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# Nucleon Electric Dipole Moments in High Scale Supersymmetric Models

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High-scale supersymmetric (SUSY) models contain heavy sfermions so it is difficult to search sfermions directly at collider experiments. Even in such case, probes based on symmetry breaking such as the nucleon electric dipole moments (EDMs) are quite useful. In ordinary high-scale SUSY models, it is considered that the Barr-Zee diagrams with chargino/neutralino loop are dominant contributions to the nucleon EDM. In the mixture model of anomaly and gauge mediated SUSY breaking, there is an additional contribution to the nucleon EDM from the gluino chromoelectric dipole moment (CEDM) induced by *CP* phase of the gluino mass. We calculated this contributions and find that the gluino CEDM can affect on the prediction of the nucleon EDM especially in some parameter regions. In such regions, there is a possibility that the gluino CEDM effect will be observed in the future.

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## 1. Introduction

In July 2012, Higgs boson was discovered at LHC and its mass is recently reported to be 125 GeV [1]. Then, all parameters of the standard model (SM) become known and the SM is established. However, there are several problems which the SM cannot solve; absence of the dark matter candidate, reasons for anomaly cancellation and charge quantization, and so on. To solve these problems, there must be some extension of the SM. One of the most attractive candidate for the physics beyond the SM is supersymmetry (SUSY). Assuming R-parity conservation, SUSY guarantees that the lightest supersymmetric particle (LSP) becomes stable so there is natural candidate for the dark matter. Supersymmetry also supports the unification of gauge couplings. In grand unified theory, embedding the SM gauge group into larger gauge group we can explain why anomaly cancels and charges are quantized. Therefore, SUSY can resolve some problems which the SM suffered from.

However, SUSY also suffers from some problems. At tree level, the minimal supersymmetric standard model (MSSM) predicts the Higgs boson with mass lighter than Z boson. To realize the observed Higgs mass 125 GeV, we must take into account radiative correction but when MSSM haves sfermion whose mass are lighter than TeV, it is difficult to explain 125 GeV even if radiative correction is considered. Another is that the MSSM has a large number of parameters. If we suppose O(1) for them, it immediately conflicts with experimental bounds of *CP* violation and flavor changing neutral current (FCNC). Furthermore, the signal of SUSY hasn't been observed yet. These status suggest a possibility that sfermions are too heavy for collider experiments to reach. Such models, predict very heavy sfermions, are called high-scale supersymmetric models. Actually, $10^{2-3}$ TeV sfermion mass can explain 125 GeV Higgs boson [2–4] and such value of mass is sufficient to suppress *CP* violation and FCNC [5] So we consider the model as sfermion mass to be $10^{2-3}$ TeV. There are also some problems related to cosmology. One of them is gravitino problem [6]. If gravitino is too light, decay of gravitino destroys nucleus created by Big-bang Nucleosynsesis. To avoid the gravitino problem, gravitino should decay before big-ban nucleosynsesis starts. In order to be the gravitino lifetime less than a few seconds, the gravitino mass is required to be more than (of order) 100 TeV. We also attempt to explain dark matter relic density. A weakly interacting massive particle can explain it well, and in supersymmetric theories wino is a good candidate of it. Since wino's coupling is fixed by $SU(2)$ gauge coupling, heavy wino cannot explain the observed relic density. In fact, a few TeV mass is desired for the wino dark matter [7].

Actually, these models are easily constructed by using the anomaly-mediation [8, 9]. If we assume no gauge singlet in hidden sector, gauginos cannot acquire mass at leading order from the gravity-mediated contribution because the leading Planck-suppressed term in gauge kinetic function is forbidden. Even in such case, Kähler potential permits sfermions to acquire mass at this order, the Planck-surpressed SUSY-breaking F-component vacuum expectation value (VEV) which is comparable to gravitino mass. On the other hand, a leading term for gaugino mass arises from the anomalous breaking of superconformal symmetry. The gaugino mass is proportional to relevant beta function and gravitino mass [8, 9]. In this case, the mass spectrum which can solve above-mentioned problems is realized.

The high-scale SUSY model is very attractive phenomenologically but sfermions are so heavy that it is difficult to search directly at collider experiment. To investigate such model we focus on the electric dipole moment (EDM), observable based on *CP* violation. The SM prediction for EDMs from the Cabbibo Kobayashi Maskawa (CKM) matrix is small enough [10] so EDMs are sensitive to new physics. In high-scale SUSY models, *CP* violation related to sfermions are sufficiently suppress due to heavy mass. In the minimal model, the dominant contribution to EDMs comes from the Barr-Zee type two-loop diagram [11] with the neutralino/chargino loop [12]. If higgsino mass is around a few TeV, the current experimental upper bound on the electron EDM has already given the constraint on the models.

