

Late leptogenesis from radiative soft terms

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We point out that the so-called soft leptogenesis can occur at the TeV scale if the B term is generated through radiative corrections which involve two-loop diagrams with the gaugino exchange. This mechanism requires the nontrivial CP phase, $\text{Im}(Am_{1/2}^*) \neq 0$, and can naturally explain the observed baryon asymmetry of the Universe associated with the TeV scale seesaw mechanism. Such a low scale leptogenesis would be a promising option in view of the tight upper limit on the reheat temperature avoiding the gravitino problem in supergravity models.

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I. INTRODUCTION

The seesaw mechanism [1] provides an elegant explanation not only for the observed neutrino masses and mixing but also for the baryon asymmetry of the Universe, $n_B/s \approx 10^{-10}$, under the name of leptogenesis. In its original suggestion [2], it was observed that an out-of-equilibrium decay of a heavy right-handed neutrino (RHN) generates lepton asymmetry, provided there are CP -violating phases in the neutrino Yukawa couplings. Then the produced lepton asymmetry is transformed to the baryon asymmetry through the standard model sphaleron process. The whole scheme can be supersymmetrized in a straightforward manner. The RHN N accompanied by its scalar partner \tilde{N} is extended to a chiral superfield \hat{N} which is added to the minimal supersymmetric standard model and allows the following superpotential:

$$W = \mu \hat{H}_1 \hat{H}_2 + h \hat{L} \hat{H}_2 \hat{N} + \frac{1}{2} M \hat{N} \hat{N}. \quad (1)$$

Here \hat{L} and $\hat{H}_{1,2}$ are the lepton and Higgs boson superfields, respectively. Now, the decays of the singlet neutrino N , sneutrino \tilde{N} , and antineutrino \tilde{N}^\dagger can contribute to the generation of lepton asymmetry defined by

$$\epsilon \equiv \frac{\sum_X [\Gamma(X \rightarrow L, \tilde{L}) - \Gamma(X \rightarrow \bar{L}, \tilde{\bar{L}})]}{\sum_X [\Gamma(X \rightarrow L, \tilde{L}) + \Gamma(X \rightarrow \bar{L}, \tilde{\bar{L}})]}, \quad (2)$$

where X denotes N , \tilde{N} , or \tilde{N}^\dagger . In the conventional ‘‘supersymmetric leptogenesis’’ [3,4], each particle X contributes to the CP asymmetric quantity (2) in the same way as described before. Namely, the required CP violation arises from the interference between the tree-level and one-loop diagrams with nontrivial CP phases in the Yukawa coupling h .

Recently, the importance of supersymmetry breaking effect in supergravity models has been realized. According to the original observations of Refs. [5,6], an enhanced contribution to leptogenesis may occur through a tiny $\tilde{N}-\tilde{N}^\dagger$ mixing requiring a nontrivial CP phase, $\text{Im}(AB^*) \neq 0$, where

A, B are dimension-one soft parameters for the scalar RHN [7]. The resulting lepton asymmetry in the so-called soft leptogenesis is given by

$$\epsilon \approx \frac{\text{Im}(AB^*)}{\Gamma^2 + |B|^2} \frac{\Gamma}{M} \Delta_{BF}, \quad (3)$$

where Δ_{BF} counts for the supersymmetry breaking effect at a finite temperature [5,6,8].

An important constraint on the leptogenesis scenario in the supergravity models comes from the gravitino problem, which requires the reheat temperature (and thus the RHN mass M) to be low enough in order not to overproduce gravitinos [9]. Otherwise, the late decay of gravitinos upsets the standard prediction of the nucleosynthesis on the primordial abundance of the light elements. Recent analysis has put a very strong upper bound on the reheat temperature, $T_R \lesssim (2 \times 10^6 - 2 \times 10^7)$ GeV, for the gravitino mass in the range of $m_{3/2} = (10^2 - 10^3)$ GeV [10]. As is well known, the supersymmetric leptogenesis cannot work with such a low reheat temperature since the following bound has to be fulfilled [11]:

$$M \gtrsim 10^9 \text{ GeV} \left(\frac{\epsilon}{10^{-7}} \right) \left(\frac{0.05 \text{ eV}}{m_{\nu_3}} \right), \quad (4)$$

where M is taken to be the lowest seesaw scale. The similar constraint also applies to the soft leptogenesis where the typical values of the soft terms are assumed: $A \sim B \sim m_{3/2}$. It is, however, possible to have a much smaller seesaw scale if the B parameter is arranged to satisfy [5,6]

$$B \approx 10^{-3} \text{ GeV} \left(\frac{M}{10^7 \text{ GeV}} \right)^2. \quad (5)$$

In this paper, we show that the soft leptogenesis works successfully for the TeV scale seesaw mechanism provided the initial condition of the soft term

$$B = 0. \quad (6)$$

This mechanism involves the two-loop diagrams carrying gauginos in the loop, and the corresponding CP phases from the soft supersymmetry breaking A term and the gaugino

mass $m_{1/2}$ [12]. While it is difficult to arrange a hierarchically small value of $B \ll m_{3/2}$ in general supergravity models, the initial condition $B=0$ may arise naturally in the no-scale type models. We also work out a concrete model in which such a feature is realized and the TeV seesaw scale M [13] can be understood in connection with the Higgsino mass parameter μ .

