Electroweak Baryogenesis from Chargino Transport in the Supersymmetric Model

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(Received July 22, 1997)

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 an electroweak anomaly. We show that the resultant ratio of the baryon number to the 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 suppressed too greatly. Compatibility with the constraints on the parameters from the electric dipole moment of the neutron is also discussed.

§1. Introduction

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, since all the necessary ingredients for baryogenesis could be available there. Although the standard model (SM) does not account for the asymmetry quantitatively, certain extensions of the SM would be able to overcome the 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 a sufficiently large amount of asymmetry between the numbers of baryons and antibaryons. The baryon asymmetry could be a unique phenomenon ever found, in addition to the \( K^0-K^0 \) 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, 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 needed for baryogenesis. In addition, the electroweak phase transition may be strongly first order in the SSM, which is also necessary for baryogenesis though not compatible with the Higgs boson mass in the SM. Indeed, the constraints on the Higgs boson masses from this requirement could be relaxed compared to the SM, owing to the richness of Higgs fields, in particular by adding a gauge singlet field. It would be thus of great importance to study whether electroweak baryogenesis is viable in the SSM.

Baryogenesis at the electroweak phase transition could occur within or outside
the bubble wall of the broken phase, where baryon number violation by an electroweak anomaly is not suppressed. We consider the baryon number generation outside the wall, which has been suggested to give a sufficiently large amount of asymmetry in the SSM.\(^6\),\(^7\) For this process the baryon number is well estimated through the charge transport mechanism.\(^6\),\(^8\) 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 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 baryogenesis could give nontrivial constraints on the SSM. Although baryogenesis within the wall might also be possible in the SSM,\(^9\) it has been generally shown that a sufficiently large amount of baryon asymmetry cannot be produced within the wall only.\(^10\)

In §2 we briefly review the source of \(CP\) violation in the chargino sector. In §3 we discuss \(CP\) asymmetries in the reflection and transmission rates for the charginos at the bubble wall. The procedure for computing these rates, which gives accurate results, is presented explicitly. In §4 we calculate the ratio of the baryon number to the entropy following the charge transport mechanism. The dependences of the ratio on various parameters are also analyzed. A summary is given in §5.

### §2. Supersymmetric model

A new source of \(CP\) violation in the SSM comes from the mass matrices of the \(SU(2) \times U(1)\) gauginos and Higgsinos. The mass terms for the charged gauginos \(\lambda^-\) and Higgsinos \(i\psi^c_1, (i\psi^c_2)^c\) are given by

\[
\mathcal{L} = - (\bar{\lambda}^- (i\psi^c_2)^c) M^- \frac{1 - \gamma_5}{2} \left( \begin{array}{c} \lambda^- \\ i\psi^c_1 \end{array} \right) + \text{h.c.,} \tag{2.1}
\]

\[
M^- = \begin{pmatrix}
\bar{m}_2 \\
-gv_2^*/\sqrt{2} \\
\end{pmatrix}
\begin{pmatrix}
-m_H \\
-m_H^* \\
\end{pmatrix}, \tag{2.2}
\]

where \(\bar{m}_2\) 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 superfields 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 (2.2) is diagonalized by unitary matrices \(C_R\) and \(C_L\) as

\[
C_R M^- C_L = \text{diag}(\bar{m}_w_1, \bar{m}_w_2), \quad (\bar{m}_w_1 < \bar{m}_w_2) \tag{2.3}
\]

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

In general, the parameters \(v_1, v_2, \bar{m}_2\) and \(m_H\) in the mass matrix (2.2) have complex values. Although there is some freedom of defining phases for the particle
fields, if the $SU(2) \times U(1)$ gauge symmetry is spontaneously broken, and thus $\nu_1$ and $\nu_2$ have non-vanishing values, the complex phases cannot all be rotated away. Redefinitions of the fields make it possible without loss of generality to take $\tilde{m}_2$, $\nu_1$ and $\nu_2$ as 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

$$m_H = |m_H| \exp(i\theta). \quad (2.4)$$

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.

