A Simple Charged Higgs Model of Soft CP Violation without Flavor Changing Neutral Currents

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Abstract

We propose a model of soft CP violation in which the CP violating mechanism naturally lies only in the charged Higgs sector. The charged Higgs mechanism not only accounts for the measured value of the CP-violating parameter $\epsilon$ but also accommodates the current limits on $\epsilon'/\epsilon$. Our model naturally prevents tree-level Flavor-Changing Neutral Currents (FCNCs) of any kind. Unlike the Weinberg-Branco Three-Higgs Doublet Model, the deviation from the Standard Model rate for $b \to s\gamma$ is small. Furthermore, leading contributions to the electron (neutron) electric dipole moment are non-zero beginning at the three (two) loop level. Surprisingly similar to the Standard Kobayashi-Maskawa Model, our model is of milliweak character but with seemingly superweak phenomenology.

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Introduction

Three decades after its surprising discovery in the kaon system\[1\], CP violation has remained mysterious. A desire for deeper insight into its origin is the driving force behind many ongoing experiments and even the construction of new machines such as the two B Factories. While a profound understanding may yet be lacking, several mechanisms have been suggested to explain observed CP violation (i.e., $\epsilon \neq 0$) within a gauge field theory. Kobayashi and Maskawa(KM)\[2\] proposed a third generation of fermions, so that CP violation would arise from the mixing of the three quark generations and is manifested by a single phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. Since then, many other mechanisms have been put forth, including new gauge interactions\[3\], neutral Higgs exchange\[4\], supersymmetric partners\[5\], and charged Higgs exchange\[6, 7\]. However, the KM model has the distinguishing feature that its mechanism is of milliweak strength, though its phenomenology is manifestly superweak\[3\], consistent with current CP related data. Such intricate character has also been the driving force behind the desire to find non-superweak CP violation in the $B$ systems.

The leading model for the charged Higgs mechanism of CP violation has long been the Weinberg Three-Doublet Model of CP violation\[7\], which became even more intriguing after Branco\[8\] proposed a version in which CP violation is softly or spontaneously broken. This scheme naturally avoids tree-level flavor changing neutral currents. Without hard CP violation the CKM matrix is purely real (the KM mechanism is inoperative); CP violation in the kaon system instead results from charged Higgs exchange. Many weaknesses of the Weinberg-Branco Model, however, have since been identified. Sanda and Deshpande pointed out\[9\] that short distance contributions to $\epsilon$, if dominant, would lead to a larger $\epsilon'/\epsilon$ than experimentally allowed, although it was subsequently demonstrated that long distance contributions to $\epsilon$ could be large enough to avoid this difficulty\[10\]. More recently, however, it has become clear that this model has other problems. A charged Higgs light enough to account for the observed $\epsilon$ has already been excluded by the LEP experiments\[11\]. The large neutron electric dipole moment\[11\] (EDM) and substantial rate for $b \rightarrow s\gamma$\[12\] predicted are also contradicted by data, leading several authors\[11, 12\] to rule out this model.

As an illustrative model for charged Higgs CP violation, the Weinberg-Branco Model...
also has the shortcoming that its neutral Higgs sector naturally also contains CP violation, which is usually ignored in the literature to simplify analysis and highlight the charged Higgs mechanism. However, for flavor conserving CP odd observables (e.g., the neutron EDM), the neutral Higgs contribution generically can be competitive with that from charged Higgs exchange.

In this letter we propose an alternative model that may serve as a generic example in which the charged Higgs mechanism of CP violation naturally dominates completely over other mechanisms. CP is broken softly or spontaneously so that the KM mechanism is inoperative. Tree-level flavor changing neutral currents are automatically absent, and the neutral Higgs sector is CP conserving at tree level. As in the KM Model, the quark and electron EDMs are severely suppressed. The electron EDM vanishes at the two-loop level, while the first non-zero contribution to the quark EDMs is at two loops. In contrast to the Weinberg-Branco model, our model easily satisfies other experimental CP violation constraints as well as the rate for $b \to s\gamma$. Finally, the parameter $\theta_{QCD}$ vanishes at tree-level, since we disallow hard CP breaking; we shall see that radiative corrections are mild and consistent with the limit on a non-zero $\theta_{QCD}$.