II. CP PHASES FROM SOFT SUPERSYMMETRY BREAKING

Let us first make a general description of CP violation coming from soft supersymmetry breaking, which leads to a nontrivial lepton asymmetry. The scalar potential from soft supersymmetry breaking can be written as

$$V_{soft} = m_0^2 |\phi|^2 + [B\mu H_1 H_2 + Ah\tilde{L}H_2\tilde{N} + \frac{1}{2}BM\tilde{N}\tilde{N} + \text{H.c.}], \quad (7)$$

where ϕ represents any scalar field, and m_0 , A , and B are dimension-one soft masses. Simply extending the standard argument of Ref. [14], we can consider mass parameters as spurion fields and then find that our Lagrangian possesses the $U(1)_R$ and $U(1)_{PQ}$ symmetry defined by the following R and PQ charges:

	m_0^2	A	B	$m_{1/2}$	μ	N	L	H_1	H_2
R	0	-2	-2	-2	0	1	0	1	1
PQ	0	0	0	0	-2	0	-1	1	1

(8)

Here $m_{1/2}$ is the gaugino mass. Since physical observables should be neutral under such symmetries, the lepton asymmetry ϵ (2) can only depend on one of the following combinations:

$$AB^*, Am_{1/2}^*, Bm_{1/2}^*(\mu\mu^*), \quad (9)$$

which shows that we have only two independent phases as usual [14]. Note that the leptogenesis from the $\tilde{N}-\tilde{N}^\dagger$ mixing requires the nontrivial CP phase of the first type AB^* [5,6]. As a simple corollary of our argument, one sees that the supersymmetry breaking contribution to leptogenesis occurs at the order of \tilde{m}^2 at most. In the following, we will discuss the gaugino contribution with a nontrivial phase in the combination $Am_{1/2}^*$.

III. GAUGINO-LOOP CONTRIBUTION TO SOFT LEPTOGENESIS

From the interaction terms in Eqs. (1) and (7), one obtains the following lepton number producing processes of the singlet sneutrinos \tilde{N} and \tilde{N}^\dagger : $\tilde{N}^\dagger \rightarrow L\tilde{H}_2, \tilde{L}H_2, \tilde{L}H_1^\dagger$ and $\tilde{N} \rightarrow \tilde{L}H_2$ which have the coupling $h, hA^*, h\mu$, and hM , respectively. There are also the usual singlet neutrino decay: $N \rightarrow LH_2$ and $\tilde{L}\tilde{H}_2$ with the coupling h . For the convenience

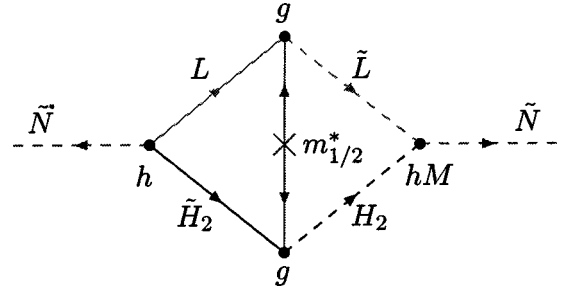


FIG. 1. Two-loop diagram with gaugino leading to non-vanishing B parameter and thereby the desired soft leptogenesis at TeV scale.

of our discussion, we take h and M to be real without a loss of generality.

Assuming the boundary condition $B=0$ imposed in a certain supersymmetry breaking mechanism, the B term received two important radiative corrections. One comes from the one-loop diagram having \tilde{L} and H_2 in the loop with couplings hM and hA , and the other is the two-loop diagram drawn in Fig. 1.

From these diagrams, one finds

$$B \approx \left(\frac{1}{\pi}A + \frac{\alpha_2}{4\pi^2}m_{1/2} \right) \frac{\Gamma}{M} \ll \Gamma, \quad (10)$$

where α_2 is the gauge coupling constant $g^2/4\pi$. While the first term does not contribute to the lepton asymmetry ϵ , Eq. (3), the second term gives

$$\epsilon \approx \frac{\alpha_2}{4\pi^2} \frac{\text{Im}(Am_{1/2}^*)}{M^2} \Delta_{BF}. \quad (11)$$

Taking $\text{Im}(Am_{1/2}^*) = 10^4 \text{ GeV}^2$, $M = 1 \text{ TeV}$, and $\Delta_{BF} = 0.1$, we obtain the right range of the lepton asymmetry $\epsilon \sim 10^{-6}$. Note that we have ignored the lepton asymmetry coming from the supersymmetry breaking vertex with the hA coupling. This is a good approximation in the regime of $|A| \ll M$ where one finds

$$\epsilon \sim \frac{\alpha_2}{4\pi^2} \frac{\text{Im}(Am_{1/2}^*)}{M^2} \frac{|A|^4}{M^4}. \quad (12)$$

This, of course, becomes important for $A \sim M$ and the above order of magnitude estimation of the lepton asymmetry still holds. Let us remark that the lepton asymmetry (11), (12) is independent of h^2 or the decay rate Γ , and thus independent of the neutrino mass. That is, the usual out-of-equilibrium condition $\Gamma < H$ has no direct impact on the lepton asymmetry apart from its effect on the quantity Δ_{BF} .

