Electroweak baryogenesis from chargino transport in the supersymmetric model

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Abstract

We study the baryon asymmetry of the universe in the supersymmetric standard model (SSM). At the electroweak phase transition, the fermionic partners of the charged SU(2) gauge bosons and Higgs bosons are reflected from or transmitted to the bubble wall of the broken phase. Owing to a physical complex phase in their mass matrix, these reflections and transmissions have asymmetries between CP conjugate processes. Equilibrium conditions in the symmetric phase are then shifted to favor a non-vanishing value for the baryon number density, which is realized through electroweak anomaly. We show that the resultant ratio of baryon number to entropy is consistent with its present observed value within reasonable ranges of SSM parameters, provided that the CP-violating phase intrinsic in the SSM is not much suppressed. The compatibility with the constraints on the parameters from the electric dipole moment of the neutron is also discussed.
I. INTRODUCTION

The astronomical observations indicate that there exist more baryons than antibaryons in our universe. This baryon asymmetry of the universe may be understood within the framework of physics at the electroweak scale [1], since all the necessary ingredients for baryogenesis could be available there [2]. Although the standard model (SM) does not account for the asymmetry quantitatively, certain extensions of the SM would be able to overcome those difficulties which the SM encounters. This possibility could give some hints for physics beyond the SM. In particular, it turned out that CP violation in the SM arising from the Kobayashi-Maskawa phase does not lead to an enough amount of asymmetry between the numbers of baryons and antibaryons. The baryon asymmetry could be a unique phenomenon ever found, other than the $K^0-\bar{K}^0$ system, which enables us to study CP violation.

In this paper, we discuss the possibility of baryogenesis at the electroweak phase transition in the supersymmetric standard model (SSM). This model [3], which is one of the most plausible extensions of the SM from the viewpoint of physics at the electroweak scale, contains new sources of CP violation [4] wanted for the baryogenesis. In addition, the electroweak phase transition may be strongly first order in the SSM, which is also necessary for the baryogenesis though not com patible with the Higgs boson mass in the SM. Indeed, the constraints on the Higgs boson masses from this requirement could be relaxed [3] compared to the SM, owing to the richness of Higgs fields, especially by adding a gauge singlet field. It would be thus of great importance to study whether the electroweak baryogenesis is viable in the SSM.

The baryogenesis at the electroweak phase transition could occur within or outside the bubble wall of the broken phase, where baryon number violation by electroweak anomaly is not suppressed. We consider the baryon number generation outside the wall, which has been suggested to give an enough amount of asymmetry in the SSM [4,5]. For this process the baryon number is well estimated through the charge transport mechanism [3,8].
The mediators on which our study is focused are charginos, which consist of the fermionic partners of the charged SU(2) gauge bosons and Higgs bosons and have a mass matrix with a physical complex phase. Since these particles couple to the Higgs bosons by the SU(2) gauge interaction, their scatterings at the wall are not so weak as the leptons, while their asymmetries in the symmetric phase are maintained longer than the quarks. It will be shown that the baryon asymmetry of the universe can be explained in the SSM within the reasonable values for its model parameters. However, the allowed range for the new CP-violating phase is not so wide as estimated before [6,7], so that the baryogenesis could give nontrivial constraints on the SSM. Although the baryogenesis within the wall might also be possible in the SSM [8], it has been generally shown that an enough amount of baryon asymmetry cannot be produced within the wall only [10].

In Sec. II we briefly review the source of CP violation in the chargino sector. In Sec. III we discuss CP asymmetries in the reaction and transmission rates for the charginos at the bubble wall. The procedure for computing these rates, which gives accurate results, is presented explicitly. In Sec. IV we calculate the ratio of baryon number to entropy following the charge transport mechanism. The dependence of the ratio on various parameters are also analyzed. Summary is given in Sec. V.