However, it is unnecessary for high-scale SUSY models to be minimal because in such models experimental bounds from *CP* violation and FCNC are quite loose. Even though gauge coupling unification and chiral anomaly cancellation are born in mind, it is possible to introduce vector-like superfields in $\mathbf{5}+\overline{\mathbf{5}}$ and/or $\mathbf{10}+\overline{\mathbf{10}}$ representation of $SU(5)$. In such generic models, vector-like matters play the role of messengers in terms of the gauge mediation. The gaugino mass also arise from messenger loop diagram so total mass of gauginos are the sum of the anomaly- and gauge-mediated contribution and relative phase difference of these contributions become the new physical *CP* phase. If this new *CP* phase contributes to EDM enormously, we can distinguish whether the model contains additional vector-like matters or not. Actually, this phase induces the gluino chromoelectric dipole moment(CEDM), which is QCD counterpart of the EDM, at 1-loop level and Weinberg operator, *CP*-odd gluon self coupling, at 2-loop level. The nucleon EDMs are estimated from *CP*-odd operator including the Weinberg operator, so in this talk we focus on this contribution to EDMs. This talk is based our work, ref. [13].

Before concluding introduction, we mention about experimental status. In EDM experiments, the frequency of the Larmor precession in electromagnetic field is measured. The neutron EDM can be measured directly using the ultra cold neutron but electron and proton are charged so they can't be trapped in electric field. Thus, for the EDM measurement of them, atoms and molecules are used, and current most stringent bounds for electron and proton EDMs come from ThO and Hg, respectively. Current upper bounds on the electron, neutron and proton EDMs are respectively given by $|d_e| < 8.7\times10^{-29}[e\ \mathrm{cm}]$, $|d_n| < 2.9\times10^{-26}[e\ \mathrm{cm}]$ and $|d_p| < 7.9\times10^{-25}[e\ \mathrm{cm}]$ [14, 15]. Some experimental organization propose the aim for future experiment sensitivity [16–19]. About 2 digits improvements are expected for electron, $|d_e| \sim 3\times10^{-31}[e\ \mathrm{cm}]$, and neutron, $|d_n| \sim 10^{-28}[e\ \mathrm{cm}]$. Surprisingly, about four digits improvement is expected for proton, $|d_p| \sim 10^{-29}[e\ \mathrm{cm}]$. This is because a new experiment as a storage ring experiment which balances with Lorentz force by rotating a proton in the magnetic field is planed.

## 2. Nucleon electric dipole moments

For elementary particles at rest, EDM must be proportional to the spin because the only vectorial quantum numbers associated with a point-like particle are its momentum and spin. Therefore the EDM for fermion named $f$ and its Hamiltonian are given as

$$\boldsymbol{d}_f = d_f \frac{\boldsymbol{s}}{|\boldsymbol{s}|}, \quad H_{\mathrm{EDM}} = -\boldsymbol{d}_f \cdot \boldsymbol{E} = -d_f \frac{\boldsymbol{s}\cdot\boldsymbol{E}}{|\boldsymbol{s}|}. \tag{2.1}$$

It can be generalized to the relativistic Lagrangian density as the *CP*-violating dimension-5 operator,

$$\mathscr{L}_{\rm EDM} = -d_f \frac{i}{2} \bar{f} \sigma^{\mu\nu} \gamma_5 f F_{\mu\nu}, \tag{2.2}$$

where $F_{\mu\nu}$ is the electromagnetic field strength tensor.

