Neutron electric dipole moment due to Higgs-boson exchange in left-right-symmetric models

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(Received 13 July 1992)

In this paper we study the neutron electric dipole moment due to Higgs-boson exchange in left-right-symmetric models. In pseudomanifest left-right-symmetric models, the neutral Higgs contribution is smaller than that from the charged Higgs boson. The charged-Higgs-contribution at the two-loop level can be as large as the experimental upper bound. In non(pseudo)manifest left-right-symmteric models, the neutral-Higgs-boson exchange contribution can reach the experimental upper bound. The Higgs-boson exchange contributions can be more important than the ones from W-boson exchange due to W_L-W_R mixing.

PACS number(s): 13.40.Fn, 11.30.Er, 12.15.Cc, 14.80.Gt

One of the outstanding problems of particle physics today is the origin of CP violation. CP violation has only been observed in the neutral kaon system, and many models have been proposed to explain it [1]. In order to determine the source (or sources) responsible for CP violation, it is important to find other processes which also violate CP. The measurement of the neutron electric dipole moment (EDM) D_n is a very promising area of investigation. A very stringent upper bound on the neutron EDM (D_n) has been obtained [2], $|D_n| < 1.2\times10^{-25}e\,\mathrm{cm}$, whereas the standard model [3] predicts a very small D_n ($< 10^{-31}e\,\mathrm{cm}$). There are similarly stringent bounds on the electron [4] and atomic [5] EDM's. Assuming that the strong CP θ parameter is negligible, if a neutron EDM within five orders of magnitude of the experimental upper bound should be detected, it signals physics beyond the standard model. In extensions of the standard model it is indeed possible to have a large neutron EDM [6, 7]. CP violation due to Higgs-boson exchange is an example of such models. Recently, several authors have exploited some new classes of two-loop diagrams which induce a large neutron EDM [8–12]. In this paper we study these new contributions due to Higgs-boson exchange in left-right-symmetric models and compare them with the contributions from W-boson exchange due to W_L-W_R mixing [11,13–15]. The neutron EDM due to Higgs-boson exchange at the one-loop level in left-right-symmetric models has been considered before [16]. Here we will discuss both the one-loop and two-loop contributions.

The gauge group of the left-right-symmetric models is $SU(3)_C\times SU(2)_L\times SU(2)_R\times U(1)_{B-L}$ [17]. Under this group the left- and right-handed fermions transform as

$$Q_L = (3,\ 2,\ 1,\ 1/3)\ ,\quad Q_R = (3,\ 1,\ 2,\ 1/3)\ ,$$
$$L_L = (1,\ 2,\ 1,\ -1)\ ,\quad L_R = (1,\ 1,\ 2,\ -1)\ , \tag{1}$$

where Q and L are quarks and leptons, respectively. In order to give fermion masses through the tree-level Higgs-fermion couplings, at least one bidoublet representation of Higgs boson, transforming as $\phi = (1,\ 2,\ 2,\ 0)$, is needed. It can be written as

$$\phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}\ , \tag{2}$$

and its vacuum expectation value (VEV) is

$$\langle\phi\rangle = \begin{pmatrix} v_1 & 0 \\ 0 & v_2 e^{i\delta} \end{pmatrix}\ . \tag{3}$$

In this notation, ϕ transforms as $U_L \phi U_R^\dagger$ under $SU(2)_L\times SU(2)_R$. In order to break $SU(2)_R$ at a higher scale, additional Higgs representations are needed. There are two traditional ways of introducing these Higgs representations:

$$\begin{aligned}&\text{(a) } H_L = (1,\ 2,\ 1,\ 1)\ ,\quad H_R = (1,\ 1,\ 2,\ 1)\ ;\\ &\text{(b) } \Delta_L = (1,\ 3,\ 1, 2),\quad \Delta_R = (1,\ 1,\ 3,\ 2)\ .\end{aligned} \tag{4}$$

In case (a) neutrinos can have only Dirac masses. In case (b) neutrinos can have both Dirac and Majorana masses and the lighter neutrinos have naturally small masses due to the seesaw mechanism. For this reason, case (b) is usually favored in the literature. However, for our purposes, the two cases result in similar phenomenology. If the VEV of $\langle H_R\rangle$ ($\langle\Delta_R\rangle$) $= v_R$ is larger than v_1, v_2, and the VEV of $\langle H_L\rangle$ ($\langle\Delta_L\rangle$) $= v_L$, the symmetry-breaking scales for $SU(2)_L$ and $SU(2)_R$ are well separated. If $v_1v_2 \neq 0$, there is a mixing between W_L and W_R with a mixing angle $\zeta \approx v_1v_2/v_R^2$ for (a) and $2v_1v_2/v_R^2$ for (b). In the following, we shall adopt case (a) for illustrative purposes whenever we need to. For simplicity we will assume $v_L = 0$. In order to make this assumption consistently, it is necessary to impose additional discrete symmetries to eliminate the terms linear in H_L in the Higgs potential [18].

