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Exotic fermions and electric dipole moments

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The contributions of mirror fermions to the electric dipole moments (EDM's) of leptons and neutrons are studied using the available limits on the mixing of the relevant fermions to their mirror partners. These limits imply EDM's several orders of magnitude larger than the current experimental bounds in the case of the electron and the neutron if the relevant *CP*-violating phases are not unnaturally small. If these phases are large, then the bounds on the EDM's can be used to improve upon the limits on mixing between the ordinary (f) and the mirror (F) fermions. In the specific case of the latter mixing angle being given by $(m_f/M_F)^{1/2}$, one can obtain the electron and the neutron EDM's close to experimental bounds.

Electric dipole moments (EDM's) D^f of fermions provide an important test of models of *CP* violation. The EDM of the neutron and of the electron have received renewed attention recently[1,2] due to the observation that these moments could obtain a sizable contribution from the hitherto neglected two-loop diagrams if Higgs bosons provide the required *CP* violation. One finds that these diagrams could lead to an EDM of order 10^{-26} e cm and 10^{-25} e cm for the electron[2] and the neutron,[1,3] respectively. In contrast, the typical values for the electron EDM D^e obtained[4] in the Kobayashi-Maskawa model, horizontal gauge models, left-right-symmetric models, and superweak-Higgs-boson models are of order 10^{-50}, 10^{-32}, 10^{-30}, and 10^{-31} e cm, respectively.

The EDM's for the ordinary fermions can also be generated[5] if theory contains exotic mirror fermions. These EDM's depend on mixings between ordinary and exotic mirror fermions. Very tight bounds have been placed on these mixings by Langacker and London[6,7] (LL) from a combined analysis of many experiments and by Bhatacharya *et al.*[8] using data from LEP at CERN. We started this investigation with a view of constraining possible exotic contributions to D^f using results in Refs. 6–8. It turned out that the constraints on mixing of ordinary fermions with their exotic mirror partners are actually too weak as far as the EDM is concerned. They lead, for example, to D^e which is about 5 orders of magnitude larger than the experimental bound[9] if the relevant *CP*-violating phase is not unnaturally small. This underlines the importance of the mirror fermionic contributions to various EDM's which we have systematically investigated in this Rapid Communication.

CP-violating EDM's for fermions can arise at the one-loop level if there exist both left- and right-handed currents coupling a pair of fermions to the same gauge or Higgs boson. This happens[4] in models with an extended gauge or Higgs sector, e.g., left-right-symmetric models, two-Higgs-doublet models, etc. This also happens in $SU(2)_L\times U(1)$ theory if additional mirror fermions[5] are present. Such fermions occur naturally in some grand unified theories. We shall, however, work with an $SU(2)_L\times U(1)$ model containing additional generations of mirror fermions consisting of the quark and leptonic $SU(2)_L$ doublets $\binom{U'}{D'}_R$, $\binom{N'}{E'}_R$ and singlets D'_L and E'_L, respectively. Related to the primed weak basis is the mass basis

$$\begin{pmatrix} f' \\ F' \end{pmatrix}_a = U_a^f \begin{pmatrix} f \\ F \end{pmatrix}_a , \tag{1}$$

where $f=e,\nu,u,d$, $F=E,N,U,D$, and $a=L,R$. The matrices U_a^f have been parametrized by LL as

$$U_a^f = \begin{pmatrix} A_a^f & E_a^f \\ F_a^f & G_a^f \end{pmatrix} . \tag{2}$$

The W and Z interactions of leptons written in terms of the mass basis are given as

$$-\mathcal{L}_W = \frac{g}{\sqrt{2}} \left[\overline{(N_R)}^c E_L^{\dagger\nu} A_L^e \gamma_\mu e_L + \bar{N}_R G_R^{\dagger\nu} F_R^e \gamma_\mu e_R \right] W^\mu + \text{H.c.} , \tag{3}$$

$$-\mathcal{L}_Z^{\rm FC} = \frac{g}{2\cos(\theta_W)} [(\bar{e}_L F_L^{\dagger e} F_L^e \gamma_\mu e_L + \bar{e}_L F_L^{\dagger e} G_L^e \gamma_\mu E_L) - (L \Longleftrightarrow R)] Z^\mu . \tag{4}$$

We have displayed only couplings between the mirror and ordinary fermions in Eq. (3) and the flavor-changing terms in Eq. (4). The above Lagrangians contain the induced right-handed currents which are responsible for generating the EDM's.