To compare with experimental values of EDMs which are measured at low energy, we must estimate EDMs at the hadronic scale. To do this, we must take the renormalization group (RG) effect into account especially for mixing of *CP*-violating operators. The EDM operator (2.2) flips chirality and typically picks up the mass of external line so it suppressed by square of heavy mass scale. Thus, we should consider up to dimension-6 operators. The *CP*-violating part in the effective theory of the QCD sector at the hadronic scale up to the dimension-6 is given as

$$\begin{aligned}\mathscr{L}_{\not{CP}} =& \bar{\theta} \frac{g_3^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \\ &- \frac{i}{2} \sum_{q=u,d,s} d_q \bar{q} \sigma^{\mu\nu} \gamma_5 q F_{\mu\nu} - \frac{i g_s}{2} \sum_{q=u,d,s} \tilde{d}_q \bar{q} \sigma^{\mu\nu} T^a \gamma_5 q G^a_{\mu\nu} \\ &- \frac{1}{3} w f^{abc} G^a_{\mu\sigma} G^{b,\sigma}_{\nu} \tilde{G}^{c,\mu\nu}\end{aligned} \tag{2.3}$$

where $G^a_{\mu\nu}$ and $\tilde{G}^{a,\mu\nu} = \frac{1}{2}\varepsilon^{\mu\nu\rho\sigma} G^a_{\rho\sigma}$ are the gluon field strength and its dual, respectively. The first term in (2.3) is QCD $\theta$-term, the *CP*-violating dimension-4 operator. it doesn't mix with other *CP*-violating operators but contributes to the nucleon EDM. The second and third terms in (2.3) are quark EDMs and CEDMs, *CP*-violating dimension-5 operators, respectively. The last term in (2.3) is Weinberg operator, *CP*-violating dimension-6 gluon self coupling. Besides the Weinberg operator there are *CP*-violating 4-fermi operators at dimension-6. However, these operators don't give dominant contribution to the nucleon EDM in our set up so these are ignored. The anomalous dimension matrix of these operators is given in ref. [20].

The nucleon EDMs are estimated from quark EDMs and CEDMs at the renormalization scale $\mu = 1$ GeV using the QCD sum rule as [21]

$$d_p = -1.2 \times 10^{-16} \ [e \ \text{cm}] \ \bar{\theta} + 0.78 d_u - 0.20 d_d + e(-0.28 \tilde{d}_u + 0.28 \tilde{d}_d + 0.021 \tilde{d}_s), \tag{2.4}$$

$$d_n = +8.2 \times 10^{-17} \ [e \ \text{cm}] \ \bar{\theta} - 0.12 d_u + 0.78 d_d + e(-0.30 \tilde{d}_u + 0.30 \tilde{d}_d - 0.014 \tilde{d}_s). \tag{2.5}$$

The nucleon EDMs are also estimated from the Weinberg operator using the naive dimensional analysis as [22]

$$d_N(w) \sim e \ (10 - 30) \ \text{MeV} \ w(1\text{GeV}). \quad (N = n, p). \tag{2.6}$$

In our numerical analysis, we use the results from the QCD sum rules with $\bar{\theta} = 0$ and the naive dimensional analysis with $d_N(w)/e = 20$ MeV $w(1$ GeV$)$. Note that the sign of Weinberg operator contribution in the naive dimensional analysis is ambiguous.

## 3. Gluino CEDM contribution

In high-scale SUSY models, gaugino masses are given by anomaly-mediated contribution as [8, 9]

$$M_a^{\rm AMSB} = \frac{g_a^2}{16\pi^2} b_a m_{3/2}, \tag{3.1}$$

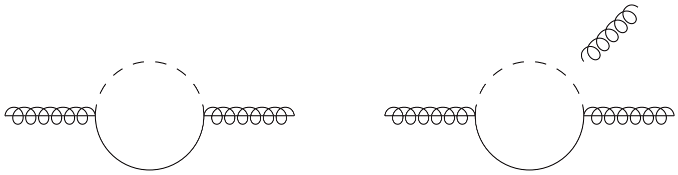

**Figure 1:** 1-loop diagram contributing to gluino mass (left) and 1-loop diagram including gluino CEDM (right). Solid and dashed lines correspond to the propagators of fermionic and scalar components of $\Phi$, $\overline{\Phi}$, respectively.

where the index $a = 1,2,3$ denotes the SM gauge groups, corresponding to $U(1)_Y$, $SU(2)_L$ and $SU(3)_C$, respectively. $b_a$ denotes the 1-loop beta function coefficient for the gauge coupling $g_a$ and $m_{3/2}$ is the gravitino mass.