The Higgs-quark couplings are given by

$$L_Y = \bar{Q}_L f\phi Q_R + \bar{Q}_L h\tau_2\phi^*\tau_2 Q_R + \text{H.c.}\ , \tag{5}$$

where f and h are 3×3 matrices. We obtain the mass matrices for quarks,

$$M_u' = fv_1 + hv_2e^{-i\delta},\quad M_d' = fv_2e^{i\delta} + hv_1\ , \tag{6}$$

which can be diagonalized by the transformation

$$M_u' = V_L^{u\dagger}M_uV_R^u\ ,\quad M_d' = V_L^{d\dagger}M_dV_R^d\ , \tag{7}$$

where $M_{u,d}$ are the diagonalized mass matrices for up and down quarks, respectively. The mixing matrices for the charged currents are

$$V_L = V_L^uV_L^{d\dagger}\ ,\quad V_R = V_R^uV_R^{d\dagger}\ . \tag{8}$$

In general V_L and V_R are independent. One can always parametrize V_L in the conventional way in which there is only one *CP*-violating phase for three generations of quarks. Then, in general, V_R will have six *CP*-violating phases. In special cases, the number of *CP*-violating phases is reduced. For simplicity, we shall impose the following left-right exchange symmetry S:

$$Q_L \leftrightarrow Q_R\ ,\quad \phi \leftrightarrow \phi^\dagger\ , \tag{9}$$

on the Lagrangian. It implies $f = f^\dagger$ and $h = h^\dagger$. In the following we shall consider three cases.

(1) *CP* is broken explicitly; however, $\delta = 0$. In this case the mass matrices are Hermitian and can be diagonalized by unitary transformations. Therefore we have

$$V_L = V_R\ . \tag{10}$$

We shall refer to this case as the manifest left-right- (MLR-)symmetric case. Since the phases in V_L and V_R can be simultaneously removed, we can assume that both are transformed into Kobayashi-Maskawa (KM) form.

(2) *CP* is assumed to be spontaneously broken. In this case, f and h are real and symmetric but $\delta \neq 0$. To diagonalize a symmetric matrix it is possible to use $V_L^* = V_R$ in the biunitary transformation. Therefore in arbitrary basis one would have [19]

$$V_R = J_uV_L^*J_d^*\ . \tag{11}$$

with

$$\begin{aligned}J_u &= \text{diag}(e^{-i\alpha_u}\ ,\ e^{-i\alpha_c}\ ,\ e^{-i\alpha_t})\ ,\\ J_d &= \text{diag}(e^{-i\alpha_d}\ ,\ e^{-i\alpha_s}\ ,\ e^{-i\alpha_b})\ .\end{aligned} \tag{12}$$

We shall refer to this case as the pseudomanifest left-right- (PMLR-)symmetric case. We shall take the basis in which V_L is in KM form.

(3) *CP* is explicitly broken and δ is also nonzero. In this case there is no simple relation between V_L and V_R. If one also does not insist on the S symmetry of Eq. (9), V_L and V_R are completely independent. We refer to this case as the nonmanifest left-right- (NMLR-)symmetric case. An interesting special case of this which produces interesting phenomenological consequences is one in which V_R can be written as [20]

$$V_R = \begin{pmatrix}1 & 0 & 0\\ 0 & V_{Rcs} & V_{Rcb}\\ 0 & V_{Rts} & V_{Rtb}\end{pmatrix}\ . \tag{13}$$

This form maximizes the effect of the flavor-changing neutral Higgs boson as we shall show later.

In order to study Higgs-boson contributions to the neutron EDM, we need to find out the physical-Higgs-boson couplings to quarks. For simplicity we will choose case (a) of Eq. (4) and assume that *CP* is broken spontaneously in case (2) or explicitly in case (3) from now on. In that case, there is one charged Higgs eigenstate χ^+ which couples directly to quarks [21]:

$$\chi^+ = \frac{1}{T}\left[(v_1^2 - v_2^2)H_R^+ + v_R(v_1\phi_1^+ + v_2e^{i\delta}\phi_2^+)\right]\ . \tag{14}$$

