Electric Dipole Moments of Neutron and Electron
in Supersymmetric Model [1]

To the memory of Yoshiki Kizukuri

Mayumi Aoki*, Tomoko Kadoyoshi*, Akio Sugamoto
Department of Physics, Ochanomizu University
Otsuka 2-1-1, Bunkyo-ku, Tokyo 112, Japan

Noriyuki Oshimo
Institute for Cosmic Ray Research, University of Tokyo
Midori-cho 3-2-1, Tanashi, Tokyo 188, Japan

Abstract

The electric dipole moments (EDMs) of the neutron and the electron are reviewed within the framework of the supersymmetric standard model (SSM) based on grand unified theories coupled to $N=1$ supergravity. Taking into account one-loop and two-loop contributions to the EDMs, we explore SSM parameter space consistent with experiments and discuss predicted values for the EDMs. Implications of baryon asymmetry of our universe for the EDMs are also discussed.

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†Graduate School of Humanities and Sciences.
‡Research Fellow of the Japan Society for the Promotion of Science.
1 Introduction

Some extension of the standard model (SM) is expected from various viewpoints, among which is \( CP \) violation. The violation of \( CP \) invariance is observed through the phenomena in the \( K^0 - \bar{K}^0 \) system [1], which can be explained by the Kobayashi-Maskawa (KM) mechanism of the SM. However, it has been suggested that baryon asymmetry of the universe could not be explained without the existence of some new source of \( CP \) violation [2]. Therefore, various extensions of the SM have been proposed to account for the baryon asymmetry. One of the extended models having such new \( CP \)-violating sources is the supersymmetric standard model (SSM), which is also plausible for describing physics at the electroweak scale.

In this report we review the electric dipole moments (EDMs) of the neutron \( d_n \) and the electron \( d_e \) coming from the new sources of \( CP \) violation in the SSM based on grand unified theories (GUTs) coupled to \( N=1 \) supergravity [3]. These EDMs arise from one-loop diagrams in which the squarks \( \tilde{q} \) or sleptons \( \tilde{l} \) propagate together with the charginos \( \omega_i \), the neutralinos \( \chi_j \), or the gluinos \( \tilde{g} \) as shown in Fig. 1 [4, 5, 6]. The EDMs also receive contributions from two-loop diagrams containing an effective \( CP \)-violating coupling of the \( W \) bosons and photon [7, 8]. The relevant diagram is shown in Fig. 2. Since in the SM the EDMs are predicted to be much smaller than their present experimental upper bounds, \(|d_n| < 10^{-25}\) cm [9] and \(|d_e| < 10^{-26}\) cm [10], they can give us an important clue to new sources of \( CP \) violation. The new sources of \( CP \) violation in the SSM could account for the baryon asymmetry of the universe [11, 12, 13]. We also discuss its implications for the EDMs.

The SSM has at least two new \( CP \)-violating phases in addition to the KM phase [4]. One of these phases comes from the gauge-Higgs sector and another from the squark-slepton sector. If these phases are not suppressed, at the one-loop level the chargino contributions to the EDMs are larger than the neutralino or the gluino contributions in wide ranges of SSM parameter space. Comparing the chargino contributions with the experimental constraints, the squark and slepton masses are predicted to be larger than 1 TeV [4]. On the other hand, if the \( CP \)-violating phase in the gauge-Higgs sector is quite small while that in the squark-slepton sector being not suppressed, the gluino or the neutralino contributions become dominant. In this case the squark and slepton masses of order 100 GeV are not contradictory to the experimental constraints for the EDMs [13].

The new phase in the gauge-Higgs sector also induces the EDM of the \( W \)-boson through the one-loop diagram mediated by charginos and neutralinos [7, 8]. The \( W \)-
boson EDM, if exists, can generally yield the neutron and the electron EDMs by the
standard electroweak interactions at the one-loop level [14]. As a result the EDMs
of the neutron and the electron receive contributions at the two-loop level. The
EDMs by these two-loop contributions could be only smaller than the experimental
upper bounds by one order of magnitude [8]. In addition, the two-loop contributions
only depend on SSM parameters for the gauge-Higgs sector, whereas the one-loop
contributions depend on both the gauge-Higgs sector and the squark-slepton sector.
We can predict the values of the EDMs induced by the $W$-boson EDM with less
uncertainly.