To start with, we neglect the intergenerational mixing and consider only mixing between a fermion and its mirror counterpart. Later on, we shall comment upon a more general situation. With the neglect of the intergenerational mixing, U_a^f reduce effectively to 2×2 matrices which we parametrize as

$$U_a^f = e^{i\delta_a^f} \begin{pmatrix} c_a^f & s_a^f e^{i\delta_{1a}^f} \\ -s_a^f e^{i\delta_{2a}^f} & c_a^f e^{i\delta_{3a}^f} \end{pmatrix} . \tag{5}$$

Let us first concentrate on the electron EDM D^e. Both the W and Z contribute to it as in Figs. 1(a) and 1(b), respectively. These contributions can be obtained from the existing calculations[10] of other similar diagrams occurring, for example, in the left-right-symmetric models.[11] Figures 1(a) and 1(b) are the only diagrams contributing to D^e in the unitary gauge and lead to

$$D_W^e = \frac{G_F M_N e}{2\sqrt{2}\pi^2}(s_L^{\nu_e} c_R^{\nu_e} s_R^e c_L^e \sin\phi_W^e) I_1(r_N)\,, \tag{6a}$$

$$D_Z^e = \frac{G_F M_E e}{4\sqrt{2}\pi^2}(s_L^e c_R^e s_R^e c_L^e \sin\phi_Z^e) I_2(r_E)\,, \tag{6b}$$

where $\phi_W^e = (\delta_L - \delta_R - \delta_{2R})^{\nu_e} - (\delta_L - \delta_R - \delta_{2R})^e$, $\phi_Z^e = \delta_{1R}^e - \delta_{1L}^e$. M_N (M_E) is the mass of N (E). $r_N = m_N^2/M_W^2$, $r_E = m_E^2/M_Z^2$, and

$$I_1(r) = \frac{1}{(1-r)^2}\left[1 - \frac{11}{4}r + \frac{1}{4}r^2 - \frac{3}{2}\frac{r^2 \ln r}{1-r}\right], \tag{7a}$$

$$I_2(r) = \frac{1}{(1-r)^2}\left[1 + \frac{1}{4}r + \frac{1}{4}r^2 + \frac{3}{2}\frac{r \ln r}{1-r}\right]. \tag{7b}$$

By virtue of unitarity, the mixing angles appearing in Eqs. (6) also appear in interactions of the ordinary fermions. Consequently, many experimental results involving the latter can be used to constrain these mixings. Specifically,[6,7] the $(s_L^i)^2$ for $i = \nu_e$, ν_μ, e, μ, u, and d are constrained by the universality of weak interactions and by the W and Z mass measurements. The induced right-handed currents involving $s_R^{e,\mu}$ are severely restricted by μ and β decay and the corresponding hadronic counterparts by the nonleptonic $K_{\pi 3}$ decay and deep-inelastic scattering. If theory contains lepton-number violations (which happens typically in the presence of the exotic neutrinos) then very strong constraints are placed[7] on the combination $|s_L^{\nu_e} c_L^{\nu_e} s_R^e|$ from the nonobservation of the neutrinoless $\beta\beta$ decay. These constraints have been summarized in Refs. 6 and 7 and we use them here. Specifically, we shall use $(s_L^e)^2 \le 0.026$, $(s_R^e)^2 \le 0.055$, and $|s_L^e c_L^e s_R^e| \le 4 \times 10^{-7}$. These lead to

$$|D_Z^e| \le (7\times 10^{-21} e\,\text{cm})\left(\frac{M_E}{M_Z}\right)\left(\frac{I_2}{1/2}\right), \tag{8a}$$

$$|D_W^e| \le (1.98\times 10^{-25} e\,\text{cm})\left(\frac{M_N}{M_W}\right)\left(\frac{I_1}{9/4}\right). \tag{8b}$$

The bounds obtained in the above equations by maximizing $\sin\phi_{W,Z}^e$ are to be compared with the present experimental bound $|D^e| \le (-1.5 \pm 5.5 \pm 1.5)\times 10^{-26}\, e\,\text{cm}$. It follows that unless the phase ϕ_Z^e is unnaturally small, $\sim 10^{-5}$, the mirror fermionic contribution to D^e implied by the analysis of LL exceeds the current experimental bound. Unlike D_Z^e, D_W^e is severely restricted by the neutrinoless $\beta\beta$ decay. But even with this restriction, D_W^e is close to the experimental upper bound. One could turn around the argument and use Eq. (6) to restrict the relevant mixing angles. Requiring $|D_Z^e| \le 7.2\times 10^{-26} e$ cm, one finds

$$|s_L^e s_R^e| \le (3.8\times 10^{-7})\left(\frac{M_Z}{M_E}\right)\left(\frac{1/2}{I_2}\right)\frac{1}{|\sin\phi_Z^e|}. \tag{9}$$

The corresponding number obtained from the individual fits to $(s_{L,R}^e)^2$ by LL is $|s_L^e s_R^e| \le 3.78\times 10^{-2}$. Hence even for M_E as low as 20 GeV and $\sin\phi_Z^e \sim 10^{-4}$, Eq. (9) represents an order-of-magnitude improvement over the bounds of LL.

