Hadronic EDMs in SUSY SU(5) GUTs with Right-handed Neutrinos

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Abstract

We discuss hadronic EDM constraints on the neutrino sector in the SUSY SU(5) GUT with the right-handed neutrinos. The hadronic EDMs are sensitive to the right-handed down-type squark mixings, especially between the second and third generations and between the first and third ones, compared with the other low-energy hadronic observables, and the flavor mixings are induced by the neutrino Yukawa interaction. The current experimental bound of the neutron EDM may imply that the right-handed tau neutrino mass is smaller than about $10^{14}$ GeV in the minimal supergravity scenario, and it may be improved furthermore in future experiments, such as the deuteron EDM measurement.
The supersymmetric grand unified models (SUSY GUTs) are ones of the well-motivated models after discovery of the gauge coupling unification at the LEP experiment. Non-vanishing light neutrino masses shown in the neutrino oscillation experiments might also suggest existence of the SUSY GUTs since the right-handed neutrino masses expected from the measurements are near the GUT scale in the seesaw mechanism [1]. Nowadays many efforts are devoted to search for the next signature from both theoretical and experimental sides.

It is well-known that the SUSY GUTs predict rich flavor violation in the SUSY breaking terms for the squarks and sleptons when origin of the SUSY breaking is the dynamics above the GUT scale, such as the gravity mediation [2, 3]. In the minimal SUSY standard model (MSSM), the sizable flavor-violating SUSY breaking terms for the left-handed squarks are induced by the large top-quark Yukawa coupling, and those for the left-handed sleptons may be also generated by the neutrino Yukawa interaction in the SUSY seesaw mechanism [4, 5]. In the SUSY GUTs the flavor-violating SUSY breaking terms for the SU(5) partners of the left-handed squarks or sleptons, right-handed squarks and sleptons, are generated by the flavor-violating interactions for the colored Higgs multiplets, that are also SU(5) partners of the doublet Higgs multiplets. This gives a chance to probe the interactions at the GUT scale by the low-energy flavor-changing processes, such as $K^0$–$\bar{K}^0$ mixing, $B$ physics, and lepton flavor violation.

On the other hand, the colored Higgs interactions may have the CP-violating phases, which are independent of the CKM phase in the MSSM. The CP-violating phases may contribute to the electric dipole moments (EDMs) of electron, neutron and atoms [6, 7, 8, 9] via the flavor-violating SUSY breaking terms. While the EDMs are flavor-conserving processes, they may depend on the flavor-violating SUSY breaking terms in the squark or slepton internal lines. Moreover, since both the left-handed and right-handed squarks or sleptons have the flavor-violating SUSY breaking mass terms in the SUSY GUTs, the EDMs are enhanced by the heavier fermion masses. Thus, the EDMs are good probes for the SUSY GUTs.

In this paper we discuss the hadronic EDMs in the SUSY SU(5) GUT with the right-handed neutrinos. The neutrino Yukawa coupling generates the flavor-violating SUSY breaking terms for the right-handed down-type squarks, which are SU(5) partners of the
left-handed sleptons. This implies that we can investigate the neutrino sector by the hadronic EDMs. We show that the structure in the neutrino sector is more constrained by the current experimental bounds for the hadronic EDMs than by the other hadronic observables. As shown in Ref. [8, 10, 11], the hadronic EDMs depend on the chromoelectric dipole moment (CEDM) for the strange quark in addition to those for the up and down quarks. It implies that the hadronic EDMs give the strong constraints on the mixings for the right-handed down-type squarks between the first and third and between the second and third generations.

A new technique for measurement of the deuteron EDM is proposed recently [12], and the sensitivity may reach to \( d_D \sim (1 - 3) \times 10^{-27} \text{e cm} \). We show the sensitivity of the experiment to the SUSY SU(5) GUT with the right-handed neutrinos. We also discuss dependence of the prediction for the hadronic EDMs on the SUSY breaking models.

First, we review the flavor structure in the squark and slepton mass matrices in the SUSY SU(5) GUT with the right-handed neutrinos. The Yukawa interactions for quarks and leptons and the Majorana mass terms for the right-handed neutrinos in this model are given by the following superpotential,

\[
W = \frac{1}{4} f_{ij}^u \Psi_i \Psi_j H + \sqrt{2} f_{ij}^d \Psi_i \Phi_j H + f_{ij}^\nu \Phi_i \mathcal{N}_j H + M_{ij} \mathcal{N}_i \mathcal{N}_j,
\]

where \( \Psi \) and \( \Phi \) are for 10- and \( \bar{5} \)-dimensional multiplets, respectively, and \( \mathcal{N} \) is for the right-handed neutrinos. \( H (\bar{H}) \) is 5- (\( \bar{5} \)-) dimensional Higgs multiplets. After removing the unphysical degrees of freedom, the Yukawa coupling constants in Eq. (1) are given as follows,

\[
\begin{align*}
    f_{ij}^u &= V_{ki} f_{uk} e^{i\varphi_u} V_{kj}, \\
    f_{ij}^d &= f_d \delta_{ij}, \\
    f_{ij}^\nu &= e^{i\varphi_d} U_{ij}^* f_{ij},
\end{align*}
\]