In the SSM, baryon asymmetry of the universe may be generated by the $CP$
violating phases which induce the EDMs. Indeed, the ratio of baryon number to
entropy consistent with its observed value, $\rho_B/s = (2 - 9) \times 10^{-11}$ [15], is obtained
in reasonable ranges of SSM parameters [12, 13], if the $CP$-violating phases are not
suppressed. For these parameter ranges the EDMs are predicted to have sizable
values.

In Sec. 2 we summarize new origins of $CP$ violation in the SSM. The EDMs
of the quarks and the leptons can arise at the one-loop level, which are given and
numerically evaluated in Sec. 3. The EDMs by the two-loop effects are discussed
in Sec. 4. The new sources of $CP$ violation generate the baryon asymmetry, whose
constraints on the EDMs are shown in Sec. 5. A summary is given in Sec. 6.

2 Model

The SSM based on GUTs coupled to $N=1$ supergravity has several complex pa-
rameters in addition to the Yukawa coupling constants. In the model with minimal

Figure 1: The Feynman diagrams for the EDM of a quark or a lepton. Photon lines
are understood.
particle contents, these complex parameters which are possible new sources of CP violation are the SU(3), SU(2), and U(1) gaugino masses $\tilde{m}_3$, $\tilde{m}_2$, and $\tilde{m}_1$, respectively, the mass parameter $m_H$ in the bilinear term of Higgs superfields in superpotential, and the dimensionless parameters $A_f$'s and $B$ in the trilinear and bilinear terms of scalar fields.

The complex parameters lead to complex mass terms for supersymmetric particles. When the SU(2)$\times$U(1) gauge symmetry is broken, the mass matrices $M^-$ and $M^0$ for the charginos and the neutralinos become

$$M^- = \begin{pmatrix} \tilde{m}_2 & -g v_1^*/\sqrt{2} \\ -g v_2^*/\sqrt{2} & \tilde{m}_H \end{pmatrix},$$

$$M^0 = \begin{pmatrix} \tilde{m}_1 & 0 & g' v_1^*/2 & -g' v_2^*/2 \\ 0 & \tilde{m}_2 & -g v_1^*/2 & g v_2^*/2 \\ g' v_1^*/2 & -g v_1^*/2 & 0 & -m_H \\ -g' v_2^*/2 & g v_2^*/2 & -m_H & 0 \end{pmatrix},$$

where $v_1$ and $v_2$ are the vacuum expectation values of the two Higgs doublets with U(1) hypercharges $-1/2$ and $1/2$, respectively. These mass matrices are diagonalized by unitary matrices $C_R$, $C_L$, and $N$ as

$$C_R^t M^- C_L = \text{diag}(\tilde{m}_{\omega_1}, \tilde{m}_{\omega_2}),$$

$$N^t M^0 N = \text{diag}(\tilde{m}_{\chi_1}, \tilde{m}_{\chi_2}, \tilde{m}_{\chi_3}, \tilde{m}_{\chi_4}),$$

giving the mass eigenstates. For the mass parameters of the gauginos we assume the relation $(g^2/g_s^2)\tilde{m}_3 = \tilde{m}_2 = (3g^2/5g'^2)\tilde{m}_1$ suggested by GUTs.

Figure 2: The Feynman diagram for the EDM of a quark or a lepton which involves an effective CP-violating coupling for the $W$-bosons and photon.
For the squarks there are two species for each flavor, the left-handed squark \( \tilde{q}_L \) and the right-handed squark \( \tilde{q}_R \), corresponding to two chiralities of the quark. There also exist sleptons \( \tilde{l}_L \) and \( \tilde{l}_R \) similarly corresponding to the leptons. The mass-squared matrix for the squarks or sleptons with flavor \( f \) becomes

\[
\tilde{M}_f^2 = \begin{pmatrix}
  m_f^2 + \cos 2\beta (T^3_f - Q_f \sin^2 \theta_W)M_Z^2 + \tilde{M}_{fL}^2 & m_f(R_f m_H + A_f^* m_{3/2}) \\
  m_f(R_f^* m_H^* + A_f m_{3/2}) & m_f^2 + Q_f \cos 2\beta \sin^2 \theta_W M_Z^2 + \tilde{M}_{fR}^2
\end{pmatrix},
\]

\[
R_f = \frac{v_1}{v_2^2} \quad (T_{3f} = \frac{1}{2}), \quad \frac{v_2}{v_1^*} \quad (T_{3f} = -\frac{1}{2}),
\]

\[
\tan \beta = \left| \frac{v_2}{v_1} \right|.
\]