where $T^2 = v^2v_R^2 + (v_1^2 - v_2^2)^2$, $v^2 = v_1^2 + v_2^2$. The charged Higgs boson associated with H_L does not mix with the others because of the discrete symmetry [18] and does not couple to fermions at all. There are three physical neutral Higgs bosons which couple to quarks. We analyze in a convenient basis $\phi_1'^0$ and $\phi_2'^0$, which are linear combinations of ϕ_1^{0*} and ϕ_2^0 such that $\langle\phi_1'^0\rangle \neq 0$ and $\langle\phi_2'^0\rangle = 0$. The physical neutral Higgs bosons are then expressed as linear combinations of H_1, H_2, and H_3. Here H_1 is the real part of $\phi_1'^0$ while H_2, H_3 are real and imaginary parts of $\phi_2'^0$. They can be written explicitly as [21]

$$\begin{aligned}H_1 &= \cos\theta\ \phi_{1R} + \sin\theta\cos\delta\ \phi_{2R} + \sin\theta\sin\delta\ \phi_{2I}\ ,\\ H_2 &= -\sin\theta\ \phi_{1R} + \cos\theta\cos\delta\ \phi_{2R} + \cos\theta\sin\delta\ \phi_{2I}\ ,\\ H_3 &= \sin\theta\ \phi_{1I} - \cos\theta\sin\delta\ \phi_{2R} + \cos\theta\cos\delta\ \phi_{2I}\ .\end{aligned} \tag{15}$$

where $\cos\theta = v_1/v$ and $\sin\theta = v_2/v$, and $\phi_{iR,L}$ denote the real and imaginary parts of ϕ_i^0, respectively.

For case (b) of Eq. (4), the situation is more complicated because it is harder to eliminate the term linear in Δ_L [22]. If these terms remain then $\langle\Delta_L\rangle \neq 0$ and the singly charged Higgs boson in Δ_L will also mix with ϕ_i^+ just as Δ_R does. The neutral components of $\Delta_{L,R}$ will also mix with H_i defined in Eq. (15) [23]. However, if $v_R \gg v_i$ these mixings will be small. The dominant components which couple to quarks are still $\chi^+ \approx \cos\theta\phi_1^+ + \sin\theta e^{i\delta}\phi_2^+$ and H_i just as in case (a).

The neutral Higgs bosons defined in Eq. (15) are in general not mass eigenstates. However in order to simplify the discussion, we will take these particles to be mass eigenstates in the following for PMLR- and NMLR-symmetric models. In these two cases, the mixings in Eq. (15) already reflect the full complexity of the problem as far as the *CP*-violating phenomenology is concerned. If *CP* is explicitly broken in the Higgs self-couplings, as is required in the case of MLR-symmetric models (since $\delta = 0$), the mixings between these neutral Higgs bosons are more complicated and important. We will comment on this later. The Yukawa interactions of these Higgs bosons to the quark sector are

$$
\begin{aligned}
L_{\text{Yukawa}} = \frac{(\sqrt{2}G_F)^{1/2}}{\cos 2\theta}\Big\{ & \sqrt{2}\Big[\bar{U}_L(M_uV_R - V_LM_d\sin 2\theta e^{-i\delta})D_R - \bar{U}_R(V_RM_d - M_uV_L\sin 2\theta e^{-i\delta})D_L\Big]\chi^+ \\
& + \bar{U}_LM_u(\cos 2\theta H_1 - \sin 2\theta H_2 + i\sin 2\theta H_3)U_R \\
& + \bar{D}_LM_d(\cos 2\theta H_1 - \sin 2\theta H_2 - i\sin 2\theta H_3)D_R \\
& + \bar{U}_L(V_LM_dV_R^\dagger)e^{-i\delta}(H_2 - iH_3)U_R + \bar{D}_L(V_L^\dagger M_uV_R)e^{i\delta}(H_2 + iH_3)D_R\Big\} + \text{H.c.}
\end{aligned}
\qquad (16)
$$

One should note that contrary to the multidoublet extensions of standard model frequently discussed in the literature [9] the charged Higgs boson χ^+ has right-handed couplings M_uV_R that are proportional to up-type quark masses, in addition to the usual left-handed ones. In particular, these new couplings depend on the V_R mixing matrix which is not severely constrained experimentally. Therefore the d_R quark can in principle have a large mixing with t_L through charged Higgs boson. This fact has been observed before [16] but has not been emphasized. Similarly, in the last term the neutral-Higgs-boson couplings are also proportional to M_uV_R. They are partly responsible for the large *CP*-violating effects that we shall discuss later.

We will use the standard KM convention [24] for V_L with Im $V_{Ltb} = 0$. We also set $|V_{us}|_{L,R} \approx |V_{us}|_{L,R} = 0.22$, $|V_{td}|_{L,R} = 0.006$, in PMLR-symmetric models. In NMLR-symmetric models, V_{Rij} can be different from V_{Lij}. We shall assume it is of the form in Eq. (13) to maximize the effect of *CP* violation. For the quark masses we will use $m_u(1\text{ GeV}) = 4.2$ MeV, $m_d(1\text{ GeV}) = 7.5$ MeV, $m_s(1\text{ GeV}) = 150$ MeV, $m_c(m_c) = 1.4$ GeV, $m_b(m_b) = 5$ GeV and $m_t(m_t) = 150$ GeV. Since $m_t \gg m_b$, a natural value for θ is $\sin 2\theta \approx 2\frac{m_b}{m_t}$.