For most of this letter, we shall assume that CP is broken softly. One can also modify our model to break CP spontaneously by introducing at least one additional CP odd scalar boson, as discussed toward the end of this work, with the bulk of the phenomenology unchanged.

**General Formalism**

The Weinberg-Branco Model augments the Standard Model (SM) with additional Higgs $SU(2)_L$ doublets, which are responsible for kaon system CP violation; in this model, then, since the charged Higgs sector must break CP, so also must the neutral Higgs sector. To mandate charged Higgs exchange as the dominant CP violation mechanism we instead introduce only additional $SU(2)_L$ singlets of quarks and scalars to the theory. The simplest model for our purposes requires two additional charged Higgs singlets, $h_\alpha(\alpha = 1, 2)$ and a vectorial pair of heavy quark fields, $Q_{L,R}$, of electromagnetic charge $-\frac{4}{3}$. This vector quark charge
assignment avoids fractionally charged hadrons. Relevant new terms in the Lagrangian are:

\[ \mathcal{L}_{h_i} = \left[ (g \lambda_{i\alpha} \bar{Q}_L d_i R h_\alpha + M_Q \bar{Q}_L Q_R) + \text{h.c.} \right] - (m^2)_{\alpha\beta} h_\alpha \dagger h_\beta - \kappa_{\alpha\beta} (\phi \dagger \phi - |\langle \phi \rangle|^2) h_\alpha \dagger h_\beta \]  

(1)

where \( \phi \) is the Standard Model Higgs doublet, and \( i \) is summed over the down quark flavors \( (i = d, s, b) \). The vector quark has purely vectorial coupling to the photon and Z boson, with respective charges \( (Q_Q, -Q_Q \sin^2 \theta_W) \), while the charged Higgs couples with charges \( (Q_h, -Q_h \sin^2 \theta_W) \) and \( Q_Q = Q_d + Q_h \). The neutral Higgs sector is identical to that in the Standard Model, with neither flavor changing couplings nor CP violation. The matrices \( m^2 \) and \( \kappa \) are hermitian. Except for the discussion at the end, we assume that CP is broken softly in this Lagrangian, implying a special basis where all the Yukawa \((\lambda, \kappa)\) and the SM couplings are real. We also require (see below) that dim-3 couplings, namely \( M_Q \), are also real. This leaves, as in the KM model, only a single CP violating parameter: \( \text{Im}(m^2)_{12} \). We can diagonalize \( (m^2)_{\alpha\beta} \) by a unitary matrix \( U_{\alpha i} \) which in general is complex: \( h_\alpha = U_{\alpha i} H_i \), with \( H_i \) the mass eigenstates. The quark-Higgs interaction in the mass eigenstate basis is

\[ \mathcal{L}_{QqH} = g \sum_{q = d, s, b} \xi_{qj} (\bar{Q}_L q R) H_j^- + \text{h.c.} \]  

(2)

with \( \xi_{qj} \equiv \lambda_{q\alpha} U_{\alpha j} \). The CP-violating transit propagators can be expressed as \( \langle h_\alpha \dagger h_\beta \rangle = \sum_{i,j = 1,2} U_{i\alpha}^\dagger U_{\beta j} \langle H_i^\dagger H_j \rangle = \sum_{i = 1,2} U_{\beta i} U_{i\alpha}^\dagger \langle H_i^\dagger H_i \rangle \). With \( m_1 \) \((m_2)\) the mass of the lighter \((\text{heavier})\) charged Higgs, CP violation explicitly vanishes if \( m_1 = m_2 \). In the limit that \( m_2 \gg m_1 \), these expressions reduce to \( \langle h_\alpha \dagger h_\beta \rangle = U_{\beta i} U_{i\alpha}^\dagger / (p^2 - m_i^2 + i\epsilon) \), where \( p \) is the momentum flowing in the propagator. The rephasing-invariant measures of CP violation are then \( A_{qq'} = \lambda_{q\alpha} \lambda_{q'\beta} U_{\beta i} U_{i\alpha}^* \xi_{q1}^* \xi_{q'1} \) with \((q, q' = d, s, b)\), and \( B = \kappa_{\alpha\beta} U_{\beta i} U_{i\alpha}^* \). For flavor changing processes, \( A_{qq'} \) plays the main role, with \( B \) its counterpart in flavor conserving processes.