IV. A MODEL

In this section, we consider the possible origin of the TeV seesaw scale M and the initial condition $B=0$. For this purpose, we invoke the model [15] where the lepton number symmetry is promoted to the Peccei-Quinn (PQ) symmetry

which is introduced to solve the strong CP problem [16]. The original motivation was to relate two intermediate scales, the seesaw scale M and the PQ symmetry breaking scale f_{PQ} , both of which are around 10^{11} GeV [15]. In this scheme, the Higgsino mass parameter μ is generated from the nonrenormalizable term which is dictated by the nontrivial PQ charge assignment to the Higgs bilinear $H_1 H_2$ [17]. Taking now a different point of view, it is conceivable to generate two TeV scale parameters μ and M from the PQ symmetry breaking. To be more specific, let us introduce the singlet fields (\hat{P} , \hat{Q} , and \hat{S}) which are responsible for the spontaneous breaking of the PQ symmetry, as is done usually. To achieve the desired pattern for the soft terms, we also introduce the supersymmetry breaking field \hat{Z} in the hidden sector with the nontrivial scalar vacuum expectation value: $\langle Z \rangle \sim M_P$, $\langle F_Z \rangle \sim m_{3/2} M_P$. Assigning the PQ and R charges to the fields as follows:

	\hat{L}	\hat{E}^c	\hat{N}	\hat{H}_1	\hat{H}_2	\hat{P}	\hat{Q}	\hat{S}	\hat{Z}
PQ	0	-1	-1	1	1	-1	1	0	0
R	-1	1	1	1	1	0	0	2	1

(13)

one obtains the allowed superpotential written as

$$W = h_e e^{\hat{Z}/M_P} \hat{L} \hat{H}_1 \hat{E}^c + h_N e^{\hat{Z}/M_P} \hat{L} \hat{H}_2 \hat{N} + h_\mu \frac{\hat{P}^2}{M_P} \hat{H}_1 \hat{H}_2 + h_M \frac{\hat{Q}^2}{M_P} \hat{N} \hat{N} + h_S \hat{S} (\hat{P} \hat{Q} - f_{PQ}^2). \quad (14)$$

Here we introduced one intermediate scale $f_{PQ} \sim \sqrt{m_{3/2} M_P}$ that might be related to the supersymmetry breaking scale $\langle F_Z \rangle$. Note that the R symmetry is nonlinearly realized by the supersymmetry breaking field Z which behaves like a dilaton field in superstring theories. Now, a crucial ingredient is to assume *no-scale supergravity* with $K = -3 \log(Z + Z^* - \phi\phi^*)$, where ϕ denotes the observable (and PQ) sector fields. In the general supergravity models, the B term receives the contribution of the order $m_{3/2}$ coming from various terms in the supergravity scalar potential [18]. The condition $B=0$ could be made by arranging cancellation among

various terms, which is, however, unlikely to occur. As is well known, the no-scale supergravity provides a restrictive prediction on the soft terms [18], which is also useful for our purpose. With the above superpotential (11), one finds the universal A and B terms as follows:

$$A = \frac{\langle F_Z \rangle}{M_P} \sim m_{3/2} \quad \text{and} \quad B = 0 \quad (15)$$

together with $\mu \sim M \sim f_{PQ}^2/M_P \sim m_{3/2}$ as alluded before.

Here, let us remark that the mechanism of dynamical relaxation for $B=0$ was considered in Ref. [19], which is advocated to resolve the associated supersymmetric CP problem. Such a resolution also works in our model as both B terms for the Higgs and scalar RHN sectors vanish.

V. CONCLUSION

Leptogenesis is a promising way of generating the baryon asymmetry of the Universe, which is linked with the origin of neutrino masses and mixing. Besides the widely discussed supersymmetric contribution, leptogenesis may receive an important contribution from supersymmetry breaking. In this paper, we point out that soft supersymmetry breaking involving CP violation in the gaugino sector, more precisely $\text{Im}(Am_{1/2}^*)$ can be the source of a successful leptogenesis if the $B=0$ boundary condition of the soft parameters is realized. This turns out to work for the TeV scale seesaw mechanism. Our analysis implies that leptogenesis can be operative even with a fairly low seesaw scale, which is compatible with the low reheat temperature inflation which evades the gravitino problem. Furthermore, it will be interesting to see if certain CP -violating phenomena can be observed in future collider experiments associated with the above ‘‘leptogenesis phase.’’

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