Electron Electric Dipole Moment from 
CP Violation in the Charged Higgs Sector

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Abstract

The leading contributions to the electron (or muon) electric dipole moment due to CP violation in the charged Higgs sector are at the two–loop level. A careful model-independent analysis of the heavy fermion contribution is provided. We also consider some specific scenarios to demonstrate how charged Higgs sector CP violation can naturally give rise to large electric dipole moments. Numerical results show that the electron electric dipole moment in such models can lie at the experimentally accessible level.

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Introduction

Experiment has established that neither parity (P) nor charge conjugation (C) are unbroken symmetries. Kaon physics show that CP also fails to be an exact symmetry. The CPT theorem then implies that time-reversal (T) is broken as well, leading to expectation of a T-odd electric dipole moment (EDM) for one or more of the elementary particles. The Standard Model (SM) of electroweak interactions explains CP violation in the $K - \bar{K}$ system as the result of a single complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix. It also predicts an electron EDM $d_e$ of about $8 \times 10^{-41} \text{e} \cdot \text{cm}$ and a muon EDM of about $2 \times 10^{-38} \text{e} \cdot \text{cm}$, while the neutron EDM (calculated from the up and down quark EDMs) is estimated to be less than $10^{-31} \text{e} \cdot \text{cm}$. The experimental limits (given at 95% C.L.) are several orders of magnitude above these predictions, with the limit on the electron EDM $|d_e| < 6.2 \times 10^{-27} \text{e} \cdot \text{cm}$. The limit on $d_\mu$ is even further removed from the SM prediction, with $|d_\mu| < 1.1 \times 10^{-18} \text{e} \cdot \text{cm}$, although there is a proposal to measure the muon EDM down to $10^{-24} \text{e} \cdot \text{cm}$. The neutron EDM limit is $|d_n| < 11 \times 10^{-26} \text{e} \cdot \text{cm}$. Clearly, measurement of a non-zero electron, muon, or neutron EDM close to current or proposed limits would point to physics beyond the Standard Model.

New sources of CP violation can come from complex couplings or vacuum expectation values (VEV) associated with the Higgs boson sector. A significant EDM for elementary fermions can be generated if CP violation is mediated by neutral Higgs-boson exchange. Dominant contributions come from one-loop or two-loop diagrams. The one-loop terms are proportional to $(m/v)^3$ (with one factor of $m/v$ due to an internal mass insertion), while the two-loop terms are proportional to $m/v$, with $m$ being the fermion mass and $v = 246 \text{ GeV}$ the vacuum expectation value of the SM Higgs field. The one-loop contributions are thus strongly suppressed relative to the two-loop terms, by a factor of $(m/v)^2$. Exhaustive studies have been carried out at the two loop level on the electron EDM generated by CP violation in the neutral Higgs-boson sector. The contributions containing a heavy fermion or gauge boson loop were considered and, within an $SU(2) \times U(1)$ theory, are more or less model-independent. Additional, relatively more model-dependent, contributions involving a physical charged Higgs-boson loop (with a CP violating charged-Higgs-neutral-Higgs coupling) have been considered in Ref. On the other hand, the corresponding
contribution to $d_e$ due solely to CP violation in charged Higgs sector has not been studied in the literature, even though this category of CP violating mechanism has been emphasized for other phenomenological effects such as top quark decay\cite{13}, the neutron electric dipole moment\cite{14,15}, and $\Gamma(b \rightarrow s\gamma)$\cite{16}.

With charged Higgs sector CP violation involving fermions, the one-loop contribution is suppressed as in the neutral Higgs case but suffers an additional factor of $m_\nu/m_e$, where $m_\nu$ is the mass of the electron neutrino. If no right-handed neutrino exists, or the neutrino is massless, the two-loop diagrams are unequivocally the leading contribution. It is also important to note that the recent measurement of the decay rate of $b \rightarrow s\gamma$ by the CLEO collaboration\cite{17} stringently constrains\cite{18} the mass of the $H^\pm$ only in the 2HDM II. The constraint is easily evaded in 2HDM III\cite{18,19,20} and other extensions.

