The Chromoelectric and Purely Gluonic Operator Contributions to the Neutron Electric Dipole Moment in $N = 1$ Supergravity

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Abstract

A complete one loop analysis of the chromoelectric dipole contribution to the electric dipole moment (edm) of the quarks and of the neutron in $N=1$ supergravity including the gluino, chargino and neutralino exchange contributions and exhibiting the dependence on the two CP violating phases allowed in the soft SUSY breaking sector of minimal supergravity models is given. It is found that in significant parts of the supergravity parameter space the chromoelectric dipole contribution to the neutron edm is comparable to the contribution from the electric dipole term and can exceed the contribution of the electric dipole term in certain regions of the parameter space. An analysis of the contribution of Weinberg’s purely gluonic CP violating dimension six operator within supergravity unification is also given. It is found that this contribution can also be comparable to the contribution from the electric dipole term in certain regions of the supergravity parameter space.
1 Introduction

The electric dipole moment (edm) of fermions is one of the important windows to new physics beyond the Standard Model (SM). In the SM the edm for the fundamental fermions arising from the Kobayashi-Maskawa CP violating phase is much smaller than the current experimental limit of $1.1 \times 10^{-25}$ecm and beyond the reach of experiment in the foreseeable future. In supersymmetric unified models new sources of CP violation arise from the complex phases of the soft SUSY breaking parameters which contribute to the edm of the quarks and of the leptons. For the case of the quarks and the neutron there are also the color dipole operator and the CP violating purely gluonic dimension six operator which contribute. However, with the exception of the work of ref.[9] virtually all previous analyses of the neutron edm have been done neglecting the contributions of these additional operators. The reason for this neglect is the presumption that their contribution to the neutron edm is small. In the analysis of this paper we show that the contributions of the color dipole operator and of the purely gluonic operator are not necessarily small and over a significant part of the supergravity parameter space their contribution to the neutron edm is comparable to the contribution from the electric dipole operator and can even exceed it in certain regions of the parameter space.

In this Letter we first derive the full one loop contribution to the color dipole operator arising from the gluino, the chargino and the neutralino exchange contributions exhibiting the dependence on the two CP violating phases allowed in the soft SUSY breaking sector of minimal supergravity models. To our knowledge this is the first complete one loop analysis of this operator. We also recompute the purely gluonic dimension six operator to incorporate the dependence on the two CP violating phases. We then give a numerical analysis of the relative strength of the color dipole contribution to the neutron edm relative to the contribution from the electric dipole term using the framework of supergravity unification under the constraint of radiative breaking of the electro-weak symmetry. Our analysis shows that the color dipole contribution relative to the electric dipole contribution can vary greatly over the parameter space of the model. We find that there are significant regions of the parameter space where the color dipole contribution can be comparable to the contribution from the electric dipole term and in some regions of the parameter space the color dipole contribution can even exceed the contribution from the electric dipole term. A similar analysis is also carried out...
for the purely gluonic dimension six operator. Here again one finds that there exist regions of the parameter space where the contribution of the purely gluonic dimension six operator to the neutron edm can be comparable to, and may even exceed, the contribution from the electric dipole term. Thus one is not justified in discarding the effects of the color dipole operator and of the gluonic dimension six operator in the neutron edm computation.

The outline of the Letter is as follows: In Sec.2 we give the complete one loop calculation including the gluino, the chargino and the neutralino exchange contribution to the color dipole operator and discuss its contribution to the electric dipole moment of the neutron including its dependence on the two CP violating phases in minimal supergravity. In Sec.3 we recompute the dimension six gluonic operator to include the effects of the two CP violating phases. In Sec.4 we give the renormalization group analysis in minimal supergravity of the relative numerical strengths of these contributions and show that they can be comparable to the electric dipole contribution in significant regions of the parameter space.