Here \( m_f \) represents a mass of the fermion \( f \), \( Q_f \) an electric charge of \( f \), and \( T_{3f} \) the third component of the weak isospin for the left-handed component of \( f \). The gravitino mass is denoted by \( m_{3/2} \), and \( \tilde{M}_{fL}^2 \) and \( \tilde{M}_{fR}^2 \) are mass-squared parameters for \( \tilde{f}_L \) and \( \tilde{f}_R \), respectively. Each mass-squared matrix for the squarks and the sleptons is diagonalized by a unitary matrix \( S_f \) as

\[
S_f^\dagger \tilde{M}_f^2 S_f = \text{diag}(\tilde{M}_{f1}^2, \tilde{M}_{f2}^2).
\]

We have neglected generation mixings.

All the complex phases of the parameters in Eqs. (1), (2), and (5) are not physical. By the redefinition of the fields we can take without loss of generality \( \tilde{m}_i \) \((i = 1 - 3)\), \( v_1 \), and \( v_2 \) for real and positive. Then the remaining parameters \( m_H \) and \( A_f \)'s cannot be made real, which are origins of \( CP \) violation. We express them as

\[
m_H = |m_H| \exp(i\theta),
\]

\[
A_f = A = |A| \exp(i\alpha).
\]

Since \( A_f \)'s are considered to have the same value of order unity at the grand unification scale, their differences at the electroweak scale are small and thus can be neglected.

### 3 EDM at one-loop level

The EDM of the quark receives contributions at the one-loop level from diagrams in which the charginos, neutralinos or gluinos are exchanged together with the squarks
Table 1: The values of $\tilde{m}_2 = |m_H|$ and $\tan \beta$ for curves (i.a)–(ii.b) in Fig. 3.

|       | (i.a) | (i.b) | (ii.a) | (ii.b) |
|-------|-------|-------|--------|--------|
| $\tilde{m}_2 = |m_H|$ (GeV) | 200   | 200   | 1000   | 1000   |
| $\tan \beta$       | 2     | 10    | 2      | 10     |

as shown in Fig. 1. The electron EDM is also induced by one-loop diagrams, where the charginos or neutralinos are exchanged together with the sleptons.

The EDM operator changes the chirality of the quark or the lepton. The gauginos couple the quark (lepton) to the squark (slepton) with the same chirality via the gauge interactions, while the Higgsinos couple the quark (lepton) to the squark (slepton) with the opposite chirality via the Yukawa interactions. Therefore the flip of the chirality can arise at the one-loop level from three origins as follows.

(i) One vertex of the loop diagram is a gauge interaction and the other is a Yukawa interaction. The gaugino and the Higgsino are mixed.

(ii) The two vertices are both gauge interactions. The scalar particles $\tilde{q}_L$ ($\tilde{l}_L$) and $\tilde{q}_R$ ($\tilde{l}_R$) are mixed.

(iii) The two vertices are both Yukawa interactions. The scalar particles are mixed.

The chargino-loop diagram originates in (i) and (iii), the gluino-loop diagram in (ii), and the neutralino diagram in all of these.

The relative magnitudes of the chargino, neutralino, and gluino contributions are crudely estimated by considering their origins. The gaugino-Higgsino mixing and the $\tilde{q}_L$-$\tilde{q}_R$ or $\tilde{l}_L$-$\tilde{l}_R$ mixing are respectively suppressed by roughly $M_W/\tilde{m}_\omega$ and $m_f/M_{\tilde{f}}$. The products for the coupling constants and suppression factor in the origins (i), (ii), and (iii) become $\alpha m_f/\tilde{m}_\omega$, $\alpha m_f/M_{\tilde{f}}$, and $\alpha m_{\tilde{f}}^3/M_W^2 M_{\tilde{f}}$, respectively, $\alpha$ being an appropriate fine structure constant. Therefore the EDM from the chargino contribution is proportional to $\alpha_2 m_f/\tilde{m}_\omega$, while that from the gluino contribution is proportional to $\alpha_s m_f/M_{\tilde{f}}$. If the squark and chargino masses satisfy the condition $M_{\tilde{f}} > (\alpha_s/\alpha_2)\tilde{m}_\omega$, the chargino contribution becomes larger than the gluino contribution. The neutralino contribution is the smallest among all the contributions and may be neglected, since the coupling strength of the neutralino is smaller than those of the gluino and the chargino.
The EDM of a quark or a lepton from the chargino contribution is given by