Before continuing, we comment on the strong CP-violation parameter \( \theta_{\text{QCD}} \). With CP symmetry imposed only on the hard \((\text{dim-4})\) terms, the \( \theta_{\text{QCD}} \) parameter is naively zero at tree level, but \( M_Q \) may still be complex. If so, alignment of the QCD vacuum with this complex quark mass will generate a non-zero tree level \( \theta_{\text{QCD}} \). To avoid this contribution, we simply impose CP symmetry on both dim-4 and dim-3 terms. \( M_Q \) will then be real in the same basis that the tree-level \( \theta_{\text{QCD}} \) vanishes. A similar scheme can also be arranged if CP is broken spontaneously (see below). The first non-zero contribution to \( \theta_{\text{QCD}} \) (occurring at two loops) will be discussed later.
Constraint from $\epsilon$

With CP conservation modulo soft-breaking enforced, the CKM matrix is real at tree level. Leading CP violating phenomena should be due solely to the CP-violating phase in the charged Higgs sector. Making the usual “$\pi\pi(I = 0)$ dominance” assumption, the CP violation parameter $\epsilon$ is approximately

$$\epsilon \simeq \frac{e^{i\pi/4}}{\sqrt{2}} \left( \frac{\text{Im} M_{12}}{2\text{Re} M_{12}} + \frac{\text{Im} A_0}{\text{Re} A_0} \right).$$  \hspace{1cm} (3)$$

We shall postpone discussion of $A_0$, but will see later that in our model, as in the KM Model, the second term is negligible. Experimentally, $\epsilon \simeq 0.00226 \exp(i\pi/4)$. The $\Delta S = 2$ part of the effective Hamiltonian to one-loop (i.e., box diagrams) can be written as:

$$\mathcal{H}_{\Delta S=2} = \frac{G_F^2 m_W^2}{16\pi^2} \sum_{I=R,L} C_{\Delta S=2}^f (\mu) O_{\Delta S=2}^f (\mu), \quad O_{\Delta S=2}^{R,L} = \bar{s}_\gamma (1 \pm \gamma_5) d \bar{s}_\gamma (1 \pm \gamma_5) d .$$  \hspace{1cm} (4)$$

The $W$-boson diagrams yield a purely real Wilson coefficient $C_{\Delta S=2}^f (\mu)$; CP violation in kaon matrix elements is due solely to the operator $O_{\Delta S=2}^R$ rather than $O_{\Delta S=2}^L$, in contrast to the KM model. The complex coefficient $C_{\Delta S=2}^R (\mu)$ is generated by the charged Higgs through a box diagram with vertices given by Eq. (2). At the scale $\mu = M_Q$, we have

$$C_{\Delta S=2}^R (M_Q) = 2 \xi_d \xi_s^* \xi_d \xi_s^* \frac{2 m_W^2}{M_Q^2} \frac{f (x_2) - f (x_1)}{x_2 - x_1} + \sum_{i=1,2} (\xi_i \xi_s^*)^2 \frac{2 m_W^2}{M_Q^2} \frac{df}{dx} (x_i),$$  \hspace{1cm} (5)$$

with $x_{1,2} = m_{H_{1,2}}^2 / M_Q^2$, $f (x) = (1 - x + x^2 \log x) / (1 - x)^2$, and $df / dx (1) = 1/3$. Clearly, $C_{\Delta S=2}^R (M_Q)$ is real when $m_2 = m_1$ as it should be. For illustration, we shall take $m_2 \gg m_1$ and $m_1 = M_Q$, in which case the first term is negligible and $C_{\Delta S=2}^R (M_Q) = \frac{2}{3} (\xi_d \xi_s^*)^2 m_W^2 / M_Q^2$.