In the bubble wall at the electroweak phase transition, the vacuum expectation values $\nu_1$ and $\nu_2$ depend on the space coordinates, changing from zero to the values in the broken phase. Accordingly, the mass matrix $M^-$, and thus the unitary matrices $C_L$ and $C_R$ vary with the coordinates. This causes $CP$ asymmetries of the reflection and transmission rates for gauginos and Higgsinos at the wall. It should be noted that in the ordinary scheme of the SSM, the complex phases of the parameters in Eq. (2.2) are independent of the space coordinates. Therefore the same redefinitions of the fields can be applied both in the broken phase and in the bubble wall, making it possible to take $\theta$ as a physical complex phase.

§3. $CP$ asymmetry

At the electroweak phase transition of the universe, if it is first order, bubbles of the broken phase nucleate in the $SU(2) \times U(1)$ 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 causes a difference in reflection and transmission probabilities 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 reflection 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

$$
\begin{pmatrix}
-i\partial/\partial t & \tilde{m}_2 & 0 & -g\nu_1^*/\sqrt{2} \\
-\tilde{m}_2^* & i\partial/\partial t & g\nu_2/\sqrt{2} & 0 \\
g\nu_1^*/\sqrt{2} & -i\partial/\partial t & -m_H^2 & i\partial/\partial t \\
g\nu_2/\sqrt{2} & 0 & m_H & i\partial/\partial t
\end{pmatrix}
\begin{pmatrix}
\lambda_1 \\
\lambda_2 \\
\psi_1 \\
\psi_3
\end{pmatrix}
= i\frac{\partial}{\partial z}
\begin{pmatrix}
\lambda_1 \\
\lambda_2 \\
\psi_1 \\
\psi_3
\end{pmatrix}, \quad (3.1)
$$
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 fields are expressed as

$$
\lambda^- = \begin{pmatrix}
\lambda_1 \\
\lambda_2 \\
\lambda_3 \\
\lambda_4
\end{pmatrix},
\frac{1 - \gamma_5}{2} i \psi^+ + \frac{1 + \gamma_5}{2} (i \psi^+)^c = \begin{pmatrix}
\psi_1 \\
\psi_2 \\
\psi_3 \\
\psi_4
\end{pmatrix}. 
$$

We have adopted the chiral representation for the Dirac $\gamma$ 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 $M_W = (g/2) \sqrt{|v_1|^2 + |v_2|^2}$. The vacuum expectation values vary along the $z$-axis in the wall. For simplicity, we assume that the wall extends from $z = 0$ to $z = 2 \delta_w$ and the $z$-dependences of $v_1$ and $v_2$ are given by

$$
\sqrt{|v_1|^2 + |v_2|^2} = \frac{M_W}{g} \left\{ 1 + \tanh \left( \frac{z}{\delta_w} - 1 \right) \pi \right\},
\frac{v_2}{v_1} = \tan \beta.
$$

where the ratio $v_2/v_1$ is taken to be constant and equal to its value $\tan \beta$ 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, as determined by angular momentum conservation. The boundary condition at $z = 0$ becomes

$$
\begin{pmatrix}
\lambda_1 \\
\lambda_3 \\
\psi_1 \\
\psi_3
\end{pmatrix} = \{ X_1(0) + AX_2(0) + BX_3(0) \} \exp(-iEt),
$$

$$
X_1(0) = \sqrt{\frac{E + p_\lambda}{2p_\lambda}} \begin{pmatrix}
1 \\
0 \\
0 \\
0
\end{pmatrix},
X_2(0) = \sqrt{\frac{E + p_\lambda}{2p_\lambda}} \begin{pmatrix}
\tilde{m}_2/(E + p_\lambda) \\
0 \\
0 \\
0
\end{pmatrix},
X_3(0) = \exp(-i\theta) \sqrt{\frac{E + p_\psi}{2p_\psi}} \begin{pmatrix}
0 \\
0 \\
m_H/(E + p_\psi) \\
1
\end{pmatrix},
$$