2 Analysis of Chromoelectric Dipole Contribution

The parameters that enter in minimal supergravity grand unification with radiative breaking of the electro-weak symmetry can be taken to be $m_0, m_{1/2}, A_0, \tan \beta$ and phase($\mu$), where $m_0$ is the universal scalar mass, $m_{1/2}$ is the universal gaugino mass, $A_0$ is the universal trilinear coupling, $\tan \beta = \langle H_2 \rangle / \langle H_1 \rangle$, where $H_2$ gives mass to the up quark and $H_1$ gives mass to the down quark, and $\mu$ is the Higgs mixing parameter[12, 13]. As noted in Sec. 1 only two phases in the soft SUSY breaking sector have a physical meaning in minimal supergravity, and we choose them to be the phase $\alpha_{A0}$ of $A_0$ and the phase $\theta_{\mu 0}$ of $\mu_0$. The quark chromoelectric dipole moment is defined to be the factor $\tilde{d}^c$ in the effective operator:

$$\mathcal{L}_1 = -\frac{i}{2} \tilde{d}^c \bar{q} \sigma_{\mu \nu} \gamma_5 T^a q G^{\mu \nu a}$$

(1)

where $T^a$ are the generators of $SU(3)$. In the following we give an analysis of the one loop contributions to $\tilde{d}^c$ from the chargino, the neutralino and the gluino exchange diagrams shown in Figs. 1a and 1b.
2.1 Gluino Contribution

The quark-squark-gluino vertex can be derived using the interaction[13]

\[-\mathcal{L}_{q-\tilde{q}-\tilde{g}} = \sqrt{2} g_s T^a_{jk} \sum_{i=u,d} \left( -\tilde{q}^i \frac{1-\gamma^5}{2} g_{\alpha R} \tilde{q}^k_{iR} + \tilde{q}^i \frac{1+\gamma^5}{2} g_{\alpha L} \tilde{q}^k_{iL} \right) + H.c., \tag{2} \]

where \(a = 1 - 8\) are the gluino color indices, and \(j, k = 1 - 3\) are the quark and squark color indices. The complex phases enter via the squark \((mass)^2\) matrix \(M^2_{\tilde{q}}\) which can be diagonalized by the transformation

\[D^\dagger_q M^2_{\tilde{q}} D_q = \text{diag}(M^2_{\tilde{q}1}, M^2_{\tilde{q}2}) \tag{3}\]

where

\[\tilde{q}_L = D_{q11} \tilde{q}_1 + D_{q12} \tilde{q}_2 \tag{4}\]
\[\tilde{q}_R = D_{q21} \tilde{q}_1 + D_{q22} \tilde{q}_2. \tag{5}\]

and where \(\tilde{q}_1\) and \(\tilde{q}_2\) are the mass eigenstates. Writing \(\mathcal{L}\) in terms of \(\tilde{q}_1\) and \(\tilde{q}_2\) and integrating out the gluino and squark fields and by using the identities

\[T^a_{ij} T^a_{kl} = \frac{1}{2} [\delta_{il} \delta_{kj} - \frac{1}{3} \delta_{ij} \delta_{kl}] \tag{6}\]

and

\[f^{abc} T^b T^c = \frac{3}{2} i T^a \tag{7}\]

one can obtain the gluino exchange contribution to \(\bar{d}^c\). We find

\[d_{\tilde{q}-\text{gluino}} = \frac{g_s \alpha_s}{4\pi} \sum_{k=1}^2 \text{Im}(\Gamma_{q1}^{1k}) \frac{m_{\tilde{q}}}{M^2_{\tilde{q}k}} C(\frac{m_{\tilde{q}}^2}{M^2_{\tilde{q}k}}), \tag{8}\]

where \(\Gamma_{q1}^{1k} = D_{q2k} D_{q1k}^*\) and \(m_{\tilde{q}}\) is the gluino mass and

\[C(r) = \frac{1}{6(r-1)^2}(10r - 26 + \frac{2rlnr}{1-r} - \frac{18lnr}{1-r}). \tag{9}\]