In this letter, we make a model-independent study of the two-loop contribution to $d_e$ and $d_\mu$ from charged Higgs exchange between fermions. Useful formulas are given. We discuss specific models to see how this type of CP nonconservation can arise. Numerical results show the electron electric dipole moment can naturally lie within reach of experiment. We also present results for the corresponding contributions to $d_n$.

**General Formalism**

We first comment on the model-independence of our analysis, which considers only those graphs that involve CP violation from charged Higgs exchange between fermions. There are other possibilities, such as quartic charged Higgs vertices involving three or four distinct charged Higgs bosons with complex coupling, but these are strongly dependent on model details and less amenable to model-independent parameterization. Secondly, one may have several charged Higgs bosons, but barring significant degeneracy, cancellation among contributions from the various charged Higgs should be mild. For simplicity we only consider contributions from the lightest charged Higgs. We shall ignore model dependent neutral Higgs sector CP violation contributions and CP violation involving both neutral and charged Higgs bosons, as our concern here is with exclusively charged Higgs sector CP violation effects. We shall also omit terms where the neutral Higgs bosons participate only incidentally,
serving as a leg of an internal loop but not contributing a CP phase. We expect that these (perhaps non-negligible) contributions should not strongly cancel with the part studied here; thus our analysis should furnish a reasonable lower limit to $d_e$ for general theories with CP violating charged Higgs exchange between fermions.

We parametrize the charged Higgs sector CP violation as follows:

$$\mathcal{L} = \frac{g}{\sqrt{2}} \left( \frac{m_t}{M_W} \bar{t}_R b_L H^+ + \frac{m_e}{M_W} \bar{\nu}_L e_R H^+ + \bar{t}_L \gamma^\alpha b_L W^+_\alpha + \bar{\nu}_L \gamma^\alpha e_L W^+_\alpha \right)$$

$$- m_e \bar{e}_L e_R - m_t \bar{t}_R t_L + \text{H.c.} \quad (1)$$

Note that in our model-independent analysis, one needs not specify the origin of the CP violation (e.g., explicit or spontaneous CP violation).

We only illustrate the most important contribution from the top-bottom generation; our study can easily be generalized to the three generations case. The bottom quark mass $m_b$ is also set to zero. The complex mixing parameters $c_t$ and $c_e$ signal deviations from the 2HDM II. If $c_t c_e^*$ has a non-zero imaginary part, the phase is intrinsic to the lagrangian and cannot be rotated away by redefinition of any or all of the fields in Eq.(1).

The two-loop charged Higgs contribution involves Feynman diagrams such as the one shown in Fig. 1. We first present a simple expression for the one-loop sub-diagram with fermion in the loop, that is, the truncated three-point Green’s function $\Gamma^\mu\nu = \langle 0 | [H^- (p) A^\mu (k) W^{+\nu} (-q)]_+ | 0 \rangle$. We note that $\Gamma^\mu\nu$ is the off-shell extension of the amplitude (and Feynman diagrams) for $H^- \rightarrow W^- \gamma$ given in Ref.[21], and that both $\Gamma^\mu\nu$ and its charge conjugate contribute to $d_e$. We consider only the (gauge-invariant) set of terms in $\Gamma^\mu\nu$ involving CP violation from charged Higgs exchange between fermions.

We have verified that our results are gauge-independent, but the calculation simplifies greatly in the non-linear $R_\xi$ gauge[23]. Since the EDM is defined in the soft photon limit, only the leading term in $k$ is kept. We also work to lowest order in $(m_e/M_W)$, to which approximation the separation of the calculation into $\Gamma^\mu\nu$ and its insertion in the full two-loop graph is gauge-invariant. We thus obtain:

$$\Gamma^\mu\nu = \frac{3e g^2}{16\pi^2 M_W} c_t \left[ (g^\mu\nu q \cdot k - q^\mu k^\nu) S + i P_\epsilon^{\mu\nu\alpha\beta} p_\alpha q_\beta \right], \quad (2)$$
\[ S = \int_0^1 \frac{q_t(1-y)^2 + q_by(1-y)}{1-yq^2/m_t^2} dy, \quad P = \int_0^1 \frac{q_t(1-y) + q_by}{1-yq^2/m_t^2} dy, \]  
\[ d_e = \left( \frac{3e g^2}{32 \pi^2} \right) \left( \frac{g^2}{32 \pi^2 M_W} \right) \left( \frac{m_e}{M_W} \right) \text{Im}(c_t^* c_e) (q_t F_t + q_b F_b) . \]  
(3)

and the quark charges are denoted \( q_t, q_b \). The above vertex is further connected to the lepton propagator to produce EDM (see Fig. 1).

