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Spontaneous CP violation in some ununified models

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We show that spontaneous CP violation can be achieved in the partially and fully ununified models with four Higgs doublets. The contributions to the K_L-K_S mass difference (Δm_K) and CP-violating effects ($\varepsilon, \varepsilon'/\varepsilon, D_n$) due to the exchange of charged gauge bosons and charged Higgs bosons in the box diagrams and due to the exchange of neutral Higgs bosons in the tree-level diagrams can be explained by a suitable choice of model parameters.

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I. INTRODUCTION

CP violation in an electroweak gauge model can occur due to a phase arising either through the complex couplings in the interaction between the quarks and Higgs fields or through the complex vacuum expectation values (VEV's) of the Higgs fields. Within the framework of the standard $SU(2)_L \times U(1)_Y$ model with one Higgs doublet the former choice gives rise to Kobayashi-Maskawa-(KM-)type or hard CP violation [1] arising through the box diagram due to W_L exchange. With the inclusion of two Higgs doublets [2], although the Higgs potential is CP invariant to start with, the model can lead to spontaneous CP violation (SCPV) if and only if after spontaneous symmetry breaking, not only a nontrivial relative phase exists between two flavor-changing neutral Higgs (FCNH) fields mediating the K^0-$\overline{K^0}$ transition but also the vacuum is CP asymmetric [2,3]. The model admits flavor-changing neutral currents (FCNC's) which can be eliminated with the introduction of other Higgs fields and an appropriate discrete symmetry [3,4]. SCPV is attractive because, in this situation, the CP-violating phase is determined in terms of the parameters in the Higgs potential.

Recently, we have discussed [5] an $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ with two Higgs bidoublets and an appropriate discrete symmetry where we have shown an interesting feature that, on soft symmetry breaking [6,7], the same phase which is responsible for SCPV through the mixing of real and imaginary parts of the neutral Higgs fields at the tree level, also contributes to the CP-violating mechanism through the box diagrams due to $W_{L,R}$ exchange. In this paper we discuss SCPV and investigate if this feature persists within the context of the partially ununified model (PUM) [8] based on the gauge group $SU(2)_{qL} \times SU(2)_{lL} \times U(1)_Y$ and the fully ununified model (FUM) [9] based on the gauge group $SU(2)_{qL} \times SU(2)_{lL} \times U(1)_{Yq} \times U(1)_{Yl}$ for three generations of quarks. The extension of the $SU(2)_L \times U(1)_Y$ gauge group leads to the existence of new gauge bosons [10] and anomaly cancellation requires new and exotic fermions. The observation of these new and extra particles would be the most promising signal for new physics beyond the standard model (SM). Moreover these ununified models, PUM and FUM, could be embedded within the grand-unified gauge groups such as SU(15) or SU(16), where the baryon number is a gauge symmetry. The most significant features of these theories are the suppression of the proton decay and the unification scale becoming much lower (at the TeV scale) [11]. Thus ununified models imply low-energy grand unification and very rich and interesting phenomenology in the next generation experiment.

It is to be noted that both the PUM [8] and FUM [9] contain no Higgs fields to generate the quark masses at the tree level as well as SCPV. In another version of PUM [12], mirror fermions are introduced to generate the quark masses at the one-loop level, but still the Higgs content is insufficient to generate SCPV. An attempt has been made to generate quark masses in the PUM incorporating a Higgs field which is a doublet under $SU(2)_{qL}$ and a singlet under $SU(2)_{lL}$ [13,14]. The FUM contains only one Higgs field which appears in the quark-Higgs Lagrangian. This has motivated us to extend the Higgs sector in the PUM and FUM incorporating additional Higgs fields in order to achieve SCPV. However, the modified Higgs content in our present model breaks the most appealing feature of the ununified model [8,12], the universality between the leptonic and semileptonic charged current weak interactions [12]. Both the leptonic and hadronic charged current strengths are enhanced due to the extension of the Higgs fields. But this enhancement can be suppressed with an appropriate choice of the VEV's of the Higgs fields in the model, so that the charged current phenomenology is consistent with experiment [12]. Similarly, in spite of the lack of the universality between the lepton and hadronic four-fermion charged current vertices in the FUM, the model can be made consistent with low-energy phenomenology with the suitable choice of the VEV's of the Higgs fields.