\[
d_f^C/e = \frac{\alpha_{EM}}{4\pi \sin^2 \theta_W} R_f \sin \theta \frac{\tilde{m}_2 |m_H|}{(\tilde{m}_{\omega_2}^2 - \tilde{m}_{\omega_1}^2) M_{\tilde{f}}^2} \times \sum_{i=1}^{2} (-1)^i [Q_{\tilde{f}}^i I \left(\frac{\tilde{m}_{\omega_2}^2}{M_{\tilde{f}}^2}\right) + (Q_f - Q_{\tilde{f}}) J \left(\frac{\tilde{m}_{\omega_3}^2}{M_{\tilde{f}}^2}\right)],
\]

(9)

where

\[
I(r) = \frac{1}{2(1-r)^2} \left(1 + r + 2 \frac{r}{1-r} \ln r\right),
\]

\[
J(r) = \frac{1}{2(1-r)^2} \left(3 - r + 2 \frac{2}{1-r} \ln r\right).
\]

Here we have neglected the tiny contribution from the origin (iii) and approximated the masses of two mass eigenstates of the squarks or the sleptons to have the same value \(M_{\tilde{f}} \equiv M_{\tilde{f}_1} \approx M_{\tilde{f}_2}\). For a crude estimate of the chargino contribution, we note that the numerical value of a factor in Eq. (9) is written by

\[
\frac{\alpha_{EM}}{4\pi \sin^2 \theta_W} \frac{m_f}{M_{\tilde{f}}^2} = 5.0 \times 10^{-25} \left(\frac{1 \text{ TeV}}{M_{\tilde{f}}^2}\right)^2 \left(\frac{m_f}{10 \text{ MeV}}\right) \text{ cm},
\]

(10)

and \(I(r)\) and \(J(r)\) vary as \(5 \times 10^{-1} - 5 \times 10^{-3}\) and \(-3 - (-5) \times 10^{-3}\), respectively, for \(10^{-2} < r < 10^2\). If the \(CP\)-violating phase \(\theta\) is not suppressed, the squark or
slepton masses or the chargino masses have to be larger than 1 TeV for satisfying the experimental constraints on the EDMs of the neutron and the electron.

The EDM of a quark from the gluino contribution is given by

$$d^G_q/e = \frac{2\alpha_s}{3\pi} \left( \sin \alpha |A| - R_q \sin \theta \frac{|m_H|}{m_{3/2}} \right) \frac{m_{3/2} m_q M_{\tilde{q}}}{M_{\tilde{Q}} \tilde{M}_{\tilde{q}}} Q_q \tilde{M}_{\tilde{q}} K \left( \frac{m_{\tilde{q}}^2}{\tilde{M}_{\tilde{q}}^2} \right),$$

(11)

where $M_{\tilde{q}}$ denotes the average of $M_{\tilde{q}1}$ and $M_{\tilde{q}2}$. Although the factor $2\alpha_s/3\pi$ is about ten times larger than the factor $\alpha_{EM}/4\pi \sin^2 \theta_W$, the function $\sqrt{r} K(r)$ takes a value about ten times smaller than $I(r)$ or $J(r)$, $-1 \times 10^{-1} < \sqrt{r} K(r) < -2 \times 10^{-3}$, for $10^{-2} < r < 10^2$. Therefore, the constraints from the gluino contribution are similar to those from the chargino contribution.

We evaluate the supersymmetric contributions to the EDM of the neutron. Assuming the nonrelativistic quark model, the EDMs of the $u$ and $d$ quarks are converted into the EDM of the neutron: $d_n = (4d_d - d_u)/3$. The mass parameters $M_{\tilde{f}L}$ and $M_{\tilde{f}R}$ appearing in Eq. (3) could be related to the gravitino mass and the gaugino masses. In the ordinary scheme for the mass generation, the gaugino masses are