where $p_\lambda$ and $p_\psi$ represent 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 $z = 2\delta_w$ becomes
\[
\begin{pmatrix}
\lambda_1 \\
\lambda_3 \\
\psi_1 \\
\psi_3
\end{pmatrix} = \{CY_1(2\delta_w) + DY_2(2\delta_w)\} \exp(-iEt), \quad (3·7)
\]
\[
Y_1(2\delta_w) = \sqrt{\frac{E + p_1}{2p_1}} \begin{pmatrix}
C_{R11} \\
C_{L11} \tilde{m}_{\omega_1}/(E + p_1) \\
C_{R21} \\
C_{L21} \tilde{m}_{\omega_1}/(E + p_1)
\end{pmatrix} \exp(i2p_1\delta_w),
\]
\[
Y_2(2\delta_w) = \sqrt{\frac{E + p_2}{2p_2}} \begin{pmatrix}
C_{R12} \\
C_{L12} \tilde{m}_{\omega_2}/(E + p_2) \\
C_{R22} \\
C_{L22} \tilde{m}_{\omega_2}/(E + p_2)
\end{pmatrix} \exp(i2p_2\delta_w), \quad (3·8)
\]
where $p_1$ and $p_2$ represent 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 $z = 2\delta_w$ are obtained by numerically solving the differential equation (3·1). The reflection and transmission amplitudes $A$, $B$, $C$ and $D$ then satisfy the simultaneous equation
\[
X_1(2\delta_w) + AX_2(2\delta_w) + BX_3(2\delta_w) = CY_1(2\delta_w) + DY_2(2\delta_w), \quad (3·9)
\]
which is solved algebraically. The reliability of these numerical calculations may be checked by the sum $|A|^2 + |B|^2 + |C|^2 + |D|^2$, which is in excellent agreement with unity in our results.

We calculate the asymmetries of the transition rates between $CP$-conjugate processes
\[
A_\lambda = R(\lambda_{(+)} \to \psi_{(-)}) + R(\lambda_{(-)} \to \psi_{(+)}) - R(\lambda_{(-)} \to \bar{\psi}_{(+)}) - R(\bar{\lambda}_{(+)} \to \bar{\psi}_{(-)}),
\]
\[
A_{\omega_i} = R(\omega_{i(+)} \to \psi_{(+)}) + R(\omega_{i(-)} \to \psi_{(-)}) - R(\omega_{i(-)} \to \bar{\psi}_{(+)}) - R(\bar{\omega}_{i(+)} \to \bar{\psi}_{(-)}), \quad (3·10)
\]
where $\lambda$ and $\psi$ denote the gaugino and the Higgsino in the symmetric phase, respectively, and $\omega_i$ the chargino in the broken phase. The subscripts $(+)$ and $(-)$ refer to positive and negative helicities, respectively. If $CP$ is not violated, $A_\lambda$ and $A_{\omega_i}$ vanish. In Fig. 1 the absolute values of these $CP$ asymmetries are shown for (a) $A_\lambda$, (b) $A_{\omega_1}$ and (c) $A_{\omega_2}$ as functions of the particle energy $E$, taking $\theta = \pi/4$, $\tan \beta = 2$, $\tilde{m}_2 = |m_H| = 200$ GeV and $\delta_w = 1/200$ (GeV)$^{-1}$. The sign of $A_\lambda$ is negative for $E < \tilde{m}_{\omega_2}$ and positive for $E > \tilde{m}_{\omega_2}$, and those of $A_{\omega_1}$ and $A_{\omega_2}$ are positive and negative, respectively. The sum of $A_\lambda$, $A_{\omega_1}$ and $A_{\omega_2}$ vanishes by $CPT$ invariance. The $CP$ asymmetry $A_\lambda$ has values of order 0.1 for the energy range slightly beyond 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 $A_\lambda$ rather small in spite of an unsuppressed value for the $CP$-violating phase.
Fig. 1. The $CP$ asymmetries for the reflections and transmissions at the bubble wall as functions of the particle energy: (a) $A_x$, (b) $A_{w_1}$, (c) $A_{w_2}$. The parameter values are taken as $\theta = \pi/4$, $\tan \beta = 2$, $\bar{m}_2 = |m_H| = 200$ GeV and $\delta_W = 1/200$ (GeV)$^{-1}$. 
§4. Baryon asymmetry