Following Ref. [14] for the renormalization group evolution and numerical evaluation of hadronic matrix elements to leading order, we obtain

$$C_{\Delta S=2}^R (\mu \leq m_c) = \left[ \frac{\alpha_s (m_c)}{\alpha_s (\mu)} \right]^{6/27} \left[ \frac{\alpha_s (m_b)}{\alpha_s (m_c)} \right]^{6/25} \left[ \frac{\alpha_s (m_t)}{\alpha_s (m_b)} \right]^{6/23} \left[ \frac{\alpha_s (M_Q)}{\alpha_s (m_t)} \right]^{6/21} C_{\Delta S=2}^R (M_Q)$$

$$\approx 0.59 \alpha_s^{-2/9} (\mu) C_{\Delta S=2}^R (M_Q) .$$  \hspace{1cm} (6)$$

We will assume that the $W$-boson contributions dominate the real part of all relevant matrix elements; analysis of $\epsilon' / \epsilon$ below shows this to be consistent. We will thus take, e.g., $\text{Re} M_{12} = \frac{1}{2} \Delta m_K$ from experiment, and have no need of the explicit value of $W$-boson contributions.
to, e.g., $C^L_{\Delta S=2}$. Let $M^R_{12}$ be the contribution of $O^R_{\Delta S=2}$ to the mass matrix. From the input parameters $B_K = 0.75, F_K = 160$ MeV, $m_K = 498$ MeV, $\Delta m_K = 3.51 \times 10^{-15}$ GeV and the relation

$$M^R_{12} = \frac{1}{2m_K} \langle \bar{K}^0 | \mathcal{H}^{\Delta S=2} | K^0 \rangle^* = \frac{G_F^2 m^2_W}{16\pi^2} \frac{1}{2m_K} C^{R}_{\Delta S=2}(\mu) \langle \bar{K}^0 | O^R_{\Delta S=2}(\mu) | K^0 \rangle^* ,$$

$$\langle \bar{K}^0 | O^R_{\Delta S=2}(\mu) | K^0 \rangle^* = \frac{8}{3} \alpha_s(\mu)^2/9 B_K F^2_K m^2_K ,$$ (7)

follows the numerical prediction $M^R_{12}/\Delta m_K = 1.2 \times 10^4 C^{R}_{\Delta S=2}(M_Q)$. Demanding that the imaginary part of $M^R_{12}$ gives enough contribution to $\epsilon$ and the corresponding real part gives just a fraction $\mathcal{F}$ of the mass difference $\Delta m_K$ (i.e. $2\text{Re}(M^R_{12}) = \mathcal{F}\Delta m_K$), we obtain constraints on the Wilson coefficients: Im $C^{R}_{\Delta S=2}(M_Q) = 2.7 \times 10^{-7}$ and Re $C^{R}_{\Delta S=2}(M_Q) = 4.2 \times 10^{-5}\mathcal{F}$. Again, with $m_2 \gg m_1, m_1 = M_Q$, we then find

$$\text{Im} \left( A_{sd}/(0.049)^2 \right)^2 R^2_Q = 1 , \quad \text{Re} \left( A_{sd}/(0.049)^2 \right)^2 R^2_Q = 156\mathcal{F} ;$$ (8)

where $R_Q = 300$ GeV/$M_Q$. The reasonable constraint $|\mathcal{F}| < 1$ can be easily satisfied.

