{M_F Q^{-5/4}}{48\pi}}$$

$$\simeq 1.3 \ \ \text{MeV} \left(\frac{M_F}{10 \ \ \text{TeV}} \right)^{-2} \left(\frac{m_{3/2}}{10 \ \ \text{MeV}} \right)^{5/2}, \tag{14}$$

where $g_* = 10.75$ counts the total number of effectively massless degrees of freedom.

Now we turn to an account of the total evaporated charge, ΔQ, and the evaporated charge at temperatures above the electroweak phase transition, ΔQ_{ew}. In fact we have only to consider the following two cases. In the other cases, the temperature during the presence of L-balls does not exceed T_C so that the evaporated lepton numbers are not converted into baryon numbers.

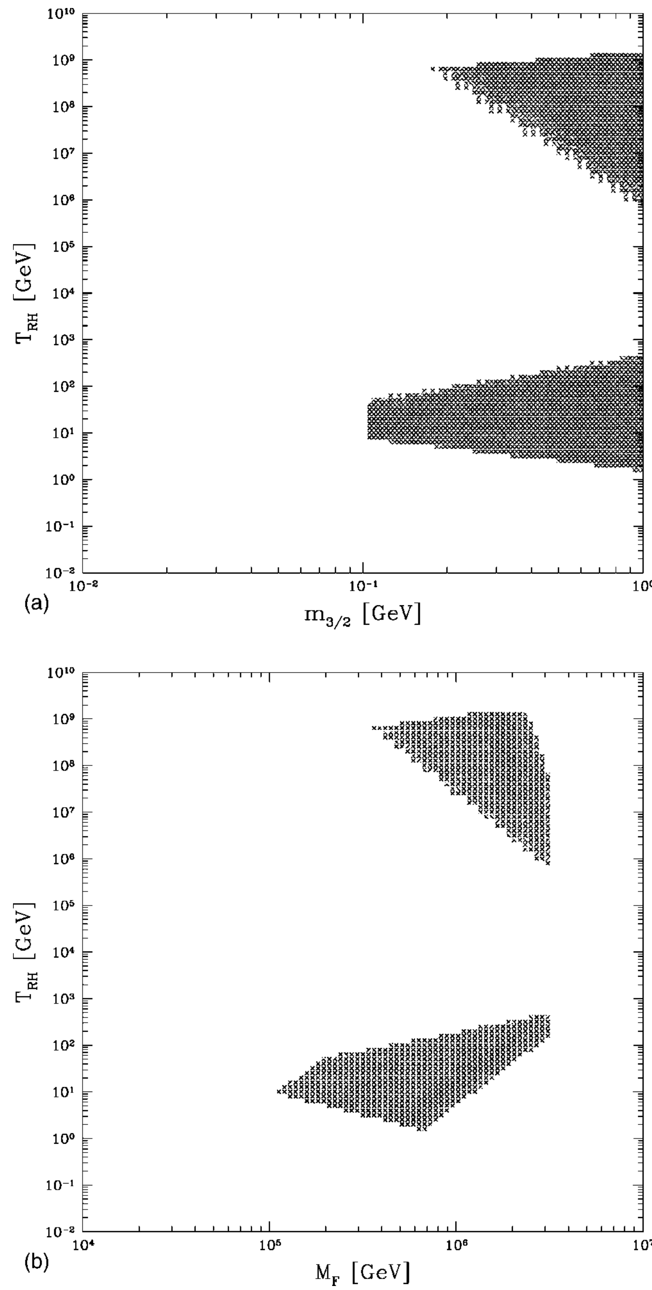

FIG. 1. The allowed region for $m_{3/2}$, M_F, and T_{RH}, where our scenario succeeds and the baryon to entropy ratio satisfies the following bounds: $10^{-11} \lesssim n_B/s \lesssim 10^{-10}$. Note that there does not exist any upper bound on T_{RH} from the gravitino problem [28,19], since the L-balls dominate the universe and their decay temperature is rather low. The two separate allowed regions roughly correspond to the cases A and B discussed in the text.