Figure 4: The three contributions to the neutron EDM for $\tan \beta = 2$ and $m_2 = |m_H| = 500$ GeV: (i) chargino, (ii) neutralino, (iii) gluino. The absolute values of the EDM are shown.
Figure 5: The neutron EDM as a function of \( m_{3/2} \) for \( \alpha = \pi/4 \) and \( \theta = 0 \). Three curves correspond to three values for \( \tilde{m}_2 \) : (i) 200 GeV, (ii) 500 GeV, (iii) 1 TeV. The other parameters are taken for \( \tan \beta = 2 \) and \( |m_H| = 200 \text{ GeV} \).

smaller than or around the gravitino mass, so that a scale characteristic of \( M_{\tilde{f}_L} \) and \( M_{\tilde{f}_R} \) is given by \( m_{3/2} \). For simplicity, we take \( M_{\tilde{u}_L} = M_{\tilde{u}_R} = M_{\tilde{d}_L} = M_{\tilde{d}_R} = m_{3/2} \). Then the masses of the squarks can be estimated approximately by \( m_{3/2} \). The magnitude of the Higgsino mass parameter \( |m_H| \) should be at most of order \( m_{3/2} \) for correctly breaking the SU(2)×U(1) symmetry. As a typical example for a natural magnitude of the \( CP \)-violating phases, we simply take \( \theta = \alpha = \pi/4 \). The absolute value of the dimensionless parameter \( A \) is fixed as \( |A| = 1 \).

In Fig. 3 the absolute value of the chargino contribution to the EDM of the neutron is plotted as a function of \( m_{3/2} \). The values of the mass parameters and \( \tan \beta \) are given in Table 1. In the ranges of \( m_{3/2} \) where curves are not drawn, the lightest squark is lighter than the lightest neutralino, which is disfavored by cosmology. In the presented parameter regions the gluino and the neutralino contributions are smaller than the chargino contribution, so that the EDM of the neutron is given by \( d_n \approx d_n^C \). Not to be conflict with the experimental upper bound of \( |d_n| < 10^{-25} \text{ ecm} \), we must have \( m_{3/2} \geq 3 \text{ TeV} \) for \( \tan \beta = 2 \) and \( m_{3/2} \geq 7 \text{ TeV} \) for \( \tan \beta = 10 \). The clear dependence on \( \tan \beta \) arises from the dominance of the \( d \)-quark EDM over the \( u \)-quark EDM. Since the former is proportional to \( \tan \beta \), the neutron EDM increases.
as $\tan \beta$ becomes large.

The difference between the three contributions of the chargino, the neutralino, and the gluino can be seen in Fig. 4, where $|d_C^n|$, $|d_N^n|$, and $|d_G^n|$ are shown as functions of $m_{3/2}$ for $\tan \beta = 2$ and $\tilde{m}_2 = |m_H| = 500$ GeV. The sign of the neutron EDM from the gluino contribution changes at $m_{3/2} \approx 800 - 900$ GeV owing to the interference of the two $CP$-violating phases $\theta$ and $\alpha$. This figure clearly shows that the charginos really give the largest contribution to $d_n$. Since $d_C^n$ is dominant, the EDM of the neutron is roughly proportional to $\sin \theta$ as seen from Eq. (4), and does not depend much on $\alpha$.

The electron EDM induced through one-loop diagrams has a value smaller than the neutron EDM by one order of magnitude. This difference comes simply from the difference between the masses of the electron and the $d$ quark. The electron EDM satisfies the constraint $|d_e| < 10^{-26} e\ cm$ in the ranges $m_{3/2} \gtrsim 1$ TeV and $m_{3/2} \gtrsim 4$ TeV for $\tan \beta = 2$ and $\tan \beta = 10$, respectively. Similarly to the neutron EDM, the electron EDM increases as $\tan \beta$ becomes large.

The EDMs of the neutron and the electron decrease as the phases $\theta$ and $\alpha$ become small. If $\theta$ is much smaller than $\alpha$, the EDMs of the neutron and the electron receive dominant contributions from the gluino-loop and the neutralino-loop diagrams, respectively. Then the constraints of the EDMs on the SSM parameters become relaxed. In Fig. 5 the neutron EDM is shown as a function of the gravitino mass for $\alpha = \pi/4$ and $\theta = 0$, taking three values for $\tilde{m}_2$ : (i) 200 GeV, (ii) 500 GeV, (iii) 1 TeV. The other parameters are fixed as $\tan \beta = 2$ and $|m_H| = 200$ GeV. In the ranges of the gravitino mass where curves are not drawn, the lightest squark is lighter than either 45 GeV or the lightest neutralino. For 500 GeV $\lesssim \tilde{m}_2$ the magnitude of the neutron EDM is below the experimental upper bound even if $m_{3/2}$ is of order 100 GeV.