(2)

Here, \( \varphi_u \) and \( \varphi_d \) are CP-violating phases inherent in the SUSY SU(5) GUT. They satisfy \( \sum_i \varphi_{f_i} = 0 \) (\( f = u \) and \( d \)). The unitary matrix \( V \) is the CKM matrix in the extension of the SM to the SUSY SU(5) GUT, and each unitary matrices \( U \) and \( V \) have only a phase. When the Majorana mass matrix for the right-handed neutrinos is diagonal in the basis of Eq. (2), \( U \) is the MNS matrix observed in the neutrino oscillation. In this paper we
assume the diagonal Majorana mass matrix in order to avoid the complexity due to the structure. In this case the light neutrino mass eigenvalues are given as

\[ m_{\nu_i} = \frac{f_i^2}{M_{N_i}} \langle H_f \rangle^2 \]  

(3)

where \( H_f \) is a doublet Higgs in \( H \).

The colored Higgs multiplets \( H_c \) and \( \overline{H}_c \) are introduced in \( H \) and \( \overline{H} \) as SU(5) partners of the Higgs doublets in the MSSM, respectively. They have new flavor-violating interactions in Eq. (1). If the SUSY-breaking terms in the MSSM are generated by dynamics above the colored Higgs masses, such as in the gravity mediation, the sfermion mass terms may get sizable corrections by the colored Higgs interactions. The interactions are also baryon-number violating, and then proton decay induced by the colored Higgs exchange is a serious problem, especially in the minimal SUSY SU(5) GUT \[13\]. However, it depends on the detailed structure in the Higgs sector \[14, 15\]. Thus, we ignore the proton decay while we adopt the minimal Yukawa structure in Eq. (1).

In the minimal supergravity scenario the SUSY breaking terms are supposed to be given at the reduced Planck mass scale (\( M_G \)). In this case, the flavor-violating SUSY breaking mass terms at low energy are induced by the radiative correction, and they are qualitatively given in a flavor basis as

\[
(m_{\tilde{q}_L}^2)_{ij} \simeq -V_{i3}V_{j3}^* \frac{f_b^2}{(4\pi)^2} \left(3m_0^2 + A_0^2\right) \left(2 \log \frac{M_G^2}{M_{H_c}^2} + \log \frac{M_{H_c}^2}{M_{SUSY}^2}\right),
\]

\[
(m_{\tilde{u}_R}^2)_{ij} \simeq -e^{-i\varphi_{u_{ij}}} V_{i3}^* V_{j3} \frac{f_b^2}{(4\pi)^2} \left(3m_0^2 + A_0^2\right) \log \frac{M_G^2}{M_{H_c}^2},
\]

\[
(m_{\tilde{d}_L}^2)_{ij} \simeq -V_{i3}^* V_{j3} \frac{f_t^2}{(4\pi)^2} \left(3m_0^2 + A_0^2\right) \left(3 \log \frac{M_G^2}{M_{H_c}^2} + \log \frac{M_{H_c}^2}{M_{SUSY}^2}\right),
\]

\[
(m_{\tilde{d}_R}^2)_{ij} \simeq -e^{i\varphi_{d_{ij}}} U_{ik}^* U_{jk} \frac{f_b^2}{(4\pi)^2} \left(3m_0^2 + A_0^2\right) \log \frac{M_G^2}{M_{H_c}^2},
\]

\[
(m_{\tilde{l}_L}^2)_{ij} \simeq -U_{ik}^* U_{jk} \frac{f_e^2}{(4\pi)^2} \left(3m_0^2 + A_0^2\right) \log \frac{M_G^2}{M_{N_k}^2},
\]

\[
(m_{\tilde{e}_R}^2)_{ij} \simeq -e^{i\varphi_{e_{ij}}} V_{i3}^* V_{j3} \frac{3f_t^2}{(4\pi)^2} \left(3m_0^2 + A_0^2\right) \log \frac{M_G^2}{M_{H_c}^2},
\]