We show that the SCPV can occur through the hard symmetry-breaking terms [15] in the quark-Higgs interaction Lagrangian and CP violation arises at the tree level due to the exchange of neutral Higgs field through the mixing of their real and imaginary parts. The flavor-changing neutral currents (FCNC's), which arise due to the exchange of neutral Higgs boson at the tree level (Fig. 1), is highly suppressed by the hard symmetry-

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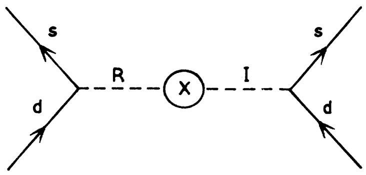

FIG. 1. Tree-level diagram for the $\Delta S = 2$ transition due to the mixing of real and imaginary parts of the neutral Higgs.

breaking parameter ξ with $\xi \ll 1$, and the mass of the neutral Higgs scalar ($M_{H_-} \sim 1$ TeV) [3,6]. Another contribution to the CP-violating parameter comes from the box diagrams (Fig. 2) due to the complex Cabibbo-Kobayashi-Maskawa (CKM) matrix.

The plan of this paper is as follows. PUM and FUM are described in Sec. II. Section III deals with the charged current sector of these models. The Higgs potential and SCPV are discussed in Sec. IV. A brief discussion on mass matrices and CP phenomenology in these models is given in Sec.V. Section VI contains our conclusions.

II. PUM AND FUM

A. Pum

The PUM [8] ununifies the SU(2) gauge group of the standard model in a way such that left-handed (LH) quarks and leptons transform as doublets under $SU(2)_{qL}$ and $SU(2)_{lL}$, respectively. Right-handed (RH) quarks and leptons transform as singlets under both SU(2) gauge groups and the U(1) corresponds to weak hyper charge as in the SM. The electric charge is given by

$$Q = T_{3q} + T_{3l} + Y \ , \tag{1}$$

where T_{3q}, T_{3l}, and Y are the generators of $SU(2)_{qL}$, $SU(2)_{lL}$, and $U(1)_Y$, respectively. The minimal electroweak symmetry-breaking sector consists of two scalars $\Phi_{1l}(1,2,\frac{1}{2})$ and $\Sigma_1(2,2,0)$ with the given choice of VEV's as

$$\langle\Phi_{1l}\rangle = \begin{pmatrix} 0 \\ v_1 \end{pmatrix} , \qquad \langle\Sigma_1\rangle = \begin{pmatrix} u & 0 \\ 0 & u \end{pmatrix} . \tag{2}$$

But these scalars are inadequate to give rise to quark masses [13,14] and SCPV. It has been shown [3,15] that SCPV can be achieved in the SM through the extension of the minimal Higgs sector to two doublets. Furthermore, natural flavor conservation (NFC) can be achieved in an electroweak model through the coupling of up- and down-type quarks with different Higgs fields. These reasons have motivated us to choose a suitable discrete symmetry for NFC and appropriate Higgs sector in the ununified model under consideration. We extend the Higgs sector as $\phi_{1q}(2,1,\frac{1}{2})$, $\phi_{2q}(2,1,\frac{1}{2})$, and $\phi_{2l}(1,2,\frac{1}{2})$ in addition to $\phi_{1l}(1,2,\frac{1}{2})$ and Σ_1(2,2,0). In order to get NFC the discrete D symmetry is incorporated as follows:

$$\begin{gathered} Q_{iL} \to Q_{iL}, \quad u_{jR} \to u_{jR}, \quad d_{jR} \to -d_{jR}, \quad \phi_{1q} \to \phi_{1q}, \\ \phi_{2q} \to -\phi_{2q}, \quad \phi_{1l} \to \phi_{1l}, \quad \phi_{2l} \to -\phi_{2l}, \quad \Sigma_1 \to \Sigma_1 \end{gathered} \tag{3}$$

where i, j=1,2,3 are the generation indices. The following choice of VEV's is taken for the Higgs fields:

$$\begin{aligned} \langle\phi_{1q}\rangle &= \begin{pmatrix} 0 \\ v_2 \end{pmatrix} , \\ \langle\phi_{2q}\rangle &= \begin{pmatrix} 0 \\ v_3 e^{i\theta} \end{pmatrix} , \\ \langle\phi_{2l}\rangle &= \begin{pmatrix} 0 \\ v_4 \end{pmatrix} . \end{aligned} \tag{4}$$