**Constraints from $(\epsilon'/\epsilon)$ and $B^0-\bar{B}^0$ mixing**

The parameter $\epsilon'$ describes direct CP violation in the kaon system. It is given in terms of the $2\pi$ decay amplitudes $A_{0,2} = A(K \rightarrow (\pi\pi)_{0,2})$, where the subscript indicates the isospin of the outgoing state. With $\omega = |A_2/A_0| = 0.045$, $\xi = \text{Im}A_0/\text{Re}A_0$, $\Phi \approx \pi/4$, and $\Omega = (1/\omega) \cdot (\text{Im}A_2/\text{Im}A_0)$,

$$\epsilon' = -\frac{\omega}{\sqrt{2}} \xi (1 - \Omega) \exp(i\Phi) .$$ (9)

The dominant contributions should be the gluon and electroweak penguins mediated by $H$ and $Q$. In contrast to the KM Model, the vector coupling of the vector quark means that the $Z$ boson penguin will be suppressed by $O(m^2_K/m^2_Z)$ due to vector current conservation. The gluon penguin contributes only to $A_0$, but the isospin-breaking electromagnetic penguin (EMP) gives rise to both $A_0$ and $A_2$. Due to its suppression by $O(\alpha/\alpha_s)$, the latter affects $\epsilon'$ solely through its contribution to $\Omega$. Including the effects of evolution from the vector quark mass down to the charm mass scale, we estimate the EMP contribution to be $\Omega_{\text{EMP}} \lesssim O(1)$. There is an additional contribution to $\Omega$ from $\eta, \eta'$ isospin-breaking, with $\Omega_{\eta-\eta'} = 0.25$. We
shall ignore the electromagnetic penguin contribution here (inclusion of the electromagnetic penguin will be studied elsewhere[15]), and set $\Omega = \Omega_{\eta-\eta'}$ to simply the analysis. The inclusion of $\Omega_{\text{EMP}}$ will not change our conclusion qualitatively.

The gluon penguin diagram, which involves the virtual vector quark $Q$ and the charge Higgs boson, produces an effective Hamiltonian at the electroweak scale:

$$H^{\Delta S=1} = (G_F/\sqrt{2}) \tilde{C}(sT^a \gamma_\mu(1 + \gamma_5)d) \times \sum_q (\bar{q} T^a \gamma^\mu q), \quad (10)$$

$$\tilde{C} = \alpha_s \sum_i \frac{\xi_i d_i^2}{6\pi} \frac{m_i^2}{M_Q^2} F \left( \frac{m_{H_i}}{M_Q^2} \right). \quad (11)$$

$$F(x) = \frac{x^2(2x-3)}{(1-x)^4} \log x + \frac{16x^2-29x+7}{6(1-x)^3}; \quad F(1) = \frac{3}{4}. \quad (12)$$

Written in terms of the operators in Ref.[14] (but of flipped chirality),

$$H^{\Delta S=1} = (G_F/\sqrt{2}) \sum_{i=3}^6 \tilde{C}_i \tilde{Q}_i,$$

with $\tilde{C}_{4,6} = \tilde{C}/4$, $\tilde{C}_{3,5} = -\tilde{C}/(4N_c)$, $Q_{3(5)} = (\bar{s}_i d_i)_{V+A} \sum_q (\bar{q}_j q_j)_{V+A(V-A)}$ and $Q_{4(6)} = (\bar{s}_i d_j)_{V+A} \sum_q (\bar{q}_j q_i)_{V+A(V-A)}$, where we have adopted the common notation $(\bar{q} q)_{V+A} (\bar{s} d)_{V-A} = \bar{q} \gamma^\mu(1 + \gamma_5)q \bar{s} \gamma^\mu(1 - \gamma_5)d$.

Again, for simplicity, we study the scenario that $m_2 \gg m_1$ and $m_1 = M_Q \simeq 300$ GeV. Numerically, $\tilde{C}(\mu = 300 \text{ GeV}) = 2.8 \times 10^{-4}(\xi d_s \xi_s') R_Q^2$. The Wilson coefficients are then run from $M_Q$ down to the charm mass scale via the leading logarithm renormalization group equations[14], so that $\tilde{C}_i(\mu = m_c) = r_i \tilde{C}(\mu = 300 \text{ GeV})$, where $(r_3, \ldots, r_6) = (-0.16, 0.22, -0.036, 0.51)$. We note that the two other Wilson coefficients, $\tilde{C}_1, \tilde{C}_2$, are not generated in the evolution. Terms contributing to CP violation, and thus $\epsilon'$, in $A_0$ are

$$\langle (\pi\pi)_0 | H^{\Delta S=1} | K \rangle = \langle (\pi\pi)_0 | \sum_{i=3}^6 \tilde{C}_i \langle (\pi\pi)_0 | \tilde{Q}_i | K \rangle. \quad (13)$$