II. SUPERSYMMETRIC MODEL

A new source of CP violation in the SSM comes from the mass matrices of the SU(2) U(1) gauginos and Higgsinos. The mass terms for the charged gauginos and Higgsinos $i_1$, $(i_2^\dagger)^c$ are given by

$$L = \begin{pmatrix} 0 & 1 \\ (i_2^\dagger)^c M \end{pmatrix} \begin{pmatrix} \frac{1}{2} \phi^5 A + h c y \\ i_1 \end{pmatrix} \begin{pmatrix} \frac{1}{2} \phi^5 A + h c y \\ i_1 \end{pmatrix}$$ (1)

$$M = \begin{pmatrix} m_2 & \sqrt{2} g v_1 \\ \sqrt{2} g v_1 & m_H \end{pmatrix} \begin{pmatrix} \frac{1}{2} \phi^5 A + h c y \\ i_1 \end{pmatrix} \begin{pmatrix} \frac{1}{2} \phi^5 A + h c y \\ i_1 \end{pmatrix}$$ (2)

where $m_2$ denotes the mass parameter for the SU(2) gauginos arising from the supersymmetry soft-breaking term; $m_H$ denotes the mass parameter for the Higgsinos from the bilinear
term of Higgs super elds in superpotential, and \( v_1 \) and \( v_2 \) are respectively the vacuum expectation values of the Higgs bosons with \( U(1) \) hypercharges \( 1 = 2 \) and \( 1 = 2 \). The mass matrix \( \mathbf{2} \) is diagonalized by unitary matrices \( C_R \) and \( C_L \) as

\[
C_R \mathbf{M} C_L = \text{diag}(m_{1,1};m_{2,2}) \quad (m_{1,1} < m_{2,2});
\]

giving the mass eigenstates for the charginos \( \psi_1 \).

In general, the parameters \( v_1, v_2, m_2 \), and \( m_H \) in the mass matrix \( \mathbf{2} \) have complex values. Although there is some freedom of defining phases for the particle elds, if the \( SU(2) \) \( U(1) \) gauge symmetry is spontaneously broken and thus \( v_1 \) and \( v_2 \) have non-vanishing values, all the complex phases cannot be rotated away. The redefinitions of the elds make it possible without loss of generality to take \( m_2, v_1, \) and \( v_2 \) for real and positive. Then \( m_H \) cannot be made real. Therefore, there is one physical complex phase in the mass matrix for the charginos, which we express as

\[
m_H = j m_H \exp(i); \quad (4)
\]

Owing to this complex phase, CP invariance is broken in the interactions for the charginos. Similarly, the mass matrix for the neutral gauginos and Higgsinos contains the CP-violating phase.

III. CP ASYMMETRY

At the electroweak phase transition of the universe, if it is first order, bubbles of the broken phase nucleate in the \( SU(2) \) \( U(1) \) symmetric phase. In the symmetric phase the gauginos and the Higgsinos are in mass eigenstates themselves. On the other hand, they are mixed to form mass eigenstates in the wall and in the broken phase, owing to non-vanishing vacuum expectation values of the Higgs bosons. Consequently, the gauginos incident on the wall from the symmetric phase can be reflected to become Higgsinos, and vice versa. The charginos from the broken phase can be transmitted to the symmetric phase and become
gauginos or Higgsinos. In these processes CP violation makes a difference in reaction or transmision probability between a particle state with a definite helicity and its CP-conjugate state. The induced CP asymmetries shift equilibrium conditions in the symmetric phase for non-vanishing baryon number.

The reaction and transmission rates at the wall are obtained by solving the Dirac equations for the charginos. In the rest frame of the wall the Dirac equations are given by

\[
\begin{align*}
0 & \quad \vec{p} = \vec{0} & m_2 & \quad 0 & \quad \vec{v}_1 = \vec{p} \quad 1 & \quad 0 & \quad 0 & \quad 1 \\
\vec{m}_2 & \quad \vec{v}_1 = \vec{p} & & & \quad v_2 = \vec{v}_2 & & & \quad 0 \\
0 & \quad \vec{v}_2 = \vec{p} & \quad \vec{m}_2 & \quad 0 & \quad \vec{v}_1 = \vec{p} & \quad 1 & \quad 0 & \quad 1 \\
\vec{g}_v & \quad \vec{v}_1 = \vec{g}_v & \quad \vec{m}_2 & \quad \vec{m}_2 & \quad \vec{v}_2 = \vec{v}_2 & \quad 1 & \quad 0 & \quad 1 \\
\vec{g}_v & \quad \vec{v}_2 = \vec{g}_v & \quad \vec{m}_2 & \quad \vec{m}_2 & \quad \vec{v}_1 = \vec{v}_1 & \quad 1 & \quad 0 & \quad 1 \\
\end{align*}
\]