First we consider the case that the delayed-type L-balls are formed before the reheating and decay after that (case A). This is realized if the following two conditions are satisfied:

$$M_F > T_{RH}, \tag{15}$$

$$T_{RH} > T_d. \tag{16}$$

Then the temperature at the L-ball formation is given by $T_{eq} = \sqrt{M_F T_{RH}}$, which automatically satisfies the requirement (11). The temperature of the universe is approximately given as

$$T \simeq \begin{cases} (T_{RH}^2 M H)^{1/4} & \text{for} \;\; T_{RH} < T, \\ (T_{RH}^{-1} M^2 H^2)^{1/3} & \text{for} \;\; T_p < T < T_{RH}, \\ (T_d^2 M H)^{1/4} & \text{for} \;\; T_d < T < T_p, \\ \sqrt{HM} & \text{for} \;\; T < T_d, \end{cases} \tag{17}$$

where $T_p \equiv (T_{RH} T_d^4)^{1/5}$ denotes the temperature when the radiation derived from the decay of the L-balls dominate over those derived from the inflaton. Note that the cosmic temperature decreases monotonically in this case. The condition that the chemical equilibrium induced by the sphaleron transition are well established is given by

$$T_{eq} = \sqrt{M_F T_{RH}} > T_C. \tag{18}$$

With the use of Eq. (17), the evaporation rate with respect to the temperature is estimated as

$$\left(\frac{dQ}{dT}\right)_{evap} \simeq \begin{cases} 4\pi \dfrac{T_{RH}^2 M}{M_F T^3} Q^{1/4} & \text{for} \;\; m_\phi, T_{RH} < T < T_{eq}, \\ 4\pi \alpha_w^2 \dfrac{T_{RH}^2 M}{m_\phi^2 M_F T} Q^{1/4} & \text{for} \;\; T_{RH} < T < m_\phi, T_{eq}, \\ 4\pi \dfrac{M}{M_F \sqrt{T T_{RH}}} Q^{1/4} & \text{for} \;\; m_\phi, T_p < T < T_{RH}, \\ 4\pi \alpha_w^2 \dfrac{M T^{3/2}}{m_\phi^2 M_F T_{RH}^{1/2}} Q^{1/4} & \text{for} \;\; T_p < T < m_\phi, T_{RH}, \\ 4\pi \dfrac{T_d^2 M}{M_F T^3} Q^{1/4} & \text{for} \;\; m_\phi, T_d < T < T_p, \\ 4\pi \alpha_w^2 \dfrac{T_d^2 M}{m_\phi^2 M_F T} Q^{1/4} & \text{for} \;\; T_d < T < m_\phi, T_p. \end{cases} \tag{19}$$

On the other hand, the diffusion rate with respect to the temperature is given by

$$\left(\frac{dQ}{dT}\right)_{diff} \simeq \begin{cases} 4\pi a \dfrac{T_{RH}^2 M}{T^4} & \text{for} \;\; T_{RH} < T < T_{eq}, \\ 4\pi a \dfrac{M}{T_{RH}^{1/2} T^{3/2}} & \text{for} \;\; T_p < T < T_{RH}, \\ 4\pi a \dfrac{T_d^2 M}{T^4} & \text{for} \;\; T_d < T < T_p. \end{cases} \tag{20}$$

By integrating Eqs. (19) and (20), the evaporated charges ΔQ and ΔQ_{ew} are found to be the same order, and given by

$$\Delta Q \simeq \Delta Q_{ew} \simeq \begin{cases} \dfrac{4\pi a}{3} \dfrac{T_{RH}^2 M}{m_\phi^3} & \text{for} \;\; T_{RH} < m_\phi < T_{eq}, \\ 8\pi a \dfrac{M}{\sqrt{m_\phi T_{RH}}} & \text{for} \;\; T_p < m_\phi < T_{RH}, \\ \dfrac{4\pi a}{3} \dfrac{T_d^2 M}{m_\phi^3} & \text{for} \;\; T_d < m_\phi < T_p, \end{cases} \tag{21}$$

where we have used $T_C \sim m_\phi$.