\[ d_e = \left( \frac{3e g^2}{32 \pi^2} \right) \left( \frac{g^2}{32 \pi^2 M_W} \right) \left( \frac{m_e}{M_W} \right) \text{Im}(c_t^* c_e) (q_t F_t + q_b F_b) . \]  
(4)

Here the form factors \( F_\alpha \) for \( \alpha = t, b \) are given by

\[ F_\alpha = \int_0^\infty \int_0^1 \frac{m_t^2 f_\alpha (2-y) dy Q^2 dQ^2}{(M_{H^+}^2 + Q^2)(m_t^2 + yQ^2)(M_W^2 + Q^2)} ; \quad f_t = (1-y), \quad f_b = y . \]  
(5)

The integrations can be carried through analytically,

\[ T(z) = \frac{1 - 3z \pi^2}{z^2} - \left( \frac{1}{z} - \frac{5}{2} \right) \ln z - \left( 2 - \frac{1}{z} \right) \left( 1 - \frac{1}{z} \right) \text{Sp}(1-z) , \]  
(6)

\[ B(z) = \frac{1}{z} + \frac{2z - 1}{z^2} \frac{\pi^2}{6} + \left( \frac{3}{2} - \frac{1}{z} \right) \ln z - \left( 2 - \frac{1}{z} \right) \frac{1}{z} \text{Sp}(1-z) , \]  
(7)

\[ F_t = \frac{T(z_H) - T(z_W)}{z_H - z_W} , \quad F_b = \frac{B(z_H) - B(z_W)}{z_H - z_W} , \]  
(8)

with \( z_H = M_{H^+}^2/m_t^2 \) and \( z_W = M_W^2/m_t^2 \), and the Spence function is defined by \( \text{Sp}(z) = - \int_0^z t^{-1} \ln(1-t) dt \) with the normalization \( \text{Sp}(1) = \pi^2/6 \).

Models

To illustrate how easily this mechanism can give rise to a measurable electron EDM, we consider some specific models. We first note that the charged Higgs contribution to \( d_e \) vanishes to two loops in the much-studied simple extension of the Standard Model — the two Higgs-doublet Model (2HDM)\(^{22}\), with the softly broken discrete symmetry\(^{23}\) imposed to enforce natural flavor conservation (NFC). At one loop level single charged Higgs exchange between fermions does not violate CP\(^{8}\). As for the two loop contribution, setting the scalar doublets \( \phi_i = (\phi_i^0, \phi_i^0) \), \( i = 1, 2 \) to have purely real VEVs \( \langle \phi_i^0 \rangle_0 = v_i \), in the unitary gauge the charged Higgs propagators \( \langle \phi_1^+ \phi_2^{+\dagger} \rangle_0, \langle \phi_1^+ \phi_1^{+\dagger} \rangle_0, \langle \phi_2^+ \phi_2^{+\dagger} \rangle_0 \) are purely real\(^{4, 8}\). Ignoring the CKM matrix, the only complex coupling and thus CP phase in the lagrangian involving
the charged Higgs appears in $\text{Re}[h(\phi_1^* \phi_2 - \nu_1 \nu_2)^2]$; thus charged Higgs CP violation in this model necessarily also involves the pseudoscalar neutral Higgs.

There are, however, several other simple models which can easily contain sufficient CP violation to produce an electron EDM at an observable level, through exchange of a charged Higgs boson between fermions.