2.2 Neutralino Contribution

Here the CP violating phases enter via the the squark \((mass)^2\) matrix, which contains the phases of \(A_q\) and \(\mu\), and via the neutralino mass matrix given by

\[M_{\chi^0} = \begin{pmatrix}
\bar{m}_1 & 0 & -M_z \sin \theta_W \cos \beta & M_z \sin \theta_W \sin \beta \\
0 & \bar{m}_2 & M_z \cos \theta_W \cos \beta & -M_z \cos \theta_W \sin \beta \\
-M_z \sin \theta_W \cos \beta & M_z \cos \theta_W \cos \beta & 0 & -\mu \\
M_z \sin \theta_W \sin \beta & -M_z \cos \theta_W \sin \beta & -\mu & 0
\end{pmatrix}. \tag{10}\]
which carries the phase of $\mu$. The matrix $M_{\chi^0}$ is a complex non hermitian and symmetric matrix, which can be diagonalized by a unitary transformation such that

$$ X^T M_{\chi^0} X = \text{diag}(\tilde{m}_{\chi_1^0}, \tilde{m}_{\chi_2^0}, \tilde{m}_{\chi_3^0}, \tilde{m}_{\chi_4^0}) $$  

Quark-quark-neutralino vertex can be derived from the interaction

$$ -\mathcal{L}_{q-q-\chi^0} = \sum_{j=1}^{4} \sqrt{2} u [(\alpha_{uj} D_{u1} - \gamma_{uj} D_{u2}) \frac{1 - \gamma_5}{2} \chi_{j}^0 \tilde{u}_1 + \sqrt{2} \bar{u} [(\alpha_{uj} D_{u12} - \gamma_{uj} D_{u22}) \frac{1 - \gamma_5}{2} \chi_{j}^0 \tilde{u}_2 + (u \to d) + H.c.] \tag{12} $$

where $\alpha$, $\beta$, $\gamma$ and $\delta$ are given by

$$ \alpha_{u(d)} = \frac{g m_{u(d)} X_{4(3),j}}{2 m_W \sin \beta (\cos \beta)} \tag{13} $$

$$ \beta_{u(d)} = e Q_{u(d)} X_{1j}^* + \frac{g}{\cos \theta_W} X_{2j}^* (T_{3u(d)} - Q_{u(d)} \sin^2 \theta_W) \tag{14} $$

$$ \gamma_{u(d)} = e Q_{u(d)} X_{1j}^* - \frac{g Q_{u(d)} \sin^2 \theta_W}{\cos \theta_W} X_{2j}^* \tag{15} $$

$$ \delta_{u(d)} = \frac{g m_{u(d)} X_{4(3),j}}{2 m_W \sin \beta (\cos \beta)} \tag{16} $$

and where

$$ X_{1j}^* = X_{1j} \cos \theta_W + X_{2j} \sin \theta_W \tag{17} $$

$$ X_{2j} = -X_{1j} \sin \theta_W + X_{2j} \cos \theta_W \tag{18} $$

The one loop analysis using Eq.(12) gives for $\tilde{d}^c$

$$ \tilde{d}^c_{q-\chi^{0\text{neutralino}}} = \frac{g s g^2}{16 \pi^2} \sum_{k=1}^{2} \sum_{i=1}^{4} \text{Im}(\eta_{qik}) \frac{\tilde{m}_{\chi^0}}{M_{qk}^2} B\left(\frac{\tilde{m}_{\chi^0}}{M_{qk}^2}\right), \tag{19} $$

where

$$ \eta_{qik} = [-\sqrt{2} \{\tan \theta_W (Q_q - T_{3q}) X_{1i} + T_{3q} X_{2i} \} D_{q1k}^* + \kappa_q X_{bi} D_{q2k}^* + \kappa_q X_{bi} D_{q2k}] \tag{20} $$

Here

$$ \kappa_u = \frac{m_u}{\sqrt{2} m_W \sin \beta}, \quad \kappa_d = \frac{m_d}{\sqrt{2} m_W \cos \beta} \tag{21} $$

where $b = 3(4)$ for $T_{3q} = -\frac{1}{2}(\frac{1}{2})$ and

$$ B(r) = \frac{1}{2(r - 1)^2} (1 + r + \frac{2r \ln r}{1 - r}). \tag{22} $$
2.3 Chargino Contribution