Next we consider the case where delayed-type L-balls are formed after the reheating and the temperature decreases monotonically (case B). This is realized if the following conditions are satisfied:

$$T_{RH} > M_F, \tag{22}$$

$$M_F > (T_{RH}^2 T_d^3)^{1/5}. \tag{23}$$

Then the temperature at the Q-ball formation is given by $T_{eq} = (M_F^4/T_{RH})^{1/3}$, which again satisfies the requirement (11). Though the time evolution of the cosmic temperature is the same as case A, the requirement for the sphaleron process to work now reads

$$T_{eq} = (M_F^4/T_{RH})^{1/3} > T_C. \tag{24}$$

The evaporated charges ΔQ and ΔQ_{ew} can be estimated similarly and given by

$$\Delta Q \simeq \Delta Q_{ew} \simeq \begin{cases} 8\pi a \dfrac{M}{\sqrt{m_\phi T_{RH}}} & \text{for } T_p < m_\phi < T_{eq}, \\ \dfrac{4\pi a}{3} \dfrac{T_d^2 M}{m_\phi^3} & \text{for } T_d < m_\phi < T_p. \end{cases} \tag{25}$$

Finally we estimate the baryon (lepton) to entropy ratio, using the results derived above. The baryon to entropy ratio is then given by

$$\frac{n_B}{s} = \frac{8}{23} \frac{m_{3/2} M^2}{\frac{2\pi^2}{45} g_* T_d^3} \frac{\frac{\pi^2}{90} g_* T_d^4}{m_{3/2}^2} \frac{\Delta Q_{ew}}{Q} = \frac{2}{23} \frac{T_d}{m_{3/2}} \frac{\Delta Q_{ew}}{Q},$$

$$\sim \begin{cases} 4\times 10^{-11} \left(\dfrac{m_\phi}{1 \text{ TeV}}\right)^{-3} \left(\dfrac{m_{3/2}}{1 \text{ GeV}}\right)^{11/2} \left(\dfrac{T_{RH}}{10 \text{ GeV}}\right)^{2} \left(\dfrac{M_F}{10^6 \text{ GeV}}\right)^{-6} & \text{for } T_{RH} < m_\phi < T_{eq} \text{ (case A)}, \\ 3\times 10^{-11} \left(\dfrac{m_\phi}{1 \text{ TeV}}\right)^{-1/2} \left(\dfrac{m_{3/2}}{1 \text{ GeV}}\right)^{11/2} \left(\dfrac{T_{RH}}{10^7 \text{ GeV}}\right)^{-1/2} \left(\dfrac{M_F}{3\times 10^6 \text{ GeV}}\right)^{-6} & \text{for } T_p < m_\phi < T_{eq} \text{ (case B)}, \end{cases} \tag{26}$$

where we have used Eqs. (7), (14), (21), and (25). Also we have assumed the maximal CP violation. In the same way, the lepton number to entropy ratio is given by

$$\frac{n_L}{s} = -\frac{T_d}{4 m_{3/2}} \sim -0.01 \times \left(\frac{m_{3/2}}{1 \text{ GeV}}\right)^{3/2} \left(\frac{M_F}{5\times 10^5 \text{ GeV}}\right)^{-2}, \tag{27}$$

which yields [7]

$$\xi_{\nu_e} \simeq -10 \times \frac{n_L}{s} \sim 0.1 \times \left(\frac{m_{3/2}}{1 \text{ GeV}}\right)^{3/2} \left(\frac{M_F}{5\times 10^5 \text{ GeV}}\right)^{-2}. \tag{28}$$

The allowed regions for $m_{3/2}$, M_F, and T_{RH} is shown in Fig. 1, where the baryon to entropy ratio takes the value required from BBN,

$$10^{-11} \lesssim \frac{n_B}{s} \lesssim 10^{-10}. \tag{29}$$

Here we adopt a rather loose constraint because of the uncertain CP phase. As can be seen from Fig. 1, there are two allowed regions: (i) $m_{3/2} \sim 0.1-1$ GeV, $M_F \sim 10^5 - 10^6$ GeV, and $T_{RH} \sim 1-10^3$ GeV, (ii) $m_{3/2} \sim 0.1 - 1$ GeV, $M_F \sim 10^6$ GeV, and $T_{RH} \sim 10^6 - 10^9$ GeV. Roughly speaking, the regions (i) and (ii) correspond to cases A and B, respectively.