Similarly, one can obtain bounds on the EDM's for other leptons using the results of Refs. 6–8. Expressions analogous to Eq. (6) in the case of τ and μ imply

$$|D_Z^\mu| \le 1.97\times 10^{-21}\, e\,\text{cm}\,, \quad |D_W^\mu| \le 5.44\times 10^{-21}\, e\,\text{cm}\,,$$
$$|D_Z^\tau| \le 3.3\times 10^{-21}\, e\,\text{cm}\,, \quad |D_W^\tau| \le 2.1\times 10^{-20}\, e\,\text{cm}\,, \tag{10}$$

where for definiteness we have assumed the mirror fermion masses occurring in diagrams analogous to Figs. 1(a) and 1(b) to be M_W and M_Z, respectively. The limits on $(s_\alpha^\tau)^2$ following from[8] the measurement of the $Z \to \tau^+\tau^-$ decay width are better than obtained by LL and we have used[12] the former in writing Eq. (10). The bounds in Eq. (10) still fall below the experimental bounds on these EDM's.[4] However, they can be larger than the values obtainable in most models considered, for example, by Cheng.[4]

The neutron EDM D^n is related to the quark EDM D^q by $D^n = \frac{4}{3} D^d = \frac{1}{3} D^u$. The mirror quarks U and D contribute to the EDM of the ordinary quarks. These contri-

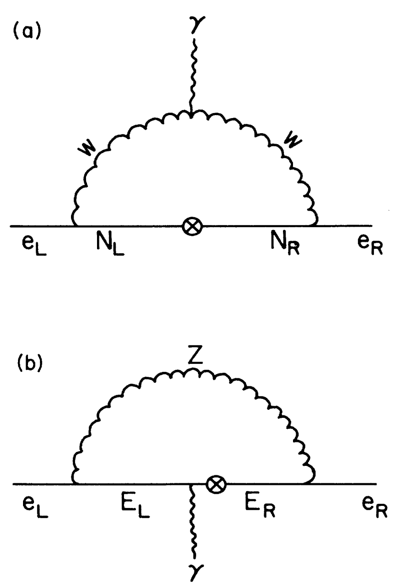

FIG. 1. Diagrams contributing to EDM of the electron. (a) and (b), respectively, denote the W and the Z contributions.

butions are given by

$$D_W^d = \frac{G_F M_U e}{2\sqrt{2}\pi^2}(s_L^u s_R^d c_R^u c_L^d \sin\phi_W^d)[I_1(r_u) + \tfrac{2}{3} I_2(r_u)]\,, \tag{11a}$$

$$D_Z^d = \frac{G_F M_D e}{4\sqrt{2}\pi^2}(s_L^d s_R^d c_R^d c_L^d \sin\phi_Z^d)[\tfrac{1}{3} I_2(r_D)]\,, \tag{11b}$$

$$D_W^u = \frac{G_F M_D e}{2\sqrt{2}\pi^2}(s_L^d s_R^u c_R^d c_L^u \sin\phi_W^u)[I_1(r_D) + \tfrac{1}{3} I_2(r_D)]\,, \tag{11c}$$

$$D_Z^u = \frac{G_F M_U e}{2\sqrt{2}\pi^2}(-s_L^u s_R^u c_R^u c_L^u \sin\phi_Z^u)[\tfrac{1}{3} I_2(r_u)]\,. \tag{11d}$$

$\phi_{W,Z}^d$ are CP-violating phases analogous to $\phi_{W,Z}^e$. Just as in the case of the electron, the limits on s_a^q derived by LL are too weak and imply the quark and, consequently, the neutron EDM of order 10^{-21} e cm if $\sin\phi_{W,Z}^q$ are of order 1. As a consequence, one could obtain bounds on the mixing angles by requiring the quark's EDM to be $\leq 10^{-25}$ e cm. For example, Eqs. (11a) and (11b) lead to

$$|s_L^u s_R^d c_L^d c_R^u| \leq \frac{1.39\times 10^{-7}}{|\sin\phi_W^d|}\left[\frac{M_W}{M_U}\right]\left[\frac{13/4}{3I_1(r_U)+2I_2(r_U)}\right], \tag{12a}$$

$$|s_L^d s_R^d c_L^d c_R^d| \leq \frac{1.59\times 10^{-6}}{|\sin\phi_Z^d|}\left[\frac{M_Z}{M_D}\right]\left[\frac{1/2}{I_2(r_D)}\right]. \tag{12b}$$