Here the CP violating phases enter via the squark (mass)\(^2\) matrix and via the chargino mass matrix given by

\[
M_C = \begin{pmatrix}
\sqrt{2}m_W \cos \beta & \sqrt{2}m_W \sin \beta \\
\sqrt{2}m_W \cos \beta & \mu
\end{pmatrix}
\] (23)

which involves the phase of \(\mu\). The chargino matrix can be diagonalized by the unitary transformation:

\[
U^*M_CV^{-1} = \text{diag}(\tilde{m}_{\chi_1^+}, \tilde{m}_{\chi_2^+})
\] (24)

The quark-squark-chargino vertex can be derived from the interaction\(^1\![\text{13}]\)

\[
-\mathcal{L}_{q-\tilde{q}-\tilde{\chi}^+} = g\bar{u}[(U_{11}D_{d11} - \kappa_d U_{12}D_{d21})\frac{1 + \gamma_5}{2}]
\]

\[
- (\kappa_u V_{12}^* D_{d11})\frac{1 + \gamma_5}{2} \tilde{\chi}_1^+ \tilde{d}_1 + g\bar{u}[(U_{21}D_{d11} - \kappa_d U_{22}D_{d21})\frac{1 + \gamma_5}{2}]
\]

\[
- (\kappa_u V_{12}^* D_{d12})\frac{1 + \gamma_5}{2} \tilde{\chi}_1^+ \tilde{d}_1 + g\bar{u}[(U_{11}D_{d12} - \kappa_u U_{12}D_{d22})\frac{1 + \gamma_5}{2}]
\]

\[
- (\kappa_u V_{22}^* D_{d12})\frac{1 + \gamma_5}{2} \tilde{\chi}_2^+ \tilde{d}_2 + g\bar{u}[(U_{21}D_{d12} - \kappa_u U_{22}D_{d22})\frac{1 + \gamma_5}{2}]
\]

\[
+(u \leftrightarrow d, U \leftrightarrow V, \tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^c) + \text{H.c.,}
\] (25)

and for \(\tilde{d}^c\) one gets for the up and down flavors

\[
d_{u-\text{chargino}}^c = \frac{-g^2 g_s}{16\pi^2} \sum_{k=1}^2 \sum_{i=1}^2 \text{Im}(\Gamma_{uik}) \frac{\tilde{m}_{\chi_i^+} \tilde{m}_{\chi_i^+}}{M_{d_k}^2 B(M_{d_k}^2)}
\] (26)

\[
d_{d-\text{chargino}}^c = \frac{-g^2 g_s}{16\pi^2} \sum_{k=1}^2 \sum_{i=1}^2 \text{Im}(\Gamma_{dik}) \frac{\tilde{m}_{\chi_i^+} \tilde{m}_{\chi_i^+}}{M_{d_k}^2 B(M_{d_k}^2)}
\] (27)

where

\[
\Gamma_{uik} = \kappa_u V_{i2}^* D_{d1k}(U_{i1}^* D_{d1k}^* - \kappa_d U_{i2}^* D_{d2k}^*)
\] (28)

\[
\Gamma_{dik} = \kappa_d U_{i2}^* D_{u1k}(V_{i1}^* D_{u1k}^* - \kappa_u V_{i2}^* D_{u2k}^*)
\] (29)

The contribution to EDM of the quarks can be computed using the naive dimensional analysis\(^1\![\text{14}]\) which gives

\[
d_q^c = \frac{e}{4\pi} \tilde{d}_q^c \eta^c
\] (30)

where \(\eta^c\) is the renormalization group evolution of the operator of Eq.(1) from the electroweak scale down to hadronic scale\(^1\![\text{15}, \text{9}]\). For the neutron electric dipole moment \(d_n\) we use the naive quark model \(d_n = (4d_d - d_u)/3\).
3 CP Violating Purely Gluonic Dimension 6 operator

The gluonic dipole moment $d^G$ is defined to be the factor in the effective operator

$$\mathcal{L}_I = -\frac{1}{6} d^G f_{\alpha\beta\gamma} G_{\alpha\mu\nu} G_{\beta\lambda\sigma} G_{\gamma\lambda\sigma} \epsilon^{\mu\nu\lambda\sigma}$$

(31)

where $G_{\alpha\mu\nu}$ is the gluon field strength tensor, $f_{\alpha\beta\gamma}$ are the Gell-Mann coefficients, and $\epsilon^{\mu\nu\lambda\sigma}$ is the totally antisymmetric tensor with $\epsilon^{0123} = +1$.