4 EDM at two-loop level

The neutron and the electron EDMs are generated at the two-loop level through the $W$-boson EDM which is induced by the one-loop diagram mediated by the charginos and neutralinos as shown in Fig. 2. At the two-loop level there also exist diagrams which involve squarks or sleptons and make contributions to the quark or lepton EDM. However, as long as the squarks and sleptons are much heavier than the charginos and neutralinos, these diagrams can be safely neglected.
Table 2: The values of $\tilde{m}_2$ and $\tan \beta$ for curves (i.a)–(ii.b) in Fig. 6.

|       | (i.a) | (i.b) | (ii.a) | (ii.b) |
|-------|-------|-------|--------|--------|
| $\tilde{m}_2$ (GeV) | 200   | 200   | 500    | 500    |
| $\tan \beta$      | 2     | 10    | 2      | 10     |

The EDM of a quark or a lepton from the two-loop diagram is given by

$$d_f = \mp e \left( \frac{\alpha_{EM}}{4\pi \sin^2 \theta_W} \right)^2 \sum_{i=1}^{4} \sum_{j=1}^{4} \text{Im}(G_{Lji}^* G_{Rji}) \frac{\tilde{m}_{\omega i} \tilde{m}_{\chi j} m_f}{M_{W_i}^2 M_{W_j}^2} \right.$$

$$\left[ \frac{1}{2(1-r'_f)^2} \int_0^1 ds \left\{ \frac{3-r'_f}{1-r'_f K_{ij} - r'_f} + \frac{1}{(K_{ij} - r'_f)^2} \right\} r'_f \ln \frac{r'_f}{K_{ij}} + \left( \frac{1}{K_{ij} - r'_f} + \frac{1}{K_{ij} - 1} \right) r'_f \right] \ln \frac{1}{K_{ij}}$$

$$K_{ij} = \frac{r_{\omega i}}{s} + \frac{r_{\chi j}}{1-s},$$

$$r'_f = \frac{m_{W_i}^2}{M_{W_i}^2}, \quad r_{\omega i} = \frac{\tilde{m}_{\omega i}^2}{M_{W_i}^2}, \quad r_{\chi j} = \frac{\tilde{m}_{\chi j}^2}{M_{W_j}^2},$$

where the coefficients $G_L$ and $G_R$ are defined as

$$G_{Lji} = \sqrt{2} N_{2j}^* C_{L1i} + N_{3j}^* C_{L2i},$$

$$G_{Rji} = \sqrt{2} N_{2j}^* C_{R1i} - N_{4j}^* C_{R2i}.$$  \hspace{1cm} (13)

The negative and positive signs of Eq. (12) are, respectively, for the fermions with the weak isospins $1/2$ and $-1/2$. This two-loop contribution only depends on the parameters $\tan \beta$, $\tilde{m}_2$, and $m_H$ contained in the gauge-Higgs sector.

In Fig. 6 the absolute value of the neutron EDM induced by the $W$-boson EDM is shown as a function of $|m_H|$. For $\tilde{m}_2$ and $\tan \beta$ we have taken four sets of values given in Table 2. The $CP$-violating phase is fixed as $\theta = \pi/4$. In the ranges of $|m_H|$ where curves are not drawn, the lighter chargino has a mass smaller than 45 GeV which has been ruled out by LEP experiments. For $\tilde{m}_2$, $|m_H| \sim 100$ GeV and $\tan \beta \sim 1$, the magnitude of the neutron EDM is around $10^{-26}$ ecm, which is smaller than the present experimental upper bound by only one order of magnitude. The EDM of the neutron decreases as $\tilde{m}_2$ or $|m_H|$ increases. Since the squarks have masses larger than 1 TeV for $\theta \sim 1$, the contributions to the neutron EDM from
two-loop diagrams mediated by the squarks are negligible. The EDM of the electron induced by the $W$-boson EDM has a value smaller than the neutron EDM by one order of magnitude, similarly depending on the SSM parameters.