We consider the extended model of high-scale SUSY, introducing vector like superfields so-called messengers. We assume that messengers are in $\mathbf{5}+\overline{\mathbf{5}}$ or $\mathbf{10}+\overline{\mathbf{10}}$ representation of $SU(5)$. If the Kähler potential $\mathscr{K}$ and superpotential $W$ for messengers are given as

$$\mathscr{K} = |\overline{\Phi}|^2 + |\Phi|^2 + (c_\Phi \overline{\Phi}\Phi + \text{h.c.}) \tag{3.2}$$

$$W = M_\Phi \overline{\Phi}\Phi \tag{3.3}$$

where $\Phi$ and $\overline{\Phi}$ denote the messenger chiral superfields, the mass matrix of the scalar components of messengers is given as

$$\mathrm{m}_\phi^2 = \begin{pmatrix} |M_\Phi + c_\Phi m_{3/2}|^2 & c_\Phi^* m_{3/2}^2 \\ c_\Phi m_{3/2}^2 & |M_\Phi + c_\Phi m_{3/2}|^2 \end{pmatrix} \equiv \begin{pmatrix} |M_{\text{mess}}|^2 & -|F|e^{-i\theta_F} \\ -|F|e^{i\theta_F} & |M_{\text{mess}}|^2 \end{pmatrix}. \tag{3.4}$$

The term proportional to $m_{3/2}$ arise according to the Giudice-Masiero mechanism [23]. In the last equality of (3.4), we parametrized diagonal mass parameter, off-diagonal component and its phase as $M_{\text{mess}}$, $F$, and $\theta_F$, respectively.

Due to introducing messengers, gauginos also obtain mass $M_a^{\text{GMSB}}$ from the gauge-mediated contribution. Gluino mass $M_3^{\text{GMSB}}$ is calculated from a diagram in fig.1 (left):

$$M_3^{\text{GMSB}} = \frac{g_3^2}{16\pi^2}(\cos\theta_F - i\sin\theta_F\gamma_5)n_3(\Phi)\left|\frac{F}{M_{\text{mess}}}\right|g(x), \tag{3.5}$$

where $x \equiv |F/M_{\text{mess}}^2|$ and $n_3(\Phi)$ is the sum of Dynkin indices of the pair of messengers, $\Phi$ and $\overline{\Phi}$. $g(x)$ is the loop function defined by

$$g(x) = \frac{(1+x)\ln(1+x) + (1-x)\ln(1-x)}{x^2}. \tag{3.6}$$

Then, gluino mass is the sum of $M_3^{\text{AMSB}}$ and $M_3^{\text{GMSB}}$ and its relative phase difference becomes a new source of $CP$ violation. For simplicity, we choose $M_3^{\text{AMSB}}$ to be real and define the real gluino mass parameter $M_{\tilde{g}}$ and the phase of the gluino mass $\theta$ as

$$M_{\tilde{g}} e^{i\gamma_5\theta} \equiv M_3^{\text{AMSB}} + M_3^{\text{GMSB}}. \tag{3.7}$$

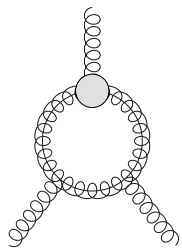

**Figure 2:** 1-loop diagram including the Weinberg operator. The blob denotes the gluino CEDM operator.



After the chiral rotation of the gluino field to take the gluino mass to be real, the new *CP* phase enters in the interaction terms between gluino and messengers.

This new *CP* phase induces the gluino CEDM at 1-loop order. As (2.3), the gluino CEDM $\widetilde{d}_{\tilde{g}}$ is defined by

$$\mathscr{L}_{\tilde{g}\ \mathrm{CEDM}} = -\frac{ig_3}{4}\widetilde{d}_{\tilde{g}}\overline{\tilde{g}^b}\sigma^{\mu\nu}\gamma_5 G^a_{\mu\nu}[T^a]_{bc}\tilde{g}^c. \tag{3.8}$$

From the diagram in fig.1 (right), $\widetilde{d}_{\tilde{g}}$ is calculated as

$$\widetilde{d}_{\tilde{g}}(M_{\mathrm{mess}}) = -\frac{g_3^2}{32\pi^2}\frac{|M|}{m_+^2}\sin(\theta+\theta_F)[A(r_+)+B(r_+)] - (m_+, r_+ \to m_-, r_-) \tag{3.9}$$

at the messenger mass scale $M_{\mathrm{mess}}$ where $m_\pm^2 \equiv |M_{\mathrm{mess}}|^2 \pm |F|$ are the mass eigenvalue of (3.4) and $r_\pm \equiv |M_{\mathrm{mess}}|^2/m_\pm^2$. The loop functions $A(r)$ and $B(r)$ are defined by

$$A(r) \equiv \frac{1}{2(1-r)^2}\left(3 - r + \frac{2\ln r}{1-r}\right), \quad B(r) \equiv \frac{1}{2(1-r)^2}\left(1 + r + \frac{2r\ln r}{1-r}\right). \tag{3.10}$$