Using the expressions for the matrix elements $\langle (\pi\pi)_0 | \tilde{Q}_i | K \rangle$ found in Ref.[14] at the scale $\mu = m_c = 1.3$ GeV, we obtain

$$\langle (\pi\pi)_0 | \{\tilde{Q}_3 \ldots \tilde{Q}_6\} | K \rangle(\mu = m_c) = \{0.012, 0.19, -0.10, -0.30\} \text{ GeV}^3,$$

$$\text{Im}A_0 = -\text{Im}(A_{sd}) R_Q^2 \times 2.5 \times 10^{-10} \text{ GeV}.$$
The second equality is derived from constraints in Eq. (8). For $R_Q = 1$ and $\mathcal{F} \approx 0$, $\epsilon'/\epsilon = 1.4 \times 10^{-5}$, which is somewhat smaller than, but certainly consistent with, the results of the FNAL-E731 measurement of $(7.4 \pm 5.9) \times 10^{-4}$ [16], but further from agreement with the CERN-NA31 result of $(23 \pm 7) \times 10^{-4}$ [17]. If we relax the constraint on the contribution to $\Delta m_K$ to allow $\mathcal{F} = -0.3$ (reflecting the uncertainty due to the large long-distance contributions), then $\epsilon'/\epsilon$ rises to $1.3 \times 10^{-4}$. If the omitted electromagnetic penguin contribution $\Omega_{EMP}$ turns out to be negative and important, it could increase the predicted value of $\epsilon'$ by perhaps as much as a factor of two, still well below the experimental limit.

Another (much weaker) constraint to be considered is that from the $B_{s,d}^0$ mass splitting [14]. Proceeding in close analogy to the calculation of the contribution to $\Delta m_K$, we obtain:

$$
\Delta M_{B^0} = 2\frac{G_F^2 m_W^2}{16\pi^2} \frac{1}{2m_B} \eta_B \left( \frac{2}{3} \text{Re} A_{bd}^2 \frac{m_W^2}{M_Q^2} \right) \left( \frac{8}{3} B_B F_B^2 m_B^2 \right),
$$

where again $m_2 \gg m_1$, $m_1 = M_Q = 300$ GeV, with the renormalization group scaling factor $\eta_B = 0.55$ evaluated as for $\Delta m_K$, and $B_B = 1$, $F_B = 180$ MeV, $m_B = 5.28$ GeV. Given the experimental value $\Delta M_{B^0} = 3.3 \times 10^{-13}$ GeV, we have

$$
\delta(\Delta M_{B^0})/\Delta M_{B^0} = 1.1 \times 10^{-6} R_Q^2 \text{Re} \left( A_{bd}/0.049^2 \right)^2.
$$

Even taking $A_{bd} = (0.13)^2$, the fractional contribution is only about 5%.

**Other Constraints**

$b \to s\gamma$: Because the operator due to charged Higgs diagrams has helicity opposite to that generated in the Standard Model contribution, the two do not interfere at amplitude level. Taking $m_2 \gg m_1 = M_Q \simeq 300$ GeV:

$$
\frac{\delta B(b \to s\gamma)}{B(b \to s\gamma)_{SM}} = 3.2 \times 10^{-6} \left| \frac{0.0389}{V_{tb}V_{ts}^*} \right|^2 R_Q^4 \left| \frac{A_{bs}}{0.049^2} \right|^2.
$$

Furthermore, the relevant parameter $A_{bd}$ is not subject to constraints from $\epsilon$ or $\epsilon'$. If it is of the same size as $A_{sd}$, the deviation from the SM would be negligible.