The neutron and electron EDMs at the two-loop level do not vary with the squark and slepton masses if these masses are enough heavy. On the other hand, the one-loop contributions to the EDMs decrease, as the squark and slepton masses become large. If the squarks and sleptons have masses around 10 TeV, the two-loop contributions become comparable with the one-loop contributions. Furthermore, it turns out that these one-loop and two-loop contributions to the EDM of the neutron or the electron have the same sign. Therefore, the neutron and electron EDMs arising from the two-loop diagrams give theoretical lower bounds for given parameter values of the gauge-Higgs sector.

5 Constraints from baryon asymmetry

The $CP$-violating phase $\theta$ could induce baryon asymmetry of the universe through the charge transport mechanism [16] mediated by the charginos. Assuming that the electroweak phase transition of the universe is first order, bubbles of the broken
phase nucleate in the symmetric phase. The charginos incident on the bubble wall from the symmetric phase or the broken phase are reflected or transmitted to the symmetric phase. In these processes \(CP\) violation makes differences in reflection or transmission probability between a particle state and its \(CP\)-conjugate state, leading to a net density of hypercharge. Equilibrium conditions in the symmetric phase are then shifted to favor a non-vanishing value for baryon asymmetry, which is realized through electroweak anomaly. The \(CP\)-violating phase \(\alpha\) also enables the \(t\) squarks to assume the role of the mediator for the charge transport mechanism.

An enough amount of baryon asymmetry can be induced by the chargino transport, if the phase \(\theta\) is not suppressed and the chargino masses are of order 100 GeV. In this case the squark and slepton masses are larger than 1 TeV. The neutron EDM is then predicted to be \(10^{-25} - 10^{-26}\) e cm for \(1 \text{ TeV} \lesssim M_\tilde{q} \lesssim 10 \text{ TeV}\) as shown in Fig. 3. If \(\theta\) is much smaller than unity while \(\alpha\) being not suppressed, the \(t\) squarks with their masses of order 100 GeV can generate an enough amount of the asymmetry. In this case the masses of the other squarks and sleptons are also of order 100 GeV. The EDM of the neutron is predicted to be \(10^{-25} - 10^{-26}\) e cm for \(500 \text{ GeV} \lesssim \tilde{m}_2 \lesssim 1 \text{ TeV}\) as shown in Fig. 5. If the baryon asymmetry originates in the new sources of \(CP\) violation in the SSM, the neutron EDM has a magnitude which can be explored in the near future. The electron EDM is also predicted not to be much smaller than its experimental upper bound.

6 Summary

We have discussed the EDMs of the neutron and the electron in the SSM, under the assumption of GUTs and \(N=1\) supergravity. The SSM has two \(CP\)-violating phases \(\theta\) and \(\alpha\) intrinsic in the model. These EDMs receive contributions at the one-loop level from the diagrams in which the charginos, neutralinos or gluinos are exchanged together with the squarks or sleptons. Among these contributions the chargino contribution dominates over the gluino and neutralino contributions in wide ranges of the parameter space. If the \(CP\)-violating phase \(\theta\) is of order unity, the experimental constraints on the neutron and the electron EDMs give the prediction that the squarks and sleptons are heavier than 1 TeV.

The EDMs also receive contributions at the two-loop level induced by the \(W\)-boson EDM. If the squarks and sleptons are much heavier than the charginos and neutralinos, other two-loop diagrams with the squarks or sleptons are neglected, which may be indeed the case for \(\theta\) of order unity and thus the squark and slepton
masses larger than 1 TeV. Since the two-loop contributions by the $W$ boson EDM do not depend on the squark or slepton masses, the resultant values of the EDMs are less ambiguous than the one-loop contributions. The neutron and the electron EDMs induced at the two-loop level are around $10^{-26} \text{ ecm}$ and $10^{-27} \text{ ecm}$, respectively, for the chargino and the neutralino masses of order 100 GeV.

We have also discussed the relation between the EDMs and baryon asymmetry of the universe. If $\theta$ or $\alpha$ are not much suppressed, the charginos or the $t$ squarks with their masses of order 100 GeV can mediate the charge transport mechanism to generate the asymmetry consistent with its observed value. Then it is likely that the neutron and electron EDMs have magnitudes of $10^{-25} - 10^{-26} \text{ ecm}$ and $10^{-26} - 10^{-27} \text{ ecm}$, respectively. These numerical outcomes are not so small compared to the experimental upper bounds at present, and thus may be accessible in near future experiments.

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