Then, the Weinberg operator is induced through the gluino 1-loop diagram in fig.2 from using the gluino CEDM. At the gluino mass scale $M_{\tilde{g}}$, the coefficient of the Weinberg operator is calculated as

$$w(M_{\tilde{g}}) = \frac{N_C g_3^3}{32\pi^2}\frac{\widetilde{d}_{\tilde{g}}(M_{\tilde{g}})}{M_{\tilde{g}}}. \tag{3.11}$$

Then, running RGE down to the scale 1 GeV we finally obtain the nucleon EDM from using the naive dimensional analysis (2.6).

## 4. Results

In our numerical analysis, we assume that sfermions, heavy Higgs bosons and gravitino are all degenerate in $M_S$ and a pair of messengers in $\mathbf{5}+\overline{\mathbf{5}}$ representation is introduced. Once $M_S$ is fixed in the calculation of the gluino CEDM contribution to the nucleon EDM, there are three remaining parameters about messengers' mass in (3.4), $|M_{\mathrm{mess}}|$ , $|F|$ and $\theta_F$. Though figures are not presented in this proceedings, we have checked dependence of the nucleon EDMs on three

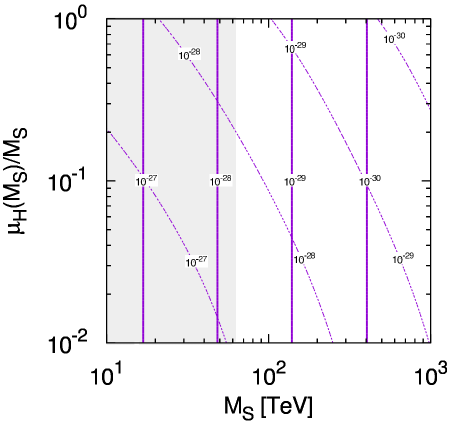


**Figure 3:** Comparison of the Barr-Zee contribution and the gluino CEDM contribution to the proton EDM in the light messenger case ($|M_{\rm mess}| = 0.1 M_S$). Dotted and solid lines correspond to the Barr-Zee contribution and the gluino CEDM contribution, respectively. The shaded region is excluded by the gluino search at the LHC. A pair of messengers in $\mathbf{5}+\overline{\mathbf{5}}$ representation is introduced.

independent parameters, $|M_{\rm mess}|$, $\theta_F$ and $x = |F/M_{\rm mess}^2|$, in original paper. We set $\theta_F = 0.125\pi$ and $x = 0.99$ to be maximal contribution in following analysis.

Here, the proton EDM is presented only in the case of light messengers as $|M_{\rm mess}| = 0.1 M_S$. Fig.3 compares two contributions to the proton EDM, the Barr-Zee diagrams with neutralino/chargino loop (dotted lines) and the gluino CEDM (solid lines). The Barr-Zee contribution to EDMs is suppressed by $m_f/M_2\mu_H$ where $\mu_H$ is the higgsino mass. Since $\mu_H$ can't be determined by fixing how to mediate the SUSY breaking, we take it as a free parameter. The Barr-Zee contribution also depends on $\tan\beta$ but it is model-dependent parameter so we simply set $\tan\beta = 3$. Shaded region in fig.3 is excluded by the gluino search at the LHC [24, 25] which corresponds to $M_{\tilde{g}}^{\rm pole} < 1.3$ TeV.

From fig.3 the gluino CEDM contribution can exceed Barr-Zee one if $M_S$ is small and $\mu_H$ is large, so it may be useful to distinguish the model. Furthermore, the gluino CEDM contribution may exceed the sensitivity of the future proton EDM experiment, $|d_p| \sim 10^{-29}[e\ {\rm cm}]$.

## 5. Conclusion

The high-scale SUSY model is very attractive phenomenologically. In this work, we pointed out a new contribution to the nucleon EDM from the gluino CEDM in extended models. This contribution affect on the prediction of the nucleon EDM in the high-scale SUSY model and may be useful to distinguish whether high-scale SUSY model includes messengers or not. In EDM experiment, improvement of the sensitivity is highly expected so there is possibility that the gluino CEDM effect will be found in the future through he proton EDM.

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