The H_1 boson behaves like the Higgs boson of the standard model. Its coupling does not mediate flavor-changing neutral currents (FCNC's) and does not violate *CP* at the tree level. But H_2 and H_3 do both. Note that in the usual multidoublet extensions of the standard model, such FCNC-mediating Higgs bosons can be avoided by introducing a discrete symmetry [25]. However they are essential parts of the usual left-right-symmetric models [14]. Therefore, in this case, instead of trying to avoid them, we shall investigate under what circumstances their effect can be large and detectable. Because H_2 induces FCNC's at the tree level, its mass must be sufficiently large in order not to yield a too large mass difference between K_L and K_S. This consideration constrains the mass of H_2 to be larger than 8 TeV [26] in the MLR- and PMLR-symmetric models. In PMLR-symmetric models with spontaneous *CP* violation, it was difficult to get $\delta \neq 0$ if one used only minimal Higgs multiplets [27]. However it was also observed [27] that such solution can indeed be obtained if one is willing to make a slight extension of Higgs sector. The lower bound on the mass derived from the absence of FCNC only applies to neutral Higgs bosons. In our estimates, for PMLR-symmetric models we will use 10 TeV for neutral-Higgs-boson mass. The charged Higgs bosons χ^+ can have a smaller mass. When V_L and V_R are independent from each other, if one takes the special form of V_R in Eq. (13), the experimental lower bound for the H_2 mass can be smaller.

We are now ready to estimate the Higgs-boson contributions to the neutron EDM. We shall consider the following three interactions which can give important contributions to the neutron EDM:

$$
\begin{aligned}
&\text{the quark EDM,} && O^\gamma = -\frac{d_q}{2}i\bar{q}\sigma_{\mu\nu}\gamma_5F^{\mu\nu}q\,, \\
&\text{the quark color EDM,} && O_q^C = -\frac{f_q}{2}ig_s\bar{q}\sigma_{\mu\nu}\gamma_5G^{\mu\nu}q\,, \\
&\text{the gluon color EDM,} && O_g^C = -\frac{1}{6}Cf_{abc}G_{\mu\nu}^aG_{\mu\alpha}^b\tilde{G}_{\nu\alpha}^c\,,
\end{aligned}
\qquad (17)
$$

where $F^{\mu\nu}$ is the photon field strength, $G^{\mu\nu}$ is the gluon field strength and $\tilde{G}^{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}G^{\alpha\beta}$.

There are many ways to estimate the contributions of these operators to the neutron electric dipole moment, D_n. Using SU(6) relations we have [6]

$$
\begin{aligned}
D_n(d_q) &= \frac{1}{3}(4d_d - d_u), \\
D_n(f_q) &= \frac{1}{3}\left(\frac{4}{3}f_d + \frac{2}{3}f_u\right)e\,.
\end{aligned}
\qquad (18)
$$

The estimate for O_q^C is more uncertain than that of O^γ. Various other estimates [10] and calculations using sum rule techniques [28] give a range between 0.05 and 1 for the ratio $D_n(f_q)/ef_q$. A recent reevaluation [29] confirms in fact the result of Eq. (18). For the contribution from O_g^C, we use the naive dimensional analysis (NDA) to estimate the neutron EDM [8]:

$$D_n \approx \frac{eM}{4\pi} C \, , \tag{19}$$

where $M = 4\pi f_\pi = 1190$ MeV is the scale of chiral-symmetry breaking. An alternative estimate using QCD sum rules [30] gives a value smaller by about a factor of 30. The sum-rule result involves additional assumptions such as η dominance and its reliability is hard to assess. However, the NDA estimate is also plagued by uncertainties, in this case an arbitrary assumption about the normalization. The comparison of these two estimates may be used as an estimate of the uncertainty in the calculation of hadronic matrix elements.

A nonzero value for f_s will also generate a neutron EDM. It was estimated to give [12]

$$D_n(f_s) \approx 0.03 f_s e \, . \tag{20}$$

As we will show later, in some scenarios, f_s can give rise to the dominant contribution.