**2HDM III.**

In Model III with two Higgs doublets[24, 19], we can choose a basis so that $\langle \phi_0^0 \rangle = \frac{v}{\sqrt{2}}$ and $\langle \phi_0' \rangle = 0$. Then $\phi$ mimics the SM Higgs, and $\phi'$ produces new physics beyond the SM; the physical charged Higgs $H^+$ is just $\phi'^+$. The Yukawa Lagrangian for Model III is

$$\mathcal{L}_Y = \eta_{ij}^U \bar{Q}_{iL} \tilde{\phi} U_{jR} + \eta_{ij}^D \bar{Q}_{iL} \phi D_{jR} + \xi_{ij}^U \bar{Q}_{iL} \phi' U_{jR} + \xi_{ij}^D \bar{Q}_{iL} \phi' D_{jR}$$

$$+ \eta_{ij}^E \bar{L}_{iL} \phi E_{jR} + \xi_{ij}^E \bar{L}_{iL} \phi' E_{jR} + \text{H.c.}$$

Here $i, j$ are generation indices. Coupling matrices $\eta$ and $\xi$ are, in general, non-diagonal. $Q_{iL}$ and $L_{iL}$ are the left-handed SU(2) doublets for quarks and leptons. $U_{jR}$, $D_{jR}$, and $E_{jR}$ are the right-handed SU(2) singlets for up-type and down-type quarks and charged leptons respectively. $\langle \phi \rangle$ generates all fermion mass matrices which are diagonalized by bi-unitary transformations, e.g. $M_U = \text{diag}(m_u, m_c, m_t) = \frac{v}{\sqrt{2}}(L_U)^\dagger \eta^U (R^U)$. In terms of the mass eigenstates $U, D, E$, and $N$ (neutrinos), the relevant charged Higgs interaction is given by

$$\mathcal{L}_{H^+} = -H^+ \bar{U} \left[ V_{KM} \xi^D \frac{1}{2} (1 + \gamma^5) - \xi^{U\dagger} V_{KM} \frac{1}{2} (1 - \gamma^5) \right] D - H^+ \bar{N} \xi^E \frac{1}{2} (1 + \gamma^5) E + \text{H.c.} ,$$

with the CKM matrix $V_{CKM} = (L_U)^\dagger (L_D)$, and $\xi^P = (L^P)^\dagger \xi (R^P)$ (for $P = U, D, E$).

Tree-level flavor changing neutral currents (FCNC) are implied by non-zero off-diagonal elements of the matrices $\xi^{U, D, E}$. We adopt the simple ansatz$[24]$ $\xi_{ij}^{U, D, E} = \lambda_{ij} g \sqrt{m_i m_j} / (\sqrt{2} M_W)$. The mass hierarchy ensures that FCNC within the first two generations are naturally suppressed by small quark masses, while a larger freedom is allowed for FCNC involving the third generations. Here $\lambda_{ij}$ can be $O(1)$ and complex. CP is already not a symmetry even if we restrict our attention to the flavor conserving diagonal entries of $\lambda_{ii}$. We consider only the third generation quark contribution and set $(V_{CKM})_{tb} = 1$. The parameters $c_t$ and $c_e$ in Eq.(11) are given as, $c_e = -\lambda_{ee}$, $c_t = \lambda_{tt}^*$. While $\lambda_{tt}$ cannot be significantly larger than
$O(1)$ without producing strong coupling to the top quark, clearly $\lambda_{ee}$ can be much larger
than $O(1)$ so that $\text{Im}(c_i^*c_e) \gg 1$ is quite allowed.

**3HDM.**

Charged Higgs sector CP violation can occur in the three Higgs doublet model\(^{25, 15}\). The first two doublets $\phi_1$ and $\phi_2$ are responsible for the masses of the $b$–like quarks and the
t–like quarks respectively. The charged leptons $e, \mu$ and $\tau$ only couple to $\phi_1$. The last doublet $\phi_3$ does not couple to the known fermions. This assignment naturally preserves NFC. The mass eigenstates $H_1^+$ and $H_2^+$ together with the unphysical charged Goldstone boson $H_3^+$ are linear combinations of $\phi_i^+$: $\phi_i^+ = \sum_{j=1}^3 U_{ij} H_j^+$ ($i = 1, 2, 3$). As with the CKM matrix for three quark generations in the SM, the mixing amplitude $U_{ij}$ matrix generally contains a single non-zero complex phase, which gives rise to CP nonconservation through the Yukawa
couplings, $c_t = U_{21}(v/v_2)$, $c_e = U_{11}(v/v_1)$. In the approximation that the lightest Higgs
dominates, the index $i$ refers to the lightest charged Higgs. As with the 2HDM III, $\text{Im}(c_i^*c_e)$
can be much larger than one — which occurs here if $v_1 \ll v_2$ (the possibility $v_2 \ll v_1$ is constrained by maintaining perturbative coupling to the top quark).