If one were to use the maximum values allowed for the s_a^q by the analysis in Ref. 6, the quantities on the left-hand side in Eqs. (12a) and (12b) are, respectively, 1.15×10^{-2} and 1.2×10^{-2}. Hence the bounds obtained here are much stronger than in Ref. 6 even for exotic masses as low as 20 GeV and $\sin\phi_Z^q \geq 10^{-4}$. The EDM given in Eqs. (6) and (11) increase with an increase in exotic fermion masses if the relevant mixing angles do not change. It is, however, most natural to assume that the latter decrease when the exotic-fermion masses are increased. The relation between mixing angles and masses is model dependent. If, for example, a 2×2 mass matrix between an ordinary and exotic fermion is of the form[6]

$$\begin{bmatrix} 0 & \varepsilon \\ \varepsilon & M_F \end{bmatrix},$$

then $(s^f)^2 \sim (m_f/M_F)$ and we obtain

$$D_Z^e = \frac{G_F m_e}{4\sqrt{2}\pi^2} e \sin\phi_Z^e I_2(r_E) \sim (1\times 10^{-24}\, e\,\text{cm})\sin\phi_Z^e\left[\frac{I_2}{1/2}\right],$$

$$D_Z^d = \frac{G_F m_d}{4\sqrt{2}\pi^2} e \sin\phi_Z^d[\tfrac{1}{3} I_2(r_D)] \sim (6.8\times 10^{-24}\, e\,\text{cm})\sin\phi_Z^d\left[\frac{I_2}{1/2}\right],$$

where we have chosen $M_U = M_D$ and $m_u = m_d$ and shown only the EDM's contributing dominantly to D^n and D^e in this limit. Both these EDM's in this case could in fact be larger than the recently discussed[1,2] Higgs-boson contribution if the CP-violating phases are $\geq 10^{-2}$. If the mixing angles depend quadratically on masses, i.e., $s^2 \sim (m_f/M)^2$ then the mirror fermionic contributions are not very large. We have so far neglected mixing among ordinary fermions and assumed that each of the latter mix with its mirror counterpart. The previous considerations are valid even in the presence of the intergenerational mixing as long as only one of the fermions of a given electric charge mixes with the corresponding mirror fermion. Consider, for example, contribution of the Z boson to D^d. In a more general situation with mixing matrices U_α^f as in Eq. (2), D^d is proportional to

$$\text{Im}[(F_L^{\dagger d} G_L^d)_{14}(G_R^{\dagger d} F_R^d)_{41}]\,,$$

where we have assumed only one generation of exotic fermions (labeled by 4) in addition to three ordinary generations. Following Ref. 6 we assume that there are no flavor-changing neutral currents between ordinary fermions. From Eq. (4) this requires that only one of the three quantities $(F_\alpha)_{4i}$ $(i=1,2,3)$ can be nonzero. Assuming this to be $(F_\alpha)_{41}$ and parametrizing it by $(-s_\alpha^d e^{i(\delta_\alpha^d+\delta_{\alpha 2}^d)})$, the above CP-violating combination can be written in terms of only two angles as in the previous case [Eq. (11)] irrespective of the nature of the intergenerational mixing. In contrast with the Z contribution, the W contribution involves elements of the 3×1 matrices E^f appearing in Eq. (2). These cannot be fixed by requiring the absence of the flavor-changing neutral currents. However, if one assumes that only one of $(E_\alpha^f)_{i4}$ is nonzero for each α, i.e., only one f_i mixes with F, then D_W^f can also be written in terms of two angles as before, independent of the nature of the 3×3 matrix A_α^f.

The importance of the contributions of the mirror fermions to EDM's have been stressed earlier also.[5] What we tried to do is to put bounds on their magnitudes using the known bounds on mixing angles between fermions and their mirror partners. In the process, we were led to bounds [Eqs. (9) and (12)] on these mixings which could be much stronger than in Refs. 6–8 if the relevant CP-violating phases are not too small. More importantly, even mixing angles of order $(m_f/M_F)^{1/2}$ could lead to fairly large EDM for the electron which may in fact exceed the recently discussed large contributions[2] in Higgs models of CP violation. Such large values, if observed, could be attributed to the presence of mirror fermions.

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