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Electric dipole moments in split supersymmetry

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Abstract

We perform a quantitative study of the neutron and electron electric dipole moments (EDM) in supersymmetry, in the limit of heavy scalars. The leading contributions arise at two loops. We give the complete analytic result, including a new contribution associated with Z-Higgs exchange, which plays an important and often leading role in the neutron EDM. The predictions for the EDM are typically within the sensitivities of the next generation experiments. We also analyse the correlation between the electron and neutron EDM, which provides a robust test of split supersymmetry.

1. Introduction

The electric dipole moments (EDMs) of the Standard Model (SM) fermions are powerful probes of physics beyond the SM. Once the strong CP problem has been taken care of, the SM predictions for the EDMs of quarks and leptons are at least 7 orders of magnitudes below [1] the present experimental limits [2–4]. The situation is drastically different in supersymmetric extensions of the SM. The supersymmetry-breaking terms involve many new sources of CP-violation. Particularly worrisome are the phases associated, in the universal and flavour-diagonal case, to the invariants $\arg(A^* M_{\tilde{g}})$ and $\arg(A^* B)$. Such phases survive in the universal limit in which all the flavour structure originates from the SM Yukawas. If these phases are of order one, the electron and neutron EDMs induced at one-loop by gaugino-sfermion exchange are typically (barring accidental cancellations [5]) a couple of orders of magnitude above the limits [6–9], a difficulty which is known as the supersymmetric CP problem.

The split limit of the MSSM [10–12] does not present a supersymmetric CP problem. Heavy sfermions suppress the dangerous one-loop contributions to a negligible level. Nevertheless, some phases survive below the sfermion mass scale and, if they do not vanish for an accidental or a symmetry reason, they give rise to EDMs that are safely below the experimental limits, but sizeable enough to be well within the sensitivity of the next generation of experiments [12]. Such contributions only arise at the two-loop level, since the new phases appear in the gaugino–higgsino sector, which is not directly coupled to the SM fermions.

In this Letter, we perform a quantitative study of the neutron and electron EDMs in the limit of split supersymmetry. First, we compute the different contributions to the light quark and electron EDMs, the only relevant CP-violating operators. Indeed, quark chromoelectric dipoles and the gluon Weinberg operator [13] cannot be generated at two loops. For the EDM, the original CP-violation in the gaugino–higgsino sector is communicated to the SM fermions by gauge boson and Higgs exchanges, specifically by (i) γh, (ii) WW, or (iii) Zh exchange. No other possibilities are allowed at the two-loop level.

The γh exchange has been widely studied in the literature in several contexts [14–17]. The case of split supersymmetry was considered in Ref. [12]. The WW exchange has also been studied in different limits [18–20]. An exact 2-loop computation has been performed in the context of split supersymmetry in Ref. [21] (see also Ref. [22] for a computation in the context of a two-

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Higgs doublet model). Our results, for which we give explicit analytic expressions, differ from those in Ref. [21]. Moreover, we identify a third, important contribution due to Zh exchange. The Zh contribution is suppressed in the case of the electron EDM by a $1-4\sin^2\theta_W$ factor, but it plays an important role in the neutron EDM. In fact, the Zh contribution is always comparable and often larger than the γh one (which in turn is tipically larger than the WW contribution). We have also recomputed the QCD renormalization effect, correcting a mistake present in the previous literature.

2. General expressions for the EDMs

CP-violating phases can enter the effective Lagrangian below the sfermion mass scale $\tilde{m}$ through the Yukawa couplings (which are irrelevant for our study), the μ-parameter, the gaugino masses M_i, $i=1,2,3$, or the Higgs–higgsino–gaugino couplings $\tilde{g}_u$, $\tilde{g}_d$, $\tilde{g}'_u$, $\tilde{g}'_d$ in

$$-\mathcal{L}=\sqrt{2}\big(\tilde{g}_u H^\dagger \tilde{W}^a T_a \tilde{H}_u+\tilde{g}'_u Y_{H_u} H^\dagger \tilde{B}\tilde{H}_u+\tilde{g}_d H_c^\dagger \tilde{W}^a T_a \tilde{H}_d+\tilde{g}'_d Y_{H_d} H_c^\dagger \tilde{B}\tilde{H}_d\big)+\text{h.c.}, \tag{1}$$

where $H_c=i\sigma_2 H^*$, T_a are the $SU(2)$ generators, and $Y_{H_u}=-Y_{H_d}=1/2$. The Higgs vev is in its usual form $\langle H\rangle=(0,v)^T$, with $v\sim 174$ GeV. The gaugino and higgsino mass parameters $M_{1,2}$ and μ, and the couplings $\tilde{g}_u$, $\tilde{g}_d$, $\tilde{g}'_u$, $\tilde{g}'_d$ are in general complex. However, only three phases are independent and they are associated to the invariants $\phi_1=\arg(\tilde{g}'^*_u\tilde{g}'^*_d M_1\mu)$, $\phi_2=\arg(\tilde{g}^*_u\tilde{g}^*_d M_2\mu)$, $\xi=\arg(\tilde{g}_u\tilde{g}^*_d\tilde{g}'_d\tilde{g}'^*_u)$. The tree-level matching with the full theory above $\tilde{m}$ gives $\arg(\tilde{g}_u)=\arg(\tilde{g}'_u)$, $\arg(\tilde{g}_d)=\arg(\tilde{g}'_d)$, and therefore $\xi=0$, thus leaving only two independent phases. Moreover, in most models of supersymmetry breaking the phases of M_1 and M_2 are equal, in which case there is actually only one CP-invariant.