In models of *CP* violation, the quark EDM d_q and the quark color EDM f_q can be generated at the one- and two-loop levels. The gluon EDM O_g^C are typically generated at the two-loop level. The one-loop contribution to d_d and f_d from the neutral Higgs boson, as shown in Fig. 1, is given by [16]

$$\begin{aligned} d_d &\approx \left(-\frac{1}{3}e\right) \frac{m_b G_F}{8\sqrt{2}\pi^2} \frac{m_t^2}{\cos^2 2\theta m_H^2} \ln\left(\frac{m_H^2}{m_b^2}\right) \\ &\quad \times \eta_d \mathrm{Im}\left(V_{Ltd}^* V_{Rtb} V_{Ltb}^* V_{Rtd} e^{2i\delta}\right) \, , \\ e f_d &\approx -3 \frac{\eta_f}{\eta_d} d_d \, . \end{aligned} \tag{21}$$

Note that it is assumed that the neutral-Higgs-boson couplings are dominated by the flavor-changing neutral current, the last term in Eq.(16). In PMLR-symmetric models, using Eqs. (11) and (12),

$$\mathrm{Im}\left(V_{Ltd}^* V_{Rtd} V_{Rtb} V_{Ltb}^* e^{i2\delta}\right) \approx |V_{td}|^2 \sin(\alpha_d + \alpha_b + 2\delta - 2\alpha_t) \, . \tag{22}$$

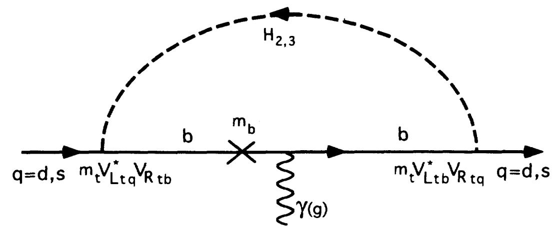

FIG. 1. One-loop contribution to $d_{d,s}(f_{d,s})$ due to the neutral Higgs bosons $H_{2,3}$. The $m_t^2 m_b$ dependence comes from the couplings in Eq. (16) and the mass m_b insertion in the internal b quark line.

For the charged-Higgs-boson contribution in Fig. 2, we obtain [16]

$$\begin{aligned} d_d &\approx \left(\frac{2}{3}e\right) \frac{m_t G_F}{4\sqrt{2}\pi^2} \sin 2\theta \frac{m_t^2}{\cos^2 2\theta m_\chi^2} \ln\left(\frac{m_\chi^2}{m_t^2}\right) \\ &\quad \times \eta_d \mathrm{Im}(V_{Ltd} V_{Rtd}^* e^{-i\delta}) \, , \\ e f_d &\approx \frac{3}{2} \frac{\eta_f}{\eta_d} d_d \, . \end{aligned} \tag{23}$$

In PMLR-symmetric models,

$$\mathrm{Im}(V_{Ltd} V_{Rtd}^*) = |V_{td}|^2 \sin(\alpha_t - \alpha_d - \delta) \, . \tag{24}$$

In Eqs. (21) and (23), $\eta_d = [\alpha_s(m_t)/\alpha_s(\mu)]^{16/23}$ and $\eta_f = [\alpha_s(m_t)/\alpha_s(\mu)]^{14/23}$ are the QCD correction factors [10]. Note that d_d is more suppressed by the QCD correction than f_d. Following Ref. [8], we will use $\alpha_s(\mu) = \frac{4\pi}{6}$ and $\alpha_s(m_t) = 0.1$. As we commented before, Eq. (23) is characterized by its m_t^3 dependence, a feature which distinguishes it from the usual multidoublet models.

Using the numerical values quoted before for the parameters, we find the contribution to D_n from neutral-Higgs-boson exchange to be less than 10^{-28} e cm with $m_H = 10$ TeV. Using the same parameters for the charged-Higgs-boson contribution in PMLR-symmetric models, we have

$$D_n(d_d) = \begin{cases} 3 \times 10^{-28} \sin(\alpha_t - \alpha_d - \delta)\, e\,\mathrm{cm} \, , & m_\chi = 10 \text{ TeV}, \\ 1.3 \times 10^{-26} \sin(\alpha_t - \alpha_d - \delta)\, c\,\mathrm{cm} \, , & m_\chi = 1 \text{ TeV} \, , \end{cases} \tag{25}$$

where we have set $\sin 2\theta \approx 2\frac{m_b}{m_t} \approx 0.04$. We see that the one-loop level Higgs-boson contributions to the neutron EDM are small. Of course if the mass of the charged Higgs boson is much lower than 1 TeV, it is possible to have a larger neutron EDM. A similar contribution also comes from f_d (about 60% of d_d contribution). The contributions from d_u and f_u are smaller because the couplings are smaller.