(5)

where the wall is taken to be parallel to the xy-plane and perpendicular to the velocity of the particles. The components of the Dirac matrices are expressed as

\[
\begin{align*}
0 & \quad 1 & \quad 2 & \quad 3 & \quad \frac{1}{2} & \quad \frac{1}{2} \quad \frac{1}{2} \\
1 & \quad 0 & \quad 3 & \quad 2 & \quad \frac{1}{2} & \quad \frac{1}{2} \quad \frac{1}{2} \\
2 & \quad 3 & \quad 0 & \quad 1 & \quad \frac{1}{2} & \quad \frac{1}{2} \quad \frac{1}{2} \\
3 & \quad 2 & \quad 1 & \quad 0 & \quad \frac{1}{2} & \quad \frac{1}{2} \quad \frac{1}{2} \\
\end{align*}
\]

(7)

We have adopted the chiral representation for the Dirac matrices. In the symmetric phase the vacuum expectation values \(v_1\) and \(v_2\) vanish, while in the broken phase they are related to the W-boson mass as \(M_w = (g=2) \cdot j_1 \cdot j_2\). The vacuum expectation values vary along the z-axis in the wall. For simplicity, we assume that the wall is situated from \(z = 0\) to \(z = 2\), and the z-dependences of \(v_1\) and \(v_2\) are given by

\[
\begin{align*}
\frac{q}{j_1 \cdot j_2} & = \frac{M_w}{g \cdot f1 + \tanh \left( \frac{z}{w} \right)} \\
\frac{v_2}{v_1} & = \tan \left( \frac{z}{w} \right) \\
\end{align*}
\]

(8)
where the ratio \( v_2 = v_1 \) is taken to be constant and equal to its value tan \( \theta \) in the broken phase. The symmetric phase is in the region \( z < 0 \).

As a prototype for the calculation of the reflection and transmission rates, we consider the case that a gaugino with a positive helicity and energy \( E \) enters from the symmetric phase. Then the reflected particle (gaugino, Higgsino) has a negative helicity and the transmitted particle (charginos) has a positive helicity by angular momentum conservation. The boundary condition at \( z = 0 \) becomes

\[
0 \begin{bmatrix} 1 \\ 1 \\ 3 \end{bmatrix} = f X_1(0) + A X_2(0) + B X_3(0) \exp(\imath E t); \quad (9)
\]

where \( p \) and \( \bar{p} \) stand for the absolute values of the momenta for the gaugino and the Higgsino. The incident gaugino, the reflected gaugino, and the reflected Higgsino correspond to \( X_1, X_2, \) and \( X_3, \) respectively. The boundary condition at \( z = 2 \) \( W \) becomes

\[
0 \begin{bmatrix} 1 \\ 1 \\ 3 \end{bmatrix} = f C Y_1(2) + D Y_2(2) \exp(\imath E t); \quad (11)
\]
where $p_1$ and $p_2$ stand for the absolute values of the momenta for the two charginos. The lighter and heavier charginos correspond to $Y_1$ and $Y_2$, respectively. For the wave functions $X_1, X_2,$ and $X_3$ given at $z = 0$, those at $z = 2 \, w$ are obtained by numerically solving the differential equation (5). The reflection and transmission amplitudes $A, B, C,$ and $D$ then satisfy the simultaneous equation

$$X_1 (2 \, w) + A \, X_2 (2 \, w) + B \, X_3 (2 \, w) = C \, Y_1 (2 \, w) + D \, Y_2 (2 \, w);$$

which is solved algebraically. The reliability of these numerical calculations may be checked by the sum $A \, \tilde{f} + B \, \tilde{f} + C \, \tilde{f} + D \, \tilde{f}$, which is in excellent agreement with unity in our results.

We calculate the asymmetries of the transition rates between CP conjugate processes

$$A = R \left( \begin{array}{c} (+) \vspace{2pt} \\ (+) \end{array} \right) \right) + R \left( \begin{array}{c} (+) \vspace{2pt} \\ (-) \end{array} \right) \right) \left( \begin{array}{c} (+) \vspace{2pt} \\ (+) \end{array} \right) \left( \begin{array}{c} (+) \vspace{2pt} \\ (+) \end{array} \right) \left( \begin{array}{c} (+) \vspace{2pt} \\ (+) \end{array} \right) \left( \begin{array}{c} (+) \vspace{2pt} \\ (+) \end{array} \right);$$

$$A_{11} = R \left( \begin{array}{c} (+) \vspace{2pt} \\ (+) \end{array} \right) \right) + R \left( \begin{array}{c} (-) \vspace{2pt} \\ (-) \end{array} \right) \right) \left( \begin{array}{c} (+) \vspace{2pt} \\ (+) \end{array} \right) \left( \begin{array}{c} (+) \vspace{2pt} \\ (+) \end{array} \right) \left( \begin{array}{c} (+) \vspace{2pt} \\ (+) \end{array} \right);$$