**Discussion**

We have analyzed the heavy fermion contribution to the electron EDM due to CP viola-
tion in the charged Higgs sector. From the general structure of the typical models discussed
above, we have shown that the relevant CP violating parameter $\text{Im}(c_i^*c_e)$ can be of order
one or larger. In Fig. 2, we show the dependence of the electron EDM on $M_{H^+}$ for the case
$\text{Im}(c_i^*c_e) = 1$. The size of $d_e$ is naturally around $10^{-26}$ e-cm, around the current limit. As
noted above, in any specific model there may be other contributions to $d_e$, but in the absence of accidental strong cancellation, we expect that the results presented here reasonably estimate a lower limit on $d_e$ which applies to a very wide class of CP violating models. In
such case, Fig. 2 may be used, for example, to rule out $m_{H^+} > 200$ GeV for $\text{Im}(c_i^*c_e) \geq 1$.

The muon EDM can be easily obtained by the replacements $m_e \rightarrow m_\mu$ and $\text{Im}(c_i^*c_e) \rightarrow \text{Im}(c_i^*c_\mu)$. In this case, the analogous case of $\text{Im}(c_i^*c_\mu) = 1$ would lead to an observable muon
EDM, assuming the proposed future sensitivity down to $d_\mu = 10^{-24}$ e-cm.
Finally, we can carry over the calculation for \( d_e \) to estimate contributes to \( d_n \), using SU(6) relations \[27\]:

\[
d_n = \frac{1}{3}(4d_d - d_u),
\]

where we obtain the down and up quark EDMs with replacements as made for \( d_\mu \), but with an additional factor \( \eta_q \) multiplying both \( d_d \) and \( d_u \) coming from QCD evolution of the quark mass and the quark EDM \[28\]:

\[
\eta_q = q(m_t, m_b)^{16/23}q(m_b, m_c)^{16/25}q(m_c, \mu)^{16/27},
\]

with \( q(m_a, m_b) = \alpha_s(m_a^2)/\alpha_s(m_b^2) \).

There are sizable uncertainties coming from the quark masses and the extraction of \( d_n \) from \( d_d \) and \( d_u \), but the resulting neutron EDM should be \( d_n \approx 10^{-27} (m_d/m_e) \text{Im}(c_t^* c_d) \ e\cdot\text{cm} \) for \( m_{H^+} \approx 100 \text{ GeV} \) (ignoring the up quark contribution). This contribution would reach the observable limit for \( \text{Im}(c_t^* c_d) > 6 \).

In contrast to the case of \( d_e \) or \( d_\mu \), there is a sizable contribution from the charged Higgs boson through the three-gluon operator \[14, 29\]. The relative magnitudes are highly model-dependent: in 2HDM III, the three-gluon operator may vanish even while the two-loop contributions presented here are non-zero, if \( c_t \) is purely real but \( c_e \) remains complex. In the 3HDM, however, the two contributions to \( d_n \) are either both zero or both non-zero. In any case, barring strong cancellations, our result places a limit of \( m_{H^+} > 100 \text{ GeV} \) for \( \text{Im}(c_t^* c_d) = 6 \).

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**Figures**

Fig. 1. A typical two-loop Feynman diagram for the electron EDM due to charged Higgs sector CP violation. The other diagrams for the one-loop subgraph \( H^- \rightarrow W^-\gamma \) may be found in Ref.\[21\].

Fig. 2. Model-independent contributions to \( d_e \) versus \( M_{H^+} \) for \( \text{Im}(c_t^* c_e) = 1/2, 1 \). The horizontal line denotes the current experimental limit.

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\[ \gamma^{(k, \mu)} \]

\[ \Gamma_{\mu \nu} \]

\[ H^{-}(p) \rightarrow t \rightarrow W^{-}(q, \nu) \]
$d_e \left(10^{-26}\text{ e cm}\right)$

- $\text{Im}(c_t, c_e) = 0.5$
- $m_t = 180\text{ GeV}$
- $M_{H^+}(\text{GeV})$