(4)

with \( i \neq j \), where \( \varphi_{u_{ij}} \equiv \varphi_{u_i} - \varphi_{u_j} \) and \( \varphi_{d_{ij}} \equiv \varphi_{d_i} - \varphi_{d_j} \) and \( M_{H_c} \) is the colored Higgs mass. Here, \( M_{SUSY} \), \( m_0 \) and \( A_0 \) are the SUSY-breaking scale in the MSSM and the
universal scalar mass and trilinear coupling, respectively. $f_t$ is the top quark Yukawa coupling constant while $f_b$ is for the bottom quark. As mentioned above, the off-diagonal components in the right-handed squarks and sleptons mass matrices are induced by the colored Higgs interactions, and they depend on the CP-violating phases in the SUSY SU(5) GUT with the right-handed neutrinos [16].

When both the left-handed and right-handed squarks have the off-diagonal components in the mass matrices, the EDMs and CEDMs for the light quarks are enhanced significantly by the heavier quark mass. The CEDMs are generated by the diagram in Fig. 1. In the SUSY SU(5) GUT with the right-handed neutrinos, the neutrino Yukawa coupling induces the flavor-violating mass terms for the right-handed down-type squarks. Since the flavor-violating mass terms for the left-handed down-type squarks are expected to be dominated by the radiative correction induced by the top quark Yukawa coupling as in Eq. (4), we can investigate or constrain the structure in the neutrino sector.

The CEDMs for the light quarks, including the strange quark, contribute to the hadronic EDMs since the CP-violating nucleon coupling is induced. Here, we consider only the CEDMs for the light quarks.\footnote{In Ref. [8], the hadronic EDMs are discussed in the SUSY SO(10) GUT, including down and strange CEDMs.} While the EDMs for the up and down quarks contribute to the neutron EDM, we find that the EDM contributions are a factor smaller than the CEDM contributions. In this evaluation we use the prediction of non-relativistic quark model for the light quark EDM contribution to neutron EDM and the estimation by the chiral Lagrangian for the CEDM contribution [11]. While the ratio may suffer from the theoretical uncertainties, it is safe to ignore the light quark EDM contribution for the purpose of the demonstration of the hadronic EDM sensitivity. The EDM of $^{199}$Hg atom, which is not sensitive to the quark EDMs, also gives similar bounds on the CEDMs to the neutron EDM as shown later.

The CEDMs of the light quarks derived by the flavor violation in the both the left-handed and right-handed quark mass matrices are given by the following dominant con-
tribution, which is enhanced by the heavier quark masses,\(^2\)

\[
d^C_{q_i} = c \frac{\alpha_s m_{\tilde{g}}}{4\pi m_{\tilde{g}}^2} f \left( \frac{m_{\tilde{g}}^2}{m_{\tilde{g}}^2} \right) \text{Im} \left[ \left( \delta^q_{ij} \right)_L \left( \delta^q_{ij} \right)_{LR} \right],
\]

(5)

where \(m_{\tilde{g}}\) and \(m_{\tilde{q}}\) are the gluino and averaged squark masses and \(c\) is the QCD correction, \(c \sim 0.9\). The mass insertion parameters are defined as

\[
\begin{align*}
(\delta^f_{ij})_{L/R} & \equiv \frac{(m^2_{f_{L/R}})_{ij}}{(m^2_f)}, \\
(\delta^d_{ij})_{LR} & \equiv \frac{m_d (A^d_{i} - \mu \tan \beta)}{m_d^2}, \\
(\delta^u_{ij})_{LR} & \equiv \frac{m_u (A^u_{i} - \mu \cot \beta)}{m_u^2}.
\end{align*}
\]

(6)

The function \(f(x)\) is given as

\[
f(x) = \frac{177 + 118x - 288x^2 - 6x^3 - x^4 + (54 + 300x + 126x^2) \log x}{18(1-x)^6},
\]

(7)

and \(f(1) = -11/180.\)^3

In order to translate the CEDMs of the light quarks to the EDMs of neutron and \(^{199}\)Hg atom, we use the evaluation of the EDMs of neutron and \(^{199}\)Hg atom in Ref. \([11]\) as\(^4\)

\[
\begin{align*}
d_n &= -1.6 \times e(d^C_u + 0.81 \times d^C_d + 0.16 \times d^C_s), \\
d_{\text{Hg}} &= -8.7 \times 10^{-3} \times e(d^C_u - d^C_d + 0.005d^C_s),
\end{align*}
\]

(8)

where \(d_n\) is generated by the charged meson loops and \(d_{\text{Hg}}\) comes from the nuclear force by the pion exchange in the chiral perturbation theory. The experimental upperbounds

\(^2\)The CEDM of the up quark is also generated by diagrams with single and double mass insertions in the SUSY SU(5) GUT with the right-handed neutrinos. They may be comparable to those with triple mass insertions in Eq. (5), since \(A^{(u)}\) may have flavor violation. In this paper we concentrate on the CEDMs for the down and strange quarks, thus, we ignore them in this paper.