The $CP$ asymmetries of the reflection 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 an electroweak anomaly. A simple procedure for relating the $CP$ asymmetries with the bias is to introduce chemical potentials for conserved and approximately conserved quantum numbers and set these quantum numbers to zero. This causes the chemical potential of the baryon number to be given by the hypercharge density, which is induced by the $CP$ asymmetries. Although this procedure may not be completely correct, it should 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) $\lambda \rightarrow \psi$, (ii) $\psi \rightarrow \lambda$, $\psi \rightarrow \omega_i$, (iii) $\omega_i \rightarrow \psi$, 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

$$f_s = \int \int \int_{D_s} \frac{d^3p}{(2\pi)^3} \left( \frac{p_z}{E_T} + v_W \right) \left[ \exp \left( \frac{E_T}{T} + 1 \right) \right]^{-1}, \quad \left( D_s : \frac{p_z}{E_T} + v_W > 0 \right)$$

$$f_b = -\int \int \int_{D_b} \frac{d^3p}{(2\pi)^3} \left( \frac{p_z}{E_T} + v_W \right) \left[ \exp \left( \frac{E_T}{T} + 1 \right) \right]^{-1}, \quad \left( D_b : \frac{p_z}{E_T} + v_W < 0 \right)$$

(4.1)

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 velocity $-v_W$ ($v_W > 0$). The net hypercharge flux therefore becomes

$$F_Y = F_\lambda + \sum_{i=1}^{2} F_{\omega_i},$$

$$F_\lambda = -\frac{1}{2} \frac{(1 - v_W^2)T}{(2\pi)^2} \int_{\tilde{m}_2}^{\infty} dE E \log \left[ 1 + \exp \left( \frac{-E - v_W \sqrt{E^2 - \tilde{m}_2^2}}{T \sqrt{1 - v_W^2}} \right) \right] A_\lambda,$$

$$F_{\omega_i} = -\frac{1}{2} \frac{(1 - v_W^2)T}{(2\pi)^2} \int_{\tilde{m}_{\omega_i}}^{\infty} dE \times E \log \left[ 1 + \exp \left( \frac{-E + v_W \sqrt{E^2 - \tilde{m}_{\omega_i}^2}}{T \sqrt{1 - v_W^2}} \right) \right] A_{\omega_i},$$

(4.2)
where $E$ represents $\sqrt{p_{\perp}^2 + m^2}$, $p_{\perp}$ 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 transitions among states of different baryon number, the rate equation of the baryon number density $\rho_B$ is given by

$$\frac{d\rho_B}{dt} = -\frac{\Gamma}{T}\mu_B,$$

where $\Gamma$ denotes the rate per unit time and unit volume for a transition between neighboring states differing by unity in baryon number, and $\mu_B$ represents the chemical potential of baryon number which represents a bias on the fluctuation of baryon number. In the symmetric phase, the rate $\Gamma$ is estimated as

$$\Gamma = 3\kappa(\alpha_W T)^4,$$

where $\kappa$ is of order unity. In the symmetric phase the gauge interactions and the $t$-quark Yukawa interactions are considered to be in chemical equilibrium. We also assume 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 sufficiently heavy. Before the net hypercharge flux 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

$$\mu_B = \frac{2\rho_Y}{7T^2},$$

where $\rho_Y$ represents the hypercharge density. The net hypercharge flux into the symmetric phase induces a net hypercharge density, which makes $\mu_B$ non-vanishing.