The contribution to the neutron EDM from f_s due to the neutral Higgs boson is given by

$$\begin{aligned} D_n(f_s) &\approx 0.03 f_s e \approx 0.03 e \frac{m_b G_F}{8\sqrt{2}\pi^2} \frac{m_t^2}{\cos^2 2\theta m_H^2} \ln\left(\frac{m_H^2}{m_b^2}\right) \eta_f \mathrm{Im}\left(V_{Lts}^* V_{Rts} V_{Rtb} V_{Ltb}^* e^{2i\delta}\right) \\ &= (2 \times 10^{-26} e\,\mathrm{cm}) \frac{1}{(0.04)^2} \mathrm{Im}\left(V_{Lts}^* V_{Rts} V_{Rtb} V_{Ltb}^* e^{2i\delta}\right) \, , \quad m_H = 1 \text{ TeV} \, . \end{aligned} \tag{26}$$

There is also a similar contribution from the charged Higgs boson. We have

$$D_n(f_s) \approx 0.03e\frac{m_t G_F}{4\sqrt{2}\pi^2}\sin 2\theta \frac{m_t^2}{\cos^2 2\theta m_\chi^2}\ln\left(\frac{m_\chi^2}{m_t^2}\right)\eta_f \mathrm{Im}\left(V_{Lts}V_{Rts}^* e^{-i\delta}\right)$$
$$= (2.7\times 10^{-26} e\,\mathrm{cm})\frac{1}{(0.04)^2}\mathrm{Im}\left(V_{Lts}V_{Rts}^* e^{-i\delta}\right)\ ,\quad m_\chi = 1\ \mathrm{TeV}\ . \qquad (27)$$

In the special case of Eq. (13), $|V_{Rts}|$ can be larger than $|V_{Lts}| \sim 0.04$, and therefore these contributions can be near the experimental upper bound. In PMLR-symmetric models, $|V_{Rts}| = |V_{Lts}|$ and the neutral-Higgs-boson masses are around 10 TeV. Then, only Eq. (27) contributes significantly, with values near those in Eq. (25).

We now turn to the two-loop contributions. Once again in this case one can take advantage of the fact that CP-violating neutral-Higgs-boson couplings can all be proportional to m_t instead of having at least one of them proportional to m_b as in the case of the multidoublet extensions of standard model. At this level, the neutral-Higgs-boson exchange in Fig. 3 will generate a quark color EDM f_q which is given by [10]

$$f_q = \frac{G_F}{16\sqrt{2}\pi^3}m_q\alpha_s(\mu)\left(\frac{\alpha_s(m_t)}{\alpha_s(\mu)}\right)^{37/23} G\left(\frac{m_t^2}{m_H^2}, q\right)\ ,$$
$$G(z,u) = f(z)\mathrm{Im}Z_{tu} + g(z)\mathrm{Im}Z_{ut}\ , \qquad (28)$$
$$G(z,d) = f(z)\mathrm{Im}Z_{td} + g(z)\mathrm{Im}Z_{dt}\ .$$

For $z \ll 1$,

$$f(z) \approx g(z) \approx \frac{1}{2}z(\ln z)^2\ , \qquad (29)$$

where $\mathrm{Im}Z_{ij}$ are defined through

$$\mathrm{Im}Z_{ij} = 2\gamma_i\beta_j\ . \qquad (30)$$

with

$$L_{int} = (2\sqrt{2}G_F)^{1/2}(\,m_t\gamma_t\bar{t}t + im_t\beta_t\bar{t}\gamma_5 t + m_d\gamma_d\bar{d}d + im_d\beta_d\bar{d}\gamma_5 d + m_u\gamma_u\bar{u}u + im_u\beta_u\bar{u}\gamma_5 u)H_2\ . \qquad (31)$$

In PMLR-symmetric models the largest contribution to f_d is from the term proportional to $\mathrm{Im}Z_{td}$, we have

$$\mathrm{Im}Z_{td} = -\frac{\sin 2\theta}{\cos^2 2\theta}\mathrm{Im}\left[\left(V_{Lud}^* V_{Rud} + \frac{m_c}{m_s}V_{Lcd}^* V_{Rcd} + \frac{m_t}{m_d}V_{Ltd}^* V_{Rtd}\right)e^{i\delta}\right]\ , \qquad (32)$$

and

$$\mathrm{Im}Z_{td} \approx -\frac{m_c}{m_d}\frac{|V_{cd}|^2}{\cos^2 2\theta}\sin 2\theta\sin(\alpha_d - \alpha_c + \delta)\ . \qquad (33)$$

The contribution to D_n is again small, $D_n < 4\times 10^{-29} e\,\mathrm{cm}$ for $m_H = 1$ TeV. The f_u contribution is even smaller.