\(^3\)We find the numerical errors in the expression of the QCD correction \(c\) and the mass function \(f(x)\) given in Ref. \([10]\).

\(^4\)The hadronic EDMs, especially neutron EDM, depend on whether the Peccei-Quinn symmetry works or not \([17]\), though the numerical difference is small. We assume the PQ symmetry in this paper. When both the left-handed and right-handed squarks have off-diagonal terms in the mass matrices, the one-loop correction to the light quark masses by the SUSY loops may induce the QCD theta term even in a case where the tree-level QCD theta parameter is zero. Thus, this assumption is natural.
on the EDMs of neutron [18] and $^{199}$Hg atom [19] are

\[ |d_n| < 6.3 \times 10^{-26} \text{ e cm}, \]
\[ |d_{\text{Hg}}| < 1.9 \times 10^{-28} \text{ e cm}, \]

respectively (90\%C.L.). Thus, the upperbounds on the quark CEDMs are

\[ e|d_{C_u}^d| < 3.9(2.2) \times 10^{-26} \text{ e cm}, \]
\[ e|d_{C_d}^d| < 4.8(2.2) \times 10^{-26} \text{ e cm}, \]
\[ e|d_{C_s}^d| < 2.4(44) \times 10^{-25} \text{ e cm}, \]

from the EDM of neutron ($^{199}$Hg atom). Here, we assume that the accidental cancellation among the CEDMs does not suppress the EDMs. The constraint on $d_s^C$ from $^{199}$Hg atom is one-order weaker than that from neutron, since the contribution to the EDM of $^{199}$Hg atom is suppressed by $\pi^0$-$\eta^0$ mixing [11].

Now we show the significance of the hadronic EDMs for investigation of the flavor-violating terms in the squark mass matrices. In Table 1 we show the current constraints on the mass insertion parameters for squarks from various hadronic processes including the EDMs of neutron and $^{199}$Hg atom. For completeness, we include the constraints on the mass insertion parameters for the up-type squarks. The bounds are derived from formulas in Refs. [20, 21]. For the CP-violating observables, we assume that the related CP-violating phases in the squark mass matrices are $O(1)$. In the MSSM the mass insertion parameters for the left-handed down-type squarks are typically

\[ (\delta_{12}^d)_L \sim \lambda^5, \quad (\delta_{13}^d)_L \sim \lambda^3, \quad (\delta_{23}^d)_L \sim \lambda^2, \]

with $\lambda \sim 0.2$, since they are generated by the top quark Yukawa coupling. Combined with these relations, we find that $(\delta_{12}^d)_R \lesssim 10^{-4}$ from $\epsilon_K$, $(\delta_{13}^d)_R \lesssim 10^{-(2-3)}$ from the EDMs of neutron and $^{199}$Hg atom, $(\delta_{23}^d)_R \lesssim 10^{-(2-3)}$ from the neutron EDM in the case of $m_{\text{SUSY}} = 500\text{GeV}$ and $\tan \beta = 10$. The other processes are less significant compared with $\epsilon_K$ and the hadronic EDMs. While $\epsilon_K$ gives a constraint on a product $(\delta_{13}^d)_R(\delta_{32}^d)_R$, the EDM constraints are severer, especially, in large $\tan \beta$. This means that we can probe efficiently the flavor violation of the tau neutrino Yukawa coupling by the hadronic EDMs, since the Yukawa coupling generates the non-vanishing $(\delta_{13}^d)_R$ and $(\delta_{23}^d)_R$. 

6
It should be careful to compare the EDM constraints with other low-energy observables, which are theoretically controlled better, since the hadronic EDMs may suffer from more hadronic uncertainties. However, the orders of the magnitude in the EDM constraints are still expected to have the significance. Recently, the Belle collaboration announced that CP asymmetry in $B \to \phi K_s$ is $-0.96 \pm 0.50$, which is 3.5 $\sigma$ deviation from the SM prediction [22], while the Babar result on the CP asymmetry is consistent with the SM prediction [23]. The deviation may be explained by introduction of the right-handed bottom and strange squarks mixing, such as in the SUSY SU(5) GUT with the right-handed neutrinos, however, the neutron EDM constraint on the strange quark CEDM gives an upperbound on the deviation [11]. Even if the discrepancy comes from the hadronic uncertainty in the evaluation of the neutron EDM, the further improvement of the bound on the hadronic EDMs is very important.