We now estimate the baryon number density $\rho_B$ from Eqs. (4.3) $\sim$ (4.5) as

$$\rho_B = \frac{2\Gamma}{7T^3} \int_{-\infty}^{1/v_W} dt \rho_Y(z - v_W t) = \frac{2\Gamma}{7T^3 v_W} \int_0^{\infty} dz \rho_Y(z) \approx \frac{2\Gamma F_Y \tau_T}{7T^3 v_W},$$

where $\tau_T$ is the time which carriers of the hypercharge flux spend in the symmetric phase. This transport time $\tau_T$ may be approximated by the mean free time of the carriers. A rough estimate for $\tau_T$ gives a value of order $10^2/T - 10^3/T$ for leptons, which would also be applicable to gauginos and Higgsinos. The ratio of the baryon number to the entropy is given by

$$\frac{\rho_B}{s} = \frac{135\kappa \alpha_W^4 F_Y \tau_T}{7\pi^2 g_s v_W T^2},$$
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![Graph showing the ratio of the baryon number to the entropy as a function of mass (GeV).](https://example.com/graph.png)

Fig. 2. The ratio of the baryon number to the entropy as a function of $m_2 (= |m_H|)$: (a) $\theta = \pi/4$, (b) $\theta = 0.1$. The values of $v_w$ and $\delta_w$ for curves (i.a)~(ii.b) are given in Table I. The other parameters are taken to be $\tan \beta = 2$ and $T = 200$ GeV.

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

We show the ratio of the baryon number to the entropy in Fig. 2 as a function of the mass parameter $m_2 (= |m_H|)$ for $\tan \beta = 2$ and (a) $\theta = \pi/4$ and (b) $\theta = 0.1$. For simplicity, we have taken the same value for $m_2$ and $|m_H|$. 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.\(^{14}\) The temperature is taken to be $T = 200$ GeV. The wall velocity $v_w$ and the wall width $\delta_w$ have been estimated in the SM as $v_w = 0.1 - 1$ and $\delta_w \sim 10/T$,\(^{15}\) although there are large uncertainties and model dependences. If the phase transition is strongly first order, the wall width generally becomes thinner. We take the four sets of values for
Table I. The values of $v_W$ and $\delta_W$ for curves (i.a)~(ii.b) in Fig. 2.

<table>
<thead>
<tr>
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<th>(i.a)</th>
<th>(i.b)</th>
<th>(ii.a)</th>
<th>(ii.b)</th>
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<tbody>
<tr>
<td>$v_W$</td>
<td>0.1</td>
<td>0.1</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>$\delta_W$</td>
<td>$1/T$</td>
<td>$5/T$</td>
<td>$1/T$</td>
<td>$5/T$</td>
</tr>
</tbody>
</table>

$v_W$ and $\delta_W$ listed in Table I, which correspond to the four curves (i.a)~(ii.b).

For definiteness we set the transport time to $\tau_T = 100/T$. The resultant ratio is approximately $10^{-10}$ for $\theta = \pi/4$ and $10^{-11}$ for $\theta = 0.1$. These values are consistent with the present observed value $\rho_B/s = (2 - 9) \times 10^{-11}$.\(^{14}\)

Except the CP-violating phase $\theta$, the ratio varies little with the SSM parameters $\tilde{m}_2$, $|m_H|$ and $\tan \beta$. In Fig. 3 the ratio of the baryon number to the entropy is shown as a function of $\theta$ for (i) $T = 100$ GeV and (ii) $T = 200$ GeV, taking $\tan \beta = 2$, $\tilde{m}_2 = |m_H| = 200$ GeV, $v_W = 0.6$ and $\delta_W = 1/T$. If the CP-violating phase is of order 0.01, a large value for $\tau_T$ of order $10^3/T$ barely gives a compatible value.