where $+$ and $-$ denote the gaugino and the Higgsino in the symmetric phase, respectively, and $i$ the chargino in the broken phase. The subscripts $(+)$ and $(-)$ refer to a positive and a negative helicities, respectively. If CP is not violated, $A$ and $A_{11}$ vanish. In Fig. 3 the absolute values of these CP asymmetries are shown for (a) $A$, (b) $A_{11}$, and (c) $A_{12}$ as functions of the particle energy $E$, taking $= 4$, $\tan = 2$, $m_2 = 200 \, \text{GeV}$, and $w = 1=200 \, \text{GeV}$. The sign of $A$ is negative for $E < m_{12}$ and positive for $E > m_{12}$, and those of $A_{11}$ and $A_{12}$ are positive and negative, respectively. The sum of $A, A_{11},$ and $A_{12}$
vanishes by CPT invariance. The CP asymmetry $A$ has values of order of 0.1 for the energy range in slightly excess of the particle mass and has much smaller values in the other energy range. Since the mass of the lighter chargino becomes smaller than that of the gaugino, the gaugino is transmitted to the broken phase at a large rate. This makes the magnitude of $A$ rather small in spite of an unsuppressed value for the CP-violating phase.

IV. BARYON ASYMMETRY

The CP asymmetries of the reaction and transmission rates for the charginos lead to a bias on equilibrium conditions favoring baryon asymmetry in the symmetric phase. The free energy is then minimized at a non-vanishing baryon number, to which the initial equilibrium state with no baryon asymmetry approaches through electroweak anomaly. A simple procedure for relating the CP asymmetries with the bias $[6]$ is to introduce chemical potentials for conserved and approximately conserved quantum numbers and set these quantum numbers for zero. This makes the chemical potential of baryon number given by a hypercharge density, which is induced by the CP asymmetries. Although this procedure may not be completely correct, it would be able to provide a rough estimate for the bias.

Since the hypercharges of the gauginos and the Higgsinos are 0 and $1=2$, respectively, the bubble wall emits a net flux of hypercharge by CP violation. The transitions which cause a change of hypercharge in the symmetric phase are (i) $!!$, (ii) $!!$, $!!_i$, (iii) $!!_i!!$, and their CP-conjugate transitions. The sum of the probabilities for the transitions in the reaction (ii) is however the same as that for their CP-conjugate transitions by CPT invariance, so that a net hypercharge flux can be induced through the reactions (i) and (iii).

The hypercharge flux is calculated by convoluting the transition rates with the thermal flux of incoming particles. In the thermal frame at temperature $T$, the incoming flux from the symmetric phase and that from the broken phase, $f_s$ and $f_b$, are given by

$$f_s = \int \frac{d^3p}{(2\pi)^3} \frac{p_z}{E_T + v_W} \left[ \exp \left( \frac{E_T}{T} + 1 \right) \right] \frac{1}{\Phi_s : \frac{p_z}{E_T} + v_W > 0};$$
\[ f_b = \frac{Z^2}{d_b} \frac{d^3p}{(2\pi)^3} \left[ \frac{p_z}{E_T} + v_w \right] \exp\left(\frac{E_T}{T} + 1\right) \exp\left[ \Phi_b \left( \frac{p_z}{E_T} + v_w \right) < 0 \right]; \quad (15) \]

where \( E_T \) and \( p_z \) represent the total energy and the z-component of the momentum for the particle. The wall is taken to be perpendicular to the z-axis and moving with the velocity \( v_w \) (\( v_w > 0 \)). The net hypercharge \( \Delta \) therefore becomes

\[ F = F + \sum_{i=1}^{\Delta} F_i; \quad (16) \]

\[ F = \frac{1}{2} \left( \frac{v_w^2}{2} - \frac{v_T^2}{2} \right) \frac{Z}{m_2} \log[1 + \exp\left( \frac{E}{q} \left( \frac{1}{v_w} - \frac{1}{v_T} \right) \right)] \]

\[ F_i = \frac{1}{2} \left( \frac{v_w^2}{2} - \frac{v_T^2}{2} \right) \frac{Z}{m_{1,i}} \log[1 + \exp\left( \frac{E + v_w}{q} \left( \frac{1}{v_w} - \frac{1}{v_T} \right) \right)] \]

where \( E \) represents \( p_z^2 + m^2 \), \( p_z \) and \( m \) denoting the component of the momentum perpendicular to the wall in the wall rest frame and the mass, respectively, for the relevant particle.