The neutrino Yukawa interaction induces the flavor-violating mass terms for the left-handed sleptons, which are related to those for the right-handed down-type squarks [24],

$$(\delta^d_{ij})_R \simeq \left(\frac{m^2_{\tilde{e}^L}}{m^2_{\tilde{l}}}\right) (\delta^l_{ij})_L^*,$$

in the SUSY SU(5) GUT with the right-handed neutrinos. Here, $(\delta^l_{ij})_L \equiv (m^2_{\tilde{l}})_{ij}/(m^2_{\tilde{e}})$. In Table 2, we show the constraints on the mass insertion parameters for sleptons from the lepton-flavor violating decay of the charged leptons and the electron EDM. In the table, we take $m_{SUSY} = 200$GeV and $\tan \beta = 10$. The current bound on $Br(\mu \to e\gamma)$ gives a stringent constraint on $(m^2_{\tilde{l}})_{12}$. On the other hand, those on $(m^2_{\tilde{l}})_{13}$ and $(m^2_{\tilde{l}})_{23}$ from the tau LFV decay are weaker than the hadronic EDM constraints under the assumption of Eq. (12). The hadronic EDM constraints imply $Br(\tau \to \mu(e)\gamma) \lesssim 10^{-7-8}$. While $Br(\mu \to e\gamma)$ can give a constraint on them, it is a product $(m^2_{\tilde{l}})_{13}(m^2_{\tilde{e}})_{32}$. The electron EDM may give a constraint on a product $(m^2_{\tilde{e}})_{13}(m^2_{\tilde{l}})_{31}$ while $(m^2_{\tilde{e}})_{13}$ depends on the CKM mixing at the GUT scale. Thus, the hadronic EDMs are more directly related to the neutrino Yukawa coupling when the CP violating phases are maximal.

In Fig. 2 we show the CEDMs for the down and strange quarks in the SUSY SU(5) GUT with the right-handed neutrinos. We assume the minimal supergravity scenario and take $M_{H_u} = 2 \times 10^{16}$GeV. The CP violating phases are taken to be maximal. In Fig. 2(a) we show the strange quark CEDM as a function of the right-handed tau neutrino
mass. We take $m_{\nu_t} = 0.05$eV and $U_{\mu 3} = 1/\sqrt{2}$ and use Eq. (3) in order to fix the neutrino Yukawa coupling constants. For the SUSY breaking parameters, we take $m_0 = 500$GeV, $A_0 = 0$, $m_{\tilde{g}} = 500$GeV and $\tan \beta = 10$, which lead to $\overline{m}_{T} \simeq 640$GeV. We ignore the contribution from the electron and muon neutrino Yukawa interactions to the flavor violation in the right-handed down-type squark mass matrix. The contribution is bounded by the constraints from the $K^0 - \overline{K^0}$ mixing and $Br(\mu \rightarrow e\gamma)$ when $|U_{e2}| \sim 1/\sqrt{2}$. From this figure, the right-handed tau neutrino mass should be smaller than $\sim 3 \times 10^{14}$GeV. In Fig. 2(b) we show the down quark CEDM as a function of the right-handed tau neutrino mass. This comes from non-vanishing $U_{e3}$ in our assumption that the right-handed neutrino mass matrix is diagonal. The current bound is not significant even when $U_{e3} = 0.2$.

The new technique for the measurement of the deuteron EDM has a great impact on the quark CEDMs if it is realized [12]. If they establish the sensitivity of $d_D \sim 10^{-27}e\text{cm}$, we may probe the new physics to the level of $ed_s^C \sim 10^{-26}e\text{cm}$ and $ed_d^C \sim ed_u^C \sim 10^{-28}e\text{cm}$, which are much stronger than the bounds from the neutron and $^{199}$Hg atom EDMs [11]. This may imply that we can probe the structure in the neutrino sector even if $M_{N_3} \sim 10^{13}$GeV and $U_{e3} \sim 0.02$.

In the above discussion we have not discussed the up quark CEDM. The right-handed up-type squarks also have the flavor-violating mass terms, which depend on the GUT CP-violating phases, and the magnitudes are controlled by the CKM matrix at the GUT scale. (See Eq. (4).) They also contribute to the hadronic EDMs in the SUSY SU(5) GUT [9]. However, the off-diagonal terms in both the left-handed and right-handed up-type squark mass matrices are induced by the bottom quark Yukawa coupling, and the up quark CEDM and EDM induced by them are proportional to $\tan^4 \beta$. We find that the CEDM for the up quark can reach to $10^{-28}cm$ when $\tan \beta \simeq 35$ and $m_{SUSY} \simeq 500$GeV. Thus, if we observe the non-vanishing deuteron EDM larger than $10^{-27}ecm$, it might be interpreted as the contribution of the down or strange quark CEDM in the SUSY GUT with the right-handed neutrinos.