*Strong CP and $\theta_{QCD}$*: There are no tree level complex quark masses in our model, and $\theta_{QCD}$ is only induced starting at the two-loop level, via generation of complex down-flavor quark
masses. A typical diagram is shown in Fig. 1; in contrast to $\epsilon$ and $\epsilon'$, this effect does not require more than one flavor of down-quark. Roughly, $\theta_{\text{QCD}} \sim g^2 A_{dd} \text{Im} B/(16\pi^2)^2$. The present constraint, $\theta_{\text{QCD}} < 10^{-9}$, can easily be accommodated, assuming a moderately small $\kappa$.

**Neutron electric dipole moment**: There is no one-loop diagram to produce the electric dipole moment (EDM) of the light quarks, so our model is very weakly constrained by neutron EDM limits. A down-flavor quark EDM, however, is generated at the two-loop level, in parallel with the generation of complex down quark masses discussed above. A typical contribution is given by Fig. 1, except with an external photon is attached to internal charged lines. An estimate of the two loop contribution is consistent with the current experimental bound.

**Electron electric dipole moment**: Unlike the down-flavor quarks, the electron couples only very indirectly with the CP violating sector. The electron EDM vanishes at the two loop level. We expect the three-loop level contribution to be insignificantly small.

**Decay of new particles**: In this model, $h$ and $Q$ can be assigned a new conserved quantum number which guarantees a lightest exotic particle, either $H_1$ or $Q$. A stable charged Higgs would lead to events with possibly large missing transverse energy, while a stable vector quark might be detected through formation of its bound states\[18\]. Alternatively, one can ignore this quantum number, so that an additional interaction, $h_\alpha L_i L_j$, should be present, which can lead to $H^-$ (on-shell or off-shell) decays into $l^- \nu$. Even in this case, lepton number is still conserved, just as in the Standard Model, since the vector quark and charged Higgs will naturally carry the lepton number ($L = \pm 2$). Another way for $H$ to decay is to introduce a second Higgs doublet and let $H$ couple to two different Higgs doublets. In that case $H$ can decay into a neutral Higgs, plus a charged Higgs which in turn decays into ordinary quarks and leptons.

**Spontaneously Broken CP symmetry**

We shall comment on the corresponding model in which CP is broken spontaneously. This can be implemented by adding a CP-odd scalar, $a$, which develops a non-zero vacuum expectation value (VEV) and breaks CP. However, this scalar will in general couple to $\bar{Q}_L Q_R$
and give rise a complex tree level vector quark mass and, therefore, a tree level $\theta_{\text{QCD}}$. To avoid this, one can add another CP-even scalar singlet, $s$, and impose discrete symmetries which change the signs of either or both $a$ and $s$ and nothing else. As a result, a term such as $iaQ\gamma_5Q$ is forbidden and the only additional term relevant for CP violation is $i \left[ sa (h_1^\dagger h_2 - h_2^\dagger h_1) \right]$. This extra term will give rise to complex $(m^2)_{12}$ after both $s$ and $a$ develop VEVs and break CP. Note that before breaking CP spontaneously, there are two possible definitions of CP symmetry, depending on which of $s$ and $a$ are defined to be CP odd; this is why both must develop VEVs in order to break CP. The extra neutral Higgs will of course mix with the SM Higgs, but since $a$ does not couple to fermions directly, it will have scalar-pseudoscalar coupling to fermions only at the loop level. As a result, its contribution to any CP violating phenomenology will be small.

**Conclusion**

We have proposed a model whose CP violation is solely mediated by charged Higgs bosons. The model is surprisingly similar to the KM model in the sense that the CP-breaking mechanism is seemingly milliweak, while its phenomenology (as studied here) is quite superweak-like. The phenomenological distinction between the two will likely be made clear in experiments planned for the B factory; although our model predicts a real CKM matrix, with corresponding collapse of the unitarity KM triangle, new CP violating contributions will be contained in all the B decay processes designed to measure this triangle. A careful and detailed analysis of such issues is clearly necessary and is in progress[15].

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Figures

Fig. 1. A typical digram contributing to a complex down-flavor quark mass. A chiral rotation transforms this contribution into the effective $\theta_{\text{QCD}}$ term. The cross represents the CP violating insertion of $(m^2)_{12}$. The same diagram, when attached with an external photon line, produces an EDM for the the $d$-quark.

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