Dai et al [11] have calculated $d^G$ considering the top quark-squark loop with a gluino exchange in terms of the complex phase $\phi$ of the gluino mass while the squark (mass)$^2$ matrix in their analysis was considered to be real. In our case the squark (mass)$^2$ matrix is complex and carries the phases of $A_q$ and of $\mu$. We have recalculated $d^G$ for our case and we find

$$d^G = -3\alpha_s m_t (\frac{g_s}{4\pi})^3 \text{Im}(\Gamma^1_{12}(-)) \frac{z_1 - z_2}{m_{\tilde{g}}^2} H(z_1, z_2, z_t)$$

(32)

where

$$z_\alpha = (\frac{M_{t\alpha}}{m_{\tilde{g}}})^2, z_t = (\frac{m_t}{m_{\tilde{g}}})^2$$

(33)

and

$$\Gamma^1_{12} = D_{t22}D_{t12}^*$$

(34)

where $D_t$ is the diagonalizing matrix for the stop (mass)$^2$ matrix, and the function $H$ is the same as in [11]. The contribution to $d_n$ from $d^G$ can be estimated by the naive dimensional analysis[14] which gives

$$d_n^G = \frac{eM}{4\pi} d^G \eta^G$$

(35)

where $M$ is the chiral symmetry breaking scale with the numerical value 1.19 GeV, and $\eta^G$ is the renormalization group evolution of the operator of Eq.(31) from the electroweak scale down to the hadronic scale. $\eta^c$ and $\eta^G$ have been estimated to be $\sim 3.3$ [15, 9].

4 RG Analysis and Results

We discuss now the relative size of the three contributions to the neutron edm, i.e., from the electric dipole operator, from the color dipole operator and from the purely gluonic operator. To study their relative contributions we consider a given
point in the supergravity parameter space characterized by the set of six quantities at the GUT scale: $m_0, m_{\tilde{t}}, A_0, \tan \beta, \theta_{\mu 0}$ and $\alpha_{A_0}$. In the numerical analysis we evolve the gauge coupling constants, the Yukawa couplings, magnitudes of the soft SUSY breaking parameters, $\mu$ and the CP violating phases from the GUT scale down to the Z boson scale. We use one-loop renormalization group equations (RGEs) for the soft SUSY breaking parameters and two-loop RGEs for the Yukawa and gauge couplings. Using the data gotten from the RG analysis at the scale $M_Z$ we compute the contributions to the quark edm from the electric dipole part ($d^E_q$), from the color dipole part ($d^C_q$), and from the purely gluonic part ($d^G_n$). These are further evolved to the hadronic scale by using renormalization group analysis as discussed in Secs. 2 and 3.

Table 1: $m_\tilde{g} = 500$ GeV, $m_0 = 2000$ GeV, $|A_0| = 1.0$

| case | $\tan \beta$ | phases (rad) | $d^E_n (10^{-26} \text{ecm})$ | $d^C_n (10^{-26} \text{ecm})$ | $d^G_n (10^{-26} \text{ecm})$ |
|------|-------------|-------------|------------------|------------------|------------------|
| (i)  | 2           | $\theta_{\mu 0} = 0.2$, $\alpha_{A_0} = -0.5$ | 0.124            | 3.049            | -1.168           |
| (ii) | 2           | $\theta_{\mu 0} = 0.2$, $\alpha_{A_0} = 0.5$  | -8.46            | 12.84            | 17.315           |
| (iii)| 4           | $\theta_{\mu 0} = 0.2$, $\alpha_{A_0} = -0.5$ | -4.33            | 0.764            | -5.13            |
| (iv) | 4           | $\theta_{\mu 0} = 0.2$, $\alpha_{A_0} = 0.5$  | -11.74           | -12.65           | 7.28             |