When the non-vanishing hadronic EDMs are observed, it would be important to take correlation among various processes. One of them is the correlation among various hadronic EDMs, including neutron and atoms. The strange quark CEDM contribution to
the neutron EDM is not suppressed compared with other light quark ones, since it comes from loop diagrams. On the other hand, the contribution to the EDMs for diamagnetic atoms, such as $^{199}$Hg atom, is suppressed by the strange quark mass. It might be possible to discriminate the CP-violating source by comparing the various hadronic EDMs.

It is also essential to survey the correlations between the hadronic EDMs and the lepton-flavor violating processes, which are imposed by the GUT relation in Eq. (12). The first one is the correlation between the strange quark CEDM and $Br(\tau \to \mu \gamma)$. In Fig. 3(a), $Br(\tau \to \mu \gamma)$ is shown as a function of the right-handed tau neutrino mass in Fig. 3(a). Here, the input parameters are the same as in Fig. 2. Compared with Fig. 2(a), it is found that $Br(\tau \to \mu \gamma)$ should be smaller than $10^{-7}$-$10^{-8}$. It is argued that the super $B$ factory may reach to $\sim 10^{-8}$ [25]. The second one is the correlation between the down quark CEDM and $Br(\mu \to e \gamma)$. The current bound on $Br(\mu \to e \gamma)$ already gives a constraint on $M_{N_2} \sim 10^{13}$GeV assuming $U_{e2} \simeq 1/\sqrt{2}$. The bound is expected to be improved by about one order of magnitude in the MEG experiment [27], which may reach to $Br(\mu \to e \gamma) \sim 10^{-14}$. In addition to it, $Br(\mu \to e \gamma)$ is also sensitive to a product $U_{e3}U_{\mu3}^*$ in our assumption that the right-handed neutrino mass matrix is diagonal. In Fig. 3(b), $Br(\mu \to e \gamma)$ is shown as a function of the right-handed tau neutrino mass. Here, we neglect the contribution proportional to $U_{e2}$. When $U_{e3}$ is maximal, the process gives a stronger constraint on the model parameters than the hadronic EDMs. Since $\mu \to e \gamma$ gives an information about the structure in the neutrino sector, which is independent of those from the hadronic EDMs, the LFV experiment is complementary to the measurement of the deuteron EDM in the SUSY GUTs.

Finally, we discuss the hadronic EDMs in the case when the SUSY breaking terms are generated below the GUT scale. In the above discussion they are assumed to be generated above the GUT scale. Below the colored Higgs masses, the interaction contributing to the right-handed down-type squark mass terms is suppressed by $M_{H_c}^2$ as

$$
\int d^4 e^{i\varphi_{dij}} \ U_{ik}U_{jk}^* \frac{f_{\varphi_{dij}}}{M_{H_c}^2} \bar{N}_k \bar{N}_k \bar{D}_i \bar{D}_j
$$

where $\bar{D}$ is for the chiral multiplet of the right-handed down-type quarks. When the SUSY breaking mass terms in the MSSM are generated by the dynamics at $M_{mess}$, which is between $M_{H_c}$ and $M_N$, the off-diagonal components in the right-handed squark mass
matrix generated by the interaction (13) is suppressed by only \( M_{mess}/M_{Hc}^2 \), compared with Eq. (4). Thus, when \( M_{mess} \) is not much smaller than \( M_{Hc} \), the sizable off-diagonal components might be generated.

In the anomaly mediation scenario [29], the SUSY breaking terms in the MSSM are insensitive to the high energy physics, and they are determined by the interactions and particle contents at low energy. However, the slepton mass squared is negative in the original model. One of the solutions is additional contribution from the \( U(1)_{B-L} \) term to the slepton mass squared. In this extension the UV insensitivity is broken by the right-handed neutrino mass terms [30], which violates the \( U(1)_{B-L} \) symmetry, even if quarks and leptons in the MSSM do not contribute to the anomaly of \( U(1)_{B-L} \). In this case the colored Higgs interaction generates the off-diagonal mass terms for the right-handed down-type squarks as