Assuming detailed balance for the transitions among the states of different baryon numbers, the rate equation of the baryon number density \( \dot{B} \) is given by [11]

\[ \frac{d\dot{B}}{dt} = \frac{1}{T} B; \quad (17) \]

where denotes the rate per unit time and unit volume for the transition between the neighboring states different by unity in baryon number, and \( \dot{B} \) stands for the chemical potential of baryon number which represents a bias on the fluctuation of baryon number. In the symmetric phase the rate is estimated as

\[ = 3 \left( \frac{v_w}{T} \right)^4; \quad (18) \]

where is of order of unity [12].

The chemical potential \( \dot{B} \) may be related to the hypercharge density through equilibrium conditions [22]. In the symmetric phase the gauge interactions and the t-quark Yukawa interactions are considered to be in chemical equilibrium. We also take that the self interactions of the Higgs bosons, the Higgsinos, and the gauginos are in equilibrium,
respectively. Among the supersymmetric particles, the squarks, sleptons, and gluinos are assumed to be heavy enough. Before the net hypercharge $\text{ux}$ is emitted from the wall, the baryon number and the lepton number vanish. We thus impose for equilibrium conditions vanishing values on the baryon and the lepton number densities in each generation, and on the number densities of the right-handed quarks and leptons except the $t$-quark. These constraints lead to the chemical potential for baryon number given by

$$\mu_B = \frac{2\gamma}{\tau^2}$$

(19)

where $\gamma$ stands for the hypercharge density. The net hypercharge $\text{ux}$ into the symmetric phase induces a net hypercharge density, which makes $\mu_B$ non-vanishing.

We now estimate the baryon number density $\mu_B$ from Eqs. (17), (18), and (19) as

$$\mu_B = \frac{2}{7T^3} \int_1^z (z-v_w \tau) dz \gamma (z) = \frac{2}{7T^3v_w} \int_0^z dz \gamma (z)$$

$$= \frac{2F_Y}{7T^3v_w}$$

(20)

where $\tau$ is the time which carriers of the hypercharge $\text{ux}$ spend in the symmetric phase. This transport time $\tau$ may be approximated by the mean free time of the carriers. The rough estimate for $\tau$ gives a value of order of $10^2=\tau$ $10^3=\tau$ for the leptons [13], which would also be applicable to the gauginos and the Higgsinos. The ratio of the baryon number to entropy is given by

$$\frac{\mu_B}{s} = \frac{135}{7} \frac{4}{g} \frac{F_Y}{v_w} \tau$$

(21)

where $g$ represents the relativistic degrees of freedom for the particles. For definiteness, we take $g = 124.75$, where SU (2) U (1) gauginos and Higgsinos are taken into account as well as gauge bosons, Higgs bosons, quarks, and leptons.

We show the ratio of baryon number to entropy in Fig. 2 as a function of the mass parameter $m_2 (= m_H \gamma)$ for $\tan = 2$ and (a) = 4 and (b) = 0.1. For simplicity, we have taken the same value for $m_2$ and $m_H \gamma$. In the mass range where curves are not drawn, the lighter chargino has a mass smaller than 45 GeV, which is ruled out by experiments.
The temperature is taken for $T = 200 \text{ GeV}$. The wall velocity $v_W$ and the wall width $w$ have been estimated in the SM as $v_W = 0.1 \text{ and } w = 10^{-3} \text{ GeV}$, although there are large uncertainties and model dependences. If the phase transition is strongly first order, the wall width generally becomes thinner. We take four sets of values for $v_W$ and $w$ listed in Table I, which correspond to four curves (i-a)-(i-b). For definiteness we set the transport time for $\tau = 100\text{-}T$. The resultant ratio is around $10^{10}$ for $\tau = 4$ and $10^{11}$ for $\tau = 0.1$, which are consistent with the present observed value $B = S = (2\ 9) \times 10^{11}$. Except for the CP-violating phase, the ratio does not vary much with the SSM parameters $m_2$, $m_H$, and $\tan \beta$. In Fig. 3 the ratio of baryon number to entropy is shown as a function of $m_2 = m_H$ for (i) $T = 100 \text{ GeV}$ and (ii) $T = 200 \text{ GeV}$, taking $\tan \beta = 2, m_2 = m_H = 200 \text{ GeV}, v_W = 0.6$, and $w = 10^{-3} \text{ GeV}$. If the CP-violating phase is of order of $0.1$, only a large value for $\tau$ of order of $10^{3} = T$ barely gives a compatible value.