In terms of mass eigenstates, the relevant interactions are

$$-\mathcal{L}=\frac{g}{c_W}\overline{\chi_i^+}\gamma^\mu\big(G^R_{ij}P_R+G^L_{ij}P_L\big)\chi_j^+ Z_\mu+\left[g\overline{\chi_i^+}\gamma^\mu\big(C^R_{ij}P_R+C^L_{ij}P_L\big)\chi_j^0 W^+_\mu+\frac{g}{\sqrt{2}}\overline{\chi_i^+}\big(D^R_{ij}P_R+D^L_{ij}P_L\big)\chi_j^+ h+\text{h.c.}\right], \tag{2}$$

where

$$G^L_{ij}=V_{iW^+}c_{W^+}V^\dagger_{W^+j}+V_{ih_u^+}c_{h_u^+}V^\dagger_{h_u^+j},\qquad -G^{R*}_{ij}=U_{iW^-}c_{W^-}U^\dagger_{W^-j}+U_{ih_d^-}c_{h_d^-}U^\dagger_{h_d^-j}, \tag{3a}$$

$$C^L_{ij}=-V_{iW^+}N^*_{jW_3}+\frac{1}{\sqrt{2}}V_{ih_u^+}N^*_{jh_u^0},\qquad C^R_{ij}=-U^*_{iW^-}N_{jW_3}-\frac{1}{\sqrt{2}}U^*_{ih_d^-}N_{jh_d^0}, \tag{3b}$$

$$gD^R_{ij}=\tilde{g}^*_u V_{ih_u^+}U_{jW^-}+\tilde{g}^*_d V_{iW^+}U_{jh_d^-},\qquad D^L=\big(D^R\big)^\dagger. \tag{3c}$$

In Eq. (3a), $c_f=T_{3f}-s_W^2 Q_f$ ($s_W^2\equiv\sin^2\theta_W$) is the neutral current coupling coefficient of the fermion $\tilde{f}$ and, accordingly, $c_{W^\pm}=\pm\cos^2\theta_W$, $c_{h_u^+,h_d^-}=\pm(1/2-s_W^2)$. The matrices U, V, N diagonalize the complex chargino and neutralino mass matrices, $M_+=U^T M_+^D V$, $M_0=N^T N_0^D N$, where $M_+^D=\mathrm{Diag}(M_1^+,M_2^+)\geqslant 0$, $M_0^D=\mathrm{Diag}(M_1^0,\dots,M_4^0)\geqslant 0$ and

$$M_+=\begin{pmatrix} M_2 & \tilde{g}_u v\\ \tilde{g}_d v & \mu\end{pmatrix},\qquad M_0=\begin{pmatrix} M_1 & 0 & -\tilde{g}'_d v/\sqrt{2} & \tilde{g}'_u v/\sqrt{2}\\ 0 & M_2 & \tilde{g}_d v/\sqrt{2} & -\tilde{g}_u v/\sqrt{2}\\ -\tilde{g}'_d v/\sqrt{2} & \tilde{g}_d v/\sqrt{2} & 0 & -\mu\\ \tilde{g}'_u v/\sqrt{2} & -\tilde{g}_u v/\sqrt{2} & -\mu & 0\end{pmatrix}. \tag{4}$$

In split supersymmetry, fermion EDMs are generated only at two loops, since charginos and neutralinos, which carry the information of CP violation, are only coupled to gauge and Higgs bosons. To identify all possible diagrams contributing to the EDM, let us first consider the case in which $M_{1,2},\mu\gg M_W$. After we integrate out charginos and neutralinos at one-loop, we generate some effective couplings among SM bosons. These can be described in terms of gauge-invariant, CP-violating operators. There are 5 dimension-6 such operators: $\epsilon_{abc}\tilde{W}^a_{\mu\nu}W^{b\nu\rho}W^{c\mu}_\rho$, $H^\dagger H\tilde{W}^a_{\mu\nu}W^{a\mu\nu}$, $H^\dagger H\tilde{B}_{\mu\nu}B^{\mu\nu}$, $D_\mu H^\dagger D_\nu H\tilde{B}^{\mu\nu}$, $D_\mu H^\dagger T_a D_\nu H\tilde{W}^{a\mu\nu}$, where $W^a_{\mu\nu}$ and $B_{\mu\nu}$ are the $SU(2)$ and $U(1)$ gauge strengths, and $\tilde{W}^a_{\mu\nu}$ and $\tilde{B}_{\mu\nu}$ are their duals. The effective couplings relevant to generate sizable two-loop contributions to the EDM must contain 3 fields, with at least one photon and at most one Higgs boson. The previously-listed operators induce only the effective couplings $\gamma\gamma h$, γZh, and γWW. Notice that CP-violating couplings of the kind $\gamma\gamma\gamma$, $\gamma\gamma Z$ and γZZ are not generated (in particular, the CP-violating operator $B_{\mu\nu}B^{\nu\rho}B^\mu_\rho$ identically vanishes unless there are three different Abelian gauge fields). The absence of these couplings is also confirmed by an explicit one-loop calculation. Once we insert the effective couplings in a loop, we obtain 3 different diagrams contributing at the two-loop level to the EDM of the light SM fermion f, shown in Fig. 1. We therefore have

$$d_f=d_f^{\gamma H}+d_f^{ZH}+d_f^{WW}, \tag{5}$$

$$d_f^{\gamma H}=\frac{eQ_f\alpha^2}{4\sqrt{2}\pi^2 s_W^2}\,\mathrm{Im}\big(D^R_{ii}\big)\frac{m_f M_i^+}{M_W m_H^2}f_{\gamma H}\big(r^+_{iH}\big), \tag{6a}$$