Also we plot the contours of the degeneracy of electron neutrinos in Fig. 2, which shows that the large and positive lepton asymmetry of the electron type can be generated in our scenario. For reference, the present constraint of ξ_{ν_e} by the analyses of BBN and CMB data is given by [29],

$$-0.01 \lesssim \xi_{\nu_e} \lesssim 0.22. \tag{30}$$

Thus, our scenario can generate both small baryon asymmetry and positive large lepton asymmetry of electron type at the same time by virtue of the AD leptogenesis and subsequently formed L-balls.

IV. DISCUSSION AND CONCLUSIONS

In this paper we have proposed a scenario which accommodates small baryon asymmetry and large lepton asymmetry simultaneously. The large lepton asymmetry is generated through the Affleck-Dine mechanism and almost all the produced lepton charges are absorbed into L-balls which are formed subsequently. Thus, most of the produced lepton numbers do not suffer from the sphaleron process. Only a small fraction evaporated from the L-balls due to thermal effects is converted into baryon asymmetry, which is responsible for the present baryon asymmetry.

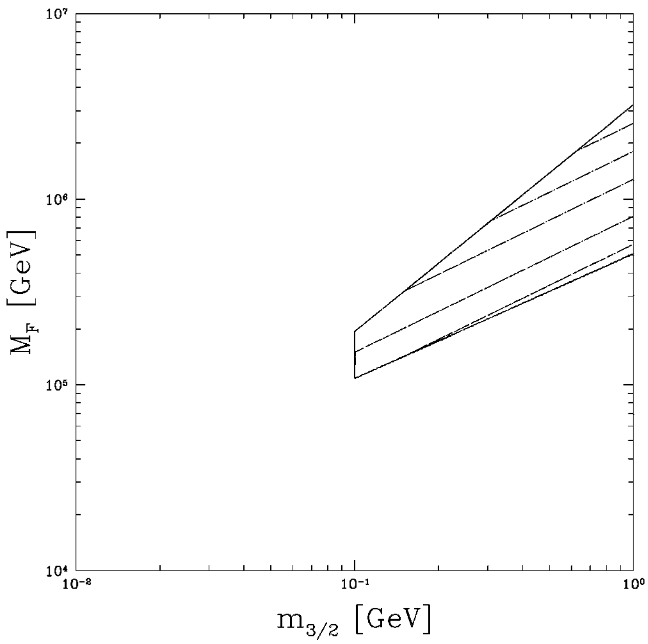

FIG. 2. The contours of the electron neutrino degeneracy are shown. The trapeziform area represents the allowed region where our scenario works and the baryon to entropy ratio satisfies the bounds: $10^{-11} \lesssim n_B/s \lesssim 10^{-10}$. The contours represent $\xi_{\nu_e} = 0.005$, 0.01, 0.02, 0.06, 0.1 from top to bottom.

As a concrete example, we consider positive large lepton asymmetry of the electron type. The excess of electron neutrinos shifts the chemical equilibrium between protons and neutrons toward protons so that the predicted primordial abundance of ^{4}He is decreased, which often gives a solution to the discrepancy of BBN itself or that between BBN and CMB. However, the sphaleron process converts lepton asymmetry into baryon asymmetry with the opposite sign. To circumvent this problem, we identify the $e_1^c L_2 L_3$ flat direction to be the AD field. Then the Affleck-Dine leptogenesis can generate positive lepton asymmetry of the electron type but totally negative lepton asymmetry, which is converted into positive baryon asymmetry. Of course, one should notice that by use of another flat direction such as $e_2^c L_1 L_3$, we can obtain negative lepton asymmetry of the electron type and also total negative lepton asymmetry.

Recently, it was pointed out that complete or partial equilibrium between all active neutrinos may be accomplished through neutrino oscillations in the presence of neutrino chemical potentials, depending on neutrino oscillation parameters [30]. In the case of partial equilibrium, our scenario needs no change. Only complete equilibrium can spoil our scenario. Even if neutrino oscillation parameters lead to complete equilibrium, our scenario may still work since it is possible that the *L*-balls decay just before BBN and the complete equilibration cannot be attained, which needs further investigation.

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