\[
(m_{\tilde{d}_R}^2)_{ij} \simeq -e^{i\varphi_{d_{ij}}} U_{ik}^{*} U_{jk} \frac{f_{\nu_k}}{(4\pi)^2} \frac{M_{N_k}}{M_{Hc}^2} \times \left\{ (2m_{\tilde{\nu_R}}^2 - m_{Hc}^2 - m_{H''c}^2) + (3m_{\tilde{\nu_R}}^2 + m_{\tilde{d}_R}^2 - m_{H''c}^2) \log \frac{M_{N_k}^2}{M_{Hc}^2} \right\},
\]

where \( m_{Hc}, m_{H''c} \) and \( m_{\tilde{\nu_R}} \) are the SUSY breaking masses for the colored Higgs multiplets and the right-handed neutrino, respectively. Since the \( U(1)_{B-L} \) contribution to the SUSY breaking scalar mass squared is proportional to the \( U(1)_{B-L} \) charge \( q \) as \(-q \langle D_{B-L} \rangle\), Eq. (14) becomes

\[
(m_{\tilde{d}_R}^2)_{ij} \simeq 2e^{i\varphi_{d_{ij}}} U_{ik}^{*} U_{jk} \frac{f_{\nu_k}}{(4\pi)^2} q_N \langle D_{B-L} \rangle \frac{M_{N_k}}{M_{Hc}^2} (1 + \log \frac{M_{N_k}^2}{M_{Hc}^2}) \left( \int d^4\theta e^{i\varphi_{d_{ij}}} U_{ik}^{*} U_{jk} \frac{f_{\nu_k}}{(4\pi)^2} \frac{e^{-2q_N V_{B-L} M_{N_k}^2}}{M_{Hc}^2} \log \frac{e^{-2q_N V_{B-L} M_{N_k}^2}}{M_{Hc}^2} \right),
\]

where \( V_{B-L} = \theta^2 \bar{\theta}^2 D_{B-L} \) and \( q_N \) is the \( U(1)_{B-L} \) charge of the right-handed neutrinos. If the colored Higgs mass is lighter than the typical GUT scale (\( \sim 2 \times 10^{16}\)GeV) and \( M_{N_3}/M_{Hc} \) is not extremely small, the correction might be observable.

In summary, we show the hadronic EDM constraints on the neutrino sector in the SUSY SU(5) GUT with the right-handed neutrinos. When the CP violating phases are maximal, the hadronic EDMs are sensitive to the right-handed down-type squark mixings, especially between the second and third generations and between the first and third ones,
which are induced by the neutrino Yukawa interaction. The current experimental bound of the neutron EDM implies that the right-handed tau neutrino mass is smaller than about $10^{14}$ GeV in the minimal supergravity scenario, and it may be improved furthermore in future experiments, such as in measurement of the deuteron EDM. When the non-vanishing hadronic EDMs are observed, we can probe the structure in the SUSY GUT models by investigating the correlations between the results of the hadronic EDM and LFV searches.

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Table 1: Constraints on the mass insertion parameters of squarks from neutral $K$, $D$ and $B$ meson mixings, $b \to s\gamma$, and EDMs of neutron and $^{199}\text{Hg}$ atom. Here, we evaluate the gluino diagram contribution to them and require them to be smaller than the experimental values or the bounds as $\Delta m_K < 3.5 \times 10^{-12}\text{MeV}$, $\epsilon_K < 2.3 \times 10^{-3}$, $\Delta m_D < 1.3 \times 10^{-10}\text{MeV}$, $\Delta m_B < 3.8 \times 10^{-14}\text{MeV}$, and $Br(b \to s\gamma) < 3.3 \times 10^{-4}$. For the hadronic EDMs, see text. We take the SUSY particle masses equal to $m_{\text{SUSY}}$. Constraints on the combination of the mass insertion parameters in this table are proportional to $m_{\text{SUSY}}^2$. Also, we consider only diagrams proportional to $\tan \beta$ for the CEDMs of the strange and down quarks and $b \to s\gamma$.