In the SSM, the CP-violating phase gives large contributions to the electric dipole moments (EDMs) of the neutron and the electron at one-loop level through the diagrams mediated by the charginos [14]. In Fig. 4 the neutron EDM is shown as a function of $m_2 = m_H$ for $\tan \beta = 2$. Four curves correspond to four sets of values for $m_2$ and the mass for the $u$- and $d$-squarks, which are listed in Table II. The experimental upper bound on the magnitude of the neutron EDM is about $10^{-25} \text{ cm}$ [14]. In order to satisfy this bound, the squark mass should be around or larger than $1 \text{ TeV}$ for $\tau = 0.1$ and $3 \text{ TeV}$ for $\tau = 1$. Similar constraints are obtained from the EDM of the electron.

V. SUMMARY

We studied the electroweak baryogenesis mediated by the charginos in the SSM following the charge transport mechanism. The observed baryon asymmetry is explained in reasonable ranges of the SSM parameters. However, the CP-violating phase cannot be so small as estimated in the literature. This is mainly because the gauginos or the Higgsinos incident on the wall from the symmetric phase can be transmitted to the broken phase, thus reducing
the overall reaction rates in the wide region of the parameter space. Assuming a moderate value for the transport time, the phase should be at least of order of 0.1. If this is the case, the squark masses are predicted to be around or larger than 1 TeV from the analysis of the EDM of the neutron.

The SSM has some ambiguities in the Higgs sector. The minimal version of the SSM contains two Higgs doublets and no singlet. However, having a singlet field may well be motivated from various standpoints in particle physics, which could make the electroweak phase transition strongly first order. It should be noted that the chargino sector relevant to our discussions does not depend much on whether the SSM has a singlet or not, so that our analyses are mostly applicable to both cases. The baryon asymmetry could also be generated by the neutralinos which consist of neutral SU(2) U(1) gauginos and Higgsinos. This neutralino contribution would be at most the same order of magnitude as the chargino contribution.

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FIGURES

FIG. 1. The CP asymmetries for the reflections and transmissions at the bubble wall as functions of the particle energy: (a) $A_1$, (b) $A_1'$, (c) $A_2'$. The parameter values are taken for $\tau = 4$, $\tan = 2$, $m_2 = j m_H j = 200 \text{ GeV}$, and $W = 1200 \text{ (GeV)}$. 

FIG. 2. The ratio of baryon number to entropy as a function of $m_2 = j m_H j$: (a) $= 4$, (b) $= 0.1$. The values of $W$ and $W$ for curves (1a)-(iiib) are given in Table I. The other parameters are taken for $\tan = 2$ and $T = 200 \text{ GeV}$. 

FIG. 3. The ratio of baryon number to entropy as a function of $m_2 = j m_H j$ for (i) $T = 100 \text{ GeV}$ and (ii) $T = 200 \text{ GeV}$. The parameters are taken for $\tan = 2$, $m_2 = j m_H j = 200 \text{ GeV}$, $v = 0.6$, and $W = 1200 \text{ GeV}$. 

FIG. 4. The electric dipole moment of the neutron as a function of $m_2 = j m_H j$. The values of $W$ and the squark mass for curves (i)-(iv) are given in Table III.
TABLE I. The values of $v_W$ and $W_\gamma$ for curves (ia)-(iib) in Fig. 2.

|       | (ia) | (ib) | (iii) | (iib) |
|-------|------|------|-------|-------|
| $v_W$ | 0.1  | 0.1  | 0.6   | 0.6   |
| $W_\gamma$ | 1/T | 5/T | 1/T   | 5/T   |

TABLE II. The values of $\lambda$ and the squark mass for curves (i)-(iv) in Fig. 3.

|       | (i) | (ii) | (iii) | (iv) |
|-------|-----|------|-------|------|
| $\lambda$ | =4  | =4   | 0.1   | 0.1  |
| Squark mass (TeV) | 1   | 5    | 1     | 5    |
CP Asymmetry

Energy (GeV)
Baryon Number / Entropy \((1.0\times10^{-10})\)

\(\text{(i)}\)

\(\text{(ii)}\)

CP-violating phase