To exhibit the importance of the color dipole operator and of the purely gluonic operator we display the relative sizes of $d^E_n$, $d^C_n$ and of $d^G_n$ for few illustrative examples in Table 1. One can understand the smallness of $d^E_n$ for case(i) in the following way. The main contributions to $d^E_n$ arise from the chargino and from the gluino exchange. The chargino exchange gives a negative contribution while the gluino exchange gives a positive contribution and the smallness of $d^E_n$ is due to a cancellation between these two. For the color dipole term $d^C_n$ there is also a cancellation but this time the cancellation is only partial and it occurs between the d-quark and the u-quark contributions. Because of a large cancellation for $d^E_n$ and only a partial cancellation for $d^C_n$ one has dominance of $|d^C_n|$ over $|d^E_n|$ in this case.

One may contrast the result of case(i) with that of case(ii) where the sign of $\alpha_{A_0}$ is switched. Here the gluino contribution in $d^E_n$ switches sign and this time one has a reinforcement of the chargino and the gluino contributions making $|d^E_n|$ much larger than for case(i). Further, in the color dipole part the d-quark contribution in the gluino exchange switches sign and there is a reinforcement of the d-quark and the u-quark contributions making $|d^C_n|$ larger than for case(i). We see then that in this case $|d^E_n|$ and $|d^C_n|$ are comparable. One may note that a very large
change occurs for the purely gluonic term in going from case(i) to case(ii). To understand the large shift in the value of $d_n^G$ we display explicitly the imaginary part of Eq. (34)

$$\text{Im}(\Gamma_t^{12}) = \frac{-m_t}{(M_{\tilde{t}_1}^2 - M_{\tilde{t}_2}^2)} (m_0 |A_t| \sin \alpha_A + |\mu| \sin \theta_\mu \cot \beta),$$

(36)

where $\theta_\mu$ and $\alpha_A$ are the values of $\theta_\mu_0$ and of $\alpha_{A_0}$ at the electro-weak scale. From Eq. (36) we see that the magnitude of $\text{Im}(\Gamma_t^{12})$ depends on the relative sign and the magnitude of $\theta_\mu$ and of $\alpha_A$. Thus one has a cancellation between the $A_t$ term and the $\mu$ term when $\theta_\mu$ and $\alpha_A$ have opposite signs as in case(i) and a reinforcement between the $A_t$ term and the $\mu$ term when $\theta_\mu$ and $\alpha_A$ have the same sign as in case(ii). Thus one can qualitatively understand the largeness of $d_n^G$ in case(ii) relative to case(i). The very large reduction in $d_n^C$ for case(iii) relative to case(ii) occurs because of a reduction in the down quark contribution, which is the dominant term in $d_n$, due to a switch in the $\alpha_{A_0}$ sign and a change in the value of $\tan \beta$. In going from case(iii) to case(iv) the further switch in the sign of $\alpha_{A_0}$ once again increases the down quark contribution making $d_n^C$ the largest in magnitude.

It is interesting to note that each of the four cases of Table 1 leads to a distinct pattern of hierarchy among the three contributions. Thus one has

(i) $|d_n^C| > |d_n^G| > |d_n^E|$, (ii) $|d_n^G| > |d_n^C| > |d_n^E|$

(iii) $|d_n^C| > |d_n^E| > |d_n^C|$, (iv) $|d_n^C| > |d_n^E| > |d_n^C|

The analysis clearly shows that any one of the three contributions can dominate $d_n$ depending on the part of the parameter space one is in. We note also that $d_n^E$ for all the four cases in Table 1 is consistent with experiment while the total edm which includes the color and the purely gluonic part for cases (ii) and (iv) would be outside the experimental bound.