$$\begin{array}{|c|c|c|}
\hline
{^{199}\text{Hg} \text{ EDM (neutron EDM) (} m_{\text{SUSY}} = 500\text{GeV and } \tan \beta = 10)} & \\
(\delta_{12}^u)_{R}(\delta_{21}^u)_{L} & 0.8(1) \times 10^{-3} & (\delta_{13}^u)_{R}(\delta_{31}^u)_{L} & 3(5) \times 10^{-6} \\
(\delta_{12}^d)_{R}(\delta_{21}^d)_{L} & 0.6(1) \times 10^{-3} & (\delta_{13}^d)_{R}(\delta_{31}^d)_{L} & 2(4) \times 10^{-5} \\
(\delta_{23}^d)_{R}(\delta_{32}^d)_{L} & 3(0.2) \times 10^{-3} & & \\
\hline
\Delta M_K (m_{\text{SUSY}} = 500\text{GeV}) & \\
(\delta_{12}^u)_{R} & 2 \times 10^{-3} & (\delta_{13}^u)_{R}(\delta_{32}^u)_{R} & 3 \times 10^{-2} \\
(\delta_{12}^d)_{R}(\delta_{21}^d)_{L} & 7 \times 10^{-6} & (\delta_{13}^d)_{R}(\delta_{32}^d)_{R}(\delta_{31}^d)_{L} & 2 \times 10^{-5} \\
(\delta_{12}^d)_{R}(\delta_{13}^d)_{R}(\delta_{32}^d)_{R} & 3 \times 10^{-3} & (\delta_{12}^d)_{R}(\delta_{31}^d)_{L}(\delta_{32}^d)_{L} & 1 \times 10^{-5} \\
\hline
\epsilon_K (m_{\text{SUSY}} = 500\text{GeV}) & \\
(\delta_{12}^u)_{R} & 1 \times 10^{-5} & (\delta_{13}^u)_{R}(\delta_{32}^u)_{R} & 2 \times 10^{-4} \\
(\delta_{12}^d)_{R}(\delta_{21}^d)_{L} & 5 \times 10^{-8} & (\delta_{13}^d)_{R}(\delta_{32}^d)_{R}(\delta_{31}^d)_{L} & 1 \times 10^{-7} \\
(\delta_{12}^d)_{R}(\delta_{13}^d)_{R}(\delta_{32}^d)_{R} & 2 \times 10^{-5} & (\delta_{12}^d)_{R}(\delta_{31}^d)_{L}(\delta_{32}^d)_{L} & 7 \times 10^{-8} \\
\hline
\Delta M_D (m_{\text{SUSY}} = 500\text{GeV}) & \\
(\delta_{12}^u)_{R} & 1 \times 10^{-2} & (\delta_{13}^u)_{R}(\delta_{32}^u)_{R} & 2 \times 10^{-1} \\
(\delta_{12}^d)_{R}(\delta_{21}^d)_{L} & 3 \times 10^{-4} & (\delta_{13}^d)_{R}(\delta_{32}^d)_{R}(\delta_{31}^d)_{L} & 6 \times 10^{-4} \\
(\delta_{12}^d)_{R}(\delta_{13}^d)_{R}(\delta_{32}^d)_{R} & 2 \times 10^{-2} & (\delta_{12}^d)_{R}(\delta_{31}^d)_{L}(\delta_{32}^d)_{L} & 4 \times 10^{-4} \\
\hline
\Delta M_B (m_{\text{SUSY}} = 500\text{GeV}) & \\
(\delta_{13}^d)_{R} & 1 \times 10^{-2} & (\delta_{13}^d)_{R}(\delta_{31}^d)_{L} & 3 \times 10^{-4} \\
(\delta_{23}^d)_{R} & 0.6 & & \\
\hline
Br(b \to s\gamma) (m_{\text{SUSY}} = 500\text{GeV and } \tan \beta = 10) & \\
\end{array}$$
Table 2: Constraints on the mass insertion parameters of sleptons from $Br(\mu \to e\gamma)$, $Br(\tau \to \mu(e)\gamma)$ and the electron EDMs. Here, we take the SUSY particle masses equal to $m_{SUSY}$ and consider the contribution to them proportional to $\tan \beta$. The experimental bounds on the processes are $Br(\mu \to e\gamma) < 1.2 \times 10^{-11}$, $Br(\tau \to \mu(e)\gamma) < 3.6(3.2) \times 10^{-7}$, and $d_e < 4.3 \times 10^{-27}e$ cm.

Figure 1: Dominant diagram contributing to the CEDMs of light quarks when both the left-handed and right-handed squarks have flavor mixings.
Figure 2: CEDMs for the strange quark in (a) and for the down quark in (b) as functions of the right-handed tau neutrino mass, $M_{N_3}$. Here, $M_{H_c} = 2 \times 10^{16}$GeV, $m_{\nu_\tau} = 0.05$eV, $U_{\mu 3} = 1/\sqrt{2}$, and $U_{e3} = 0.2$, 0.02, and 0.002. For the MSSM parameters, we take $m_0 = 500$GeV, $A_0 = 0$, $m_{\tilde{g}} = 500$GeV and $\tan \beta = 10$.

Figure 3: $Br(\tau \rightarrow \mu \gamma)$ in (a) and $Br(\mu \rightarrow e \gamma)$ (b) as functions of the right-handed tau neutrino mass, $M_{N_3}$. Here, the input parameters are the same as in Fig. 2. The dashed lines are the experimental bounds [26, 28].