![Baryon Number / Entropy](image1.png)

**Fig. 3.** The ratio of the baryon number to the entropy as a function of $\theta$ for (i) $T = 100$ GeV and (ii) $T = 200$ GeV. The parameters are given by $\tan \beta = 2$, $\tilde{m}_2 = |m_H| = 200$ GeV, $v_W = 0.6$ and $\delta_W = 1/T$.

![Electric Dipole Moment of Neutron](image2.png)

**Fig. 4.** The electric dipole moment of the neutron as a function of $\tilde{m}_2(= |m_H|)$. The values of $\theta$ and the squark mass for curves (i)~(iv) are given in Table II.
Table II. The values of $\theta$ and the squark mass for curves (i)–(iv) in Fig. 4.

<table>
<thead>
<tr>
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<th>(i)</th>
<th>(ii)</th>
<th>(iii)</th>
<th>(iv)</th>
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<tbody>
<tr>
<td>$\theta$</td>
<td>$\pi/4$</td>
<td>$\pi/4$</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Squark mass (TeV)</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>

In the SSM the $CP$-violating phase $\theta$ gives large contributions to the electric dipole moments (EDMs) of the neutron and the electron at the one-loop level through the diagrams mediated by the charginos. In Fig. 4 the neutron EDM is shown as a function of $m_2(=|m_H|)$ for $\tan\beta = 2$. The four curves correspond to the four sets of values for $\theta$ 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 $10^{-25}$cm. In order to satisfy this bound, the squark mass should be around or larger than 1 TeV for $\theta \sim 0.1$ and 3 TeV for $\theta \sim 1$. Similar constraints are obtained on the sleptons from the EDM of the electron.

§5. Summary

We studied 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 due mainly to the fact that gauginos or Higgsinos incident on the wall from the symmetric phase can be transmitted to the broken phase, thus reducing the overall reflection rates in the wide region of parameter space. Assuming a moderate value for the transport time, the phase should be at least of order 0.1. If this is the case, the squark masses are predicted to be around or larger than 1 TeV from analysis of the EDM of the neutron.

Finally we make comments on some ambiguous points which have not been mentioned in the preceding sections. For the critical temperature, which should be of order 100 GeV, we have taken $T = 200$ GeV in most of our calculations. As shown in Fig. 3, the results are not altered significantly for $T = 100$ GeV. We have neglected thermal effects for the reflection and transmission rates of the charginos at the wall. Incorporating these effects could lead to some alterations of the results, which would nevertheless be within the range of approximation in our calculations. The value of $\kappa$ in Eq. (4-4) has not been well established, which is in proportion to the baryon asymmetry. Although our analyses have been performed for $\kappa = 1$, a recent study claims $\kappa < 0.1$. In this case the maximal value for the $CP$-violating phase $\theta$ can barely lead to a sufficient asymmetry. Another large uncertainty is in strong spharelon transitions. If these processes are fast enough to be in thermal equilibrium at the critical temperature, our results might be reduced by two orders of magnitude. Then, it would be difficult to account for the baryon asymmetry by chargino transport.

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 discussion does not depend strongly on whether the SSM has a singlet or not, so that our analyses are for the most part applicable to both cases. The baryon asymmetry could also be generated by the neutralinos which consist of neutral $SU(2) \times U(1)$ gauginos and Higgsinos. This neutralino contribution would be at most the same order of magnitude as the chargino contribution. Therefore, the sum of these two contributions would not be much different from the contribution of the charginos alone, unless they cancel out accidentally. Another possibility of baryogenesis is through top squark transport. However, if the squark masses are almost degenerated, as suggested by $N = 1$ supergravity, top squarks should have masses of around 1 TeV or larger. Then, the top squark contribution would give a baryon asymmetry much smaller than that generated by the charginos with their masses of order 100 GeV.

Acknowledgements

One of the authors (N. O.) thanks A. E. Nelson for informing him of Ref. 6). We thank T. Uesugi and K. Yamamoto for helpful discussions. This work is supported in part by the Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture (No. 08640357).

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