In the special case of Eq. (13), the contribution from f_s again dominates over other contributions. Changing the subscript d to s in Eqs. (28) and (32), we obtain f_s. The resulting value of the neutron EDM is given by

$$D_n(f_s) \approx 0.03 f_s e$$
$$\approx (2\times 10^{-27} e\,\mathrm{cm})\mathrm{Im}\left(V_{Lcs}^* V_{Rcs}e^{i\delta} + \frac{m_t}{m_c}V_{Lts}^* V_{Rts}e^{i\delta}\right),\quad m_H = 1\ \mathrm{TeV}\ . \qquad (34)$$

This contribution is small.

The operator O_g^C will also be generated at the two-loop level. We find the neutral-Higgs-boson contribution to D_n through this mechanism to be [8]

$$D_n \approx e\xi M\frac{\sqrt{2}G_F}{(4\pi)^2}\mathrm{Im}Z_{tt}h\left(\frac{m_t^2}{m_H^2}\right)\ ,$$
$$\xi = \left(\frac{g(\mu)}{4\pi}\right)^3\left(\frac{\alpha_s(m_b)}{\alpha_s(m_t)}\right)^{-54/23}\left(\frac{\alpha_s(m_c)}{\alpha_s(m_b)}\right)^{-54/25}\left(\frac{\alpha_s(\mu)}{\alpha_s(m_c)}\right)^{-54/27} \approx 6\times 10^{-5}\ . \qquad (35)$$

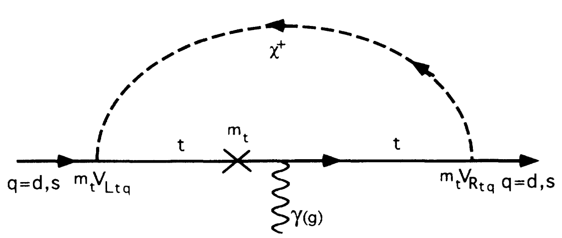

FIG. 2. One-loop contribution to $d_{d,s}(f_{d,s})$ due to the charged Higgs boson χ^+. The m_t^3 dependence comes from the couplings in Eq. (16) and the mass m_t insertion in the internal t-quark line.

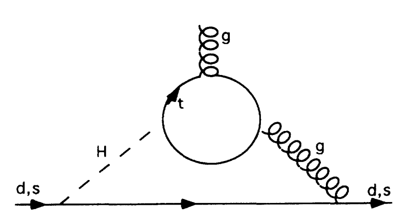

FIG. 3. Leading two-loop contribution to the quark color EDM due to the neutral-Higgs-boson exchange and the virtual top-quark loop effect.

For $z \ll 1$,

$$h(z) \approx \frac{1}{2} z \ln z \, . \tag{36}$$

We have

$$\mathrm{Im} Z_{tt} = -\frac{m_b}{m_t} \frac{\sin 2\theta}{\cos^2 2\theta} \mathrm{Im}(V_{Ltb} V^*_{Rtb} e^{-i\delta}) \, . \tag{37}$$

This effect is extremely small $D_n < 10^{-30} e\,\mathrm{cm}$. In the special case of Eq. (13), this contribution can be larger ($\sim 10^{-28} e\,\mathrm{cm}$) because the neutral-Higgs-boson mass is less constrained.

The charged-Higgs-boson contribution in Fig. 4 to the neutron EDM via the operator O^C_g is given by [8]

$$\begin{aligned} D_n &\approx e\xi' M \frac{\sqrt{2} G_F}{(4\pi)^2} \mathrm{Im} Z' h' \left(\frac{m_t^2}{m_H^2} \right) , \\ \xi' &= \left(\frac{g_s(\mu)}{4\pi} \right)^3 \left(\frac{\alpha_s(m_b)}{\alpha_s(m_t)} \right)^{-14/23} \left(\frac{\alpha_s(m_c)}{\alpha_s(m_b)} \right)^{-54/25} \\ &\quad \times \left(\frac{\alpha_s(\mu)}{\alpha_s(m_c)} \right)^{-54/27} \approx 3 \times 10^{-4}. \end{aligned} \tag{38}$$

For $z \ll 1$,

$$h'(z) \approx \frac{1}{2} z \ln z \, . \tag{39}$$

$\mathrm{Im} Z'$ is defined by

$$\begin{aligned} L_{int} &= (2\sqrt{2} G_F)^{1/2} (a m_b \bar{t}_L b_R + b m_t \bar{t}_R b_L) \chi^+ \, , \\ \mathrm{Im} Z' &= 2 \mathrm{Im}(a b^*) \, . \end{aligned} \tag{40}$$

We have

$$\mathrm{Im} Z' = 2 \frac{m_t}{m_b} \frac{\sin 2\theta}{\cos^2 2\theta} \mathrm{Im}(V_{Rtb} V^*_{Ltb} e^{i\delta}) \, , \tag{41}$$

and, in PMLR-symmetric models,

$$\mathrm{Im} Z' = 2 \frac{m_t}{m_b} \frac{\sin 2\theta}{\cos^2 2\theta} \sin(\delta + \alpha_b - \alpha_t) \, . \tag{42}$$