In Fig. 2 we display the magnitudes of $d_n^E$, $d_n^C$ and $d_n^G$ as a function of $m_{\tilde{g}}$ for a specific set of $m_0$, $A_0$, $\tan \beta$, $\alpha_{A_0}$ and $\theta_{\mu 0}$ values. Here we find that $|d_n^C|$ is comparable to $|d_n^E|$ over most of the $m_{\tilde{g}}$ region and in fact exceeds it for values of $m_{\tilde{g}}$ below $\sim 800$ GeV. Further $|d_n^G|$ also exceeds $|d_n^E|$ for values of $m_{\tilde{g}}$ below $\sim 400$ GeV in this case. The broad peak in $d_n^E$ arises from a destructive interference between the gluino and the chargino components of $d_n^E$ which leads to a relatively rapid fall off of $d_n^E$ for values of $m_{\tilde{g}}$ below $\sim 500$ GeV. There are other regions where similar phenomena occur. To exhibit the commonality of the largeness of $d_n^C$ we
give in Fig.(3a) a scatter plot of the ratio $|d^C_n/d^E_n|$ for the ranges indicated in the Fig.(3a) caption. We see that there exist significant regions of the parameter space where the ratio $|d^C_n/d^E_n| \sim O(1)$ and hence $d^C_n$ is non-negligible in these regions. A scatter plot of $|d^G_n/d^E_n|$ is given in Fig.(3b) and it exhibits a similar phenomenon.

In conclusion we have given the first complete one loop analysis of the chromoelectric contribution to the electric dipole moment of the quarks and of the neutron exhibiting the dependence on the two arbitrary CP violating phases allowed in minimal supergravity unification. We find that the relative strength of the chromoelectric contribution varies sharply depending on what part of the supergravity parameter space one is in. In significant parts of the parameter space the chromoelectric contribution is comparable to the electric dipole contribution and can even exceed it in certain regions of the parameter space. A similar conclusion also holds for the contribution of Weinberg’s CP violating purely gluonic dimension six operator. The analysis of the neutron edm exploring the full parameter space of supergravity unified models is outside the scope of this Letter and will be discussed elsewhere. We only state here that the inclusion of all the three components of the neutron edm, i.e., $d^E_n$, $d^C_n$, and $d^G_n$, is essential in making reliable predictions of the neutron edm. In fact, the full analysis shows there exist regions of the supergravity parameter space where internal cancellation among the three components lead to an acceptable value of the neutron edm without either the use of an excessively heavy SUSY spectrum or an excessive finetuning of phases. These results have important implications for the mechanisms needed to suppress the neutron edm in SUSY, for the effect of CP violating phases on dark matter and on the analyses of baryon asymmetry in the universe.

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6 Figure Captions

Fig. 1a: One loop diagram contributing to the color dipole operator where the external gluon line ends on an exchanged squark line in the loop. Squarks are represented by $\tilde{q}_k$ in the internal lines.
Fig. 1b: One loop diagram contributing to the color dipole operator where the external gluon line ends on an exchanged gluino line labelled by $\tilde{g}$ in the loop.

Fig. 2: Plot of $d^E_n$, $d^C_n$, and $d^G_n$ as a function of $m_{\tilde{g}}$ when $m_0=2000$ GeV, $\tan\beta=3.0$, $|A_0|=1.0$, $\theta_{\mu_0}=0.1$ and $\alpha_{A_0}=0.5$.

Fig. 3a: Scatter plot of the ratio $|d^C_n/d^E_n|$ as a function of $m_0$ for the case $|A_0|=1.0$, $\tan\beta = 2.0$ and the other parameters in the range $200$ GeV $< m_{\tilde{g}} <$ 600 GeV and $-\pi/5 < \theta_{\mu_0}, \alpha_{A_0} < \pi/5$.

Fig. 3b: Scatter plot of the ratio $|d^G_n/d^E_n|$ as a function of $m_0$ for the same range of parameters as in Fig. 3a.

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Fig. 1a

Fig. 1b

Fig. 2

Fig. 3a

Fig. 3b