The neutron EDM from this contribution is

$$D_n = \begin{cases} 2.5 \times 10^{-27} \sin(\delta + \alpha_b - \alpha_t) e\,\mathrm{cm} \, , \\ \qquad\qquad m_\chi = 10 \text{ TeV} \, , \\ 10^{-25} \sin(\delta + \alpha_b - \alpha_t) e\,\mathrm{cm} \, , \\ \qquad\qquad m_\chi = 1 \text{ TeV} \, . \end{cases} \tag{43}$$

This result is also valid for the special case of Eq. (13).

Several comments about our results are in order.

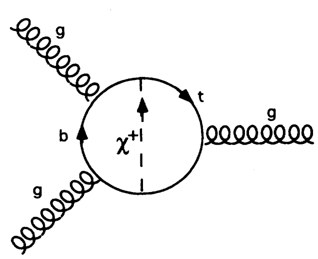

FIG. 4. Leading two-loop contribution to the gluon color EDM due to the charged Higgs-boson exchange.

(1) It is clear from our discussion that the neutral Higgs contributions to the neutron EDM in PMLR-symmetric models are small, while the charged-Higgs-boson contributions can be as large as the experimental upper bound. The one-loop contribution from the charged Higgs boson is smaller than the two-loop contribution. However QCD sum rule calculations show that the dimensional analysis estimate for the O^C_g contribution may be overestimated [30] and the contribution from f_q may be larger than the SU(6) prediction [28]. In this case, the contribution from the charged Higgs boson at the one-loop level may be as important as the two-loop contribution.

If V_L and V_R are independent from each other, the neutral-Higgs-boson masses can be smaller. The contribution to the neutron EDM can then be close to the experimental upper bound.

In MLR-symmetric models, because $V_L = V_R$ and $\delta = 0$ all the contributions discussed above are equal to zero if there is no CP-violating couplings in the Higgs potential. We have mentioned before that in general such couplings exist. In this case even $\delta = 0$ exchange of Higgs particle will violate CP. The calculations are similar to those discussed before. One only needs to change the CP-violating phases in the previous equations to the CP-violating mixing parameters in this case. The Higgs-boson contributions to the neutron EDM are similar to those in PMLR-symmetric models.

(2) Many calculations for the neutron EDM in left-right-symmetric models have concentrated on the contributions from W_L-W_R mixing. All these contributions are proportional to the mixing angle ζ. A large contribution can be obtained from a four-quark operator generated by exchange of the light W boson at the tree level. This was estimated in Ref. [31] to be

$$D_n \approx 2 \times 10^{-19} \zeta \, \mathrm{Im}(V_{Lud} V^*_{Rud}) \, .$$

It is interesting to note that unless there are fortuitous cancellations, ζ is bounded from experimental data on ϵ'/ϵ to be less than 10^{-5} if the CP-violating phase involved is close to one [13]. In that case this contribution will be smaller than the charged-Higgs-boson contribution if the charged-Higgs-boson mass is less than 1 TeV and the phases of $V_{Rtb} V^*_{Ltb} e^{i\delta}$ and $V_{Lud} V_{Rud}$ are the same order of magnitude.

(3) Exchange of Higgs particles in left-right-symmetric models will also generate CP-violating electron-nucleon and nucleon-nucleon interactions which will induce a nonzero atomic EDM. The electron-nucleon interactions will be generated by exchange of neutral Higgs boson at the tree level. We find that these interactions are small [32] (c_S, $c_P < 10^{-10}$). The contribution to CP-violating nucleon-nucleon interactions due to the operator O^C_g from the charged Higgs boson are the largest contributions due to Higgs bosons. However it is also very small [33] ($\eta < 10^{-4}$).

To summarize, we have studied the neutron EDM due to Higgs-boson exchange in left-right-symmetric models. We find that in PMLR-symmetric models the most important effect is from the charged Higgs boson at the two-loop level. In NMLR-symmetric models, the neutral and charged-Higgs-boson contributions at the one-loop level can reach the experimental upper bound. These contributions can be more important than the contributions from W_L-W_R mixing.

X.G.H. would like to thank K.S. Babu for useful discussions. This work was initiated at the Department of Energy's Institute for Nuclear Theory, Seattle, which X.G.H., B.McK., and D.W. thank for its hospitality. X.G.H. also thanks the University of Illinois at Chicago for hospitality where part of this work was done. The partial support of the U.S. Department of Energy, and of the Australian Research Grants Committee, are gratefully acknowledged.

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