B. Fum

The FUM [9] ununifies the quarks and leptons completely in the sense that the quarks (leptons) transform as doublets under $SU(2)_{qL}$ [$SU(2)_{lL}$] and singlet under $SU(2)_{lL}$ [$SU(2)_{qL}$]. The electric charge in the model is given by

$$Q = T_{3q} + T_{3l} + Y_q + Y_l \ . \tag{5}$$

The scalar sector is given by

$$\begin{gathered} \phi_{1q}(2,1,\tfrac{1}{2},0) = \begin{pmatrix} \phi_{1q}^+ \\ \phi_{1q}^0 \end{pmatrix} , \quad \phi_{1l}(1,2,\tfrac{1}{2},0) = \begin{pmatrix} \phi_{1l}^+ \\ \phi_{1l}^0 \end{pmatrix} , \\ \Sigma_2(1,1,-\tfrac{1}{6},\tfrac{1}{6}), \quad \Delta(2,2,0,0) = \begin{pmatrix} \Delta_1^0 & \Delta^+ \\ \Delta^- & \Delta_2^0 \end{pmatrix} . \end{gathered} \tag{6}$$

We incorporate the Higgs fields $\phi_{2q}(2,1,\frac{1}{2},0)$,

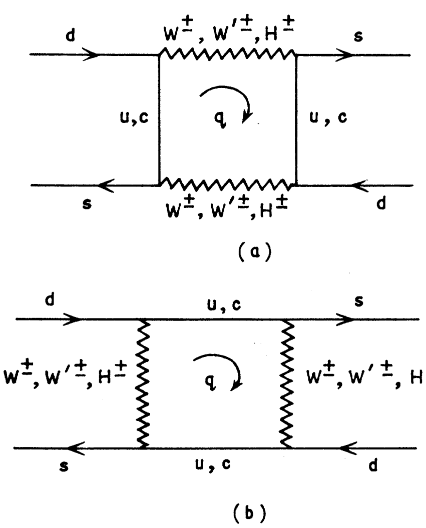

FIG. 2. Box diagrams for the K^0-$\overline{K^0}$ transition due to W, W', $H^\pm$ exchanges.

$\phi_{2l}(1,2,0,\frac{1}{2})$ to achieve SCPV and postulate the following type of discrete symmetry:

$$\begin{aligned}&Q_{iL}\to Q_{iL},\;\; u_{jR}\to u_{jR},\;\; d_{jR}\to -d_{jR},\;\; \phi_{1q}\to\phi_{1q},\\ &\phi_{1l}\to\phi_{1l},\;\; \phi_{2q}\to-\phi_{2q},\;\; \phi_{2l}\to-\phi_{2l},\\ &\Sigma_2\to\Sigma_2,\;\; \Delta\to\Delta\,,\end{aligned} \tag{7}$$

where i,j =1,2,3 are the generation indices. The VEV's are given as

$$\begin{aligned}\langle\phi_{1q}\rangle&=\begin{pmatrix}0\\ v_2\end{pmatrix},\quad \langle\phi_{2q}\rangle=\begin{pmatrix}0\\ v_3e^{i\theta}\end{pmatrix},\\ \langle\phi_{1l}\rangle&=\begin{pmatrix}0\\ v_1\end{pmatrix},\quad \langle\phi_{2l}\rangle=\begin{pmatrix}0\\ v_4\end{pmatrix}.\end{aligned} \tag{8}$$

III. THE CHARGED CURRENTS IN THE UNUNIFIED MODELS

The effective charged current weak Hamiltonian at low energy in the original PUM [8,12] is given by

$$\mathcal{H}_{\rm eff}^{\rm cc}=\frac{2}{v_1^2}\left[(j_q+j_l)^2+\frac{1}{x}j_q^2\right], \tag{9}$$

where $x=(u/v_l)^2$. The nonleptonic weak interactions are enhanced by a factor $(1+1/x)$ relative to the SM where the value of x is estimated to be $x=5$ in order to be consistent with the B-meson semileptonic branching fraction [16]. In the present PUM with an extended Higgs sector [13,14] the effective charged current weak Hamiltonian is given by

$$\mathcal{H}_{\rm eff}^{\rm cc}=A\left[(j_q+j_l)^2+\frac{1}{x_1}j_l^2+\frac{1}{x_2}j_q^2\right], \tag{10}$$

where $A=u^2/(u^2v^2+v_q^2v_l^2)$, $v_q^2=v_2^2+v_3^2$, $v_l^2=v_1^2+v_4^2$, $x_1=(u/v_q)^2$, and $x_2=(u/v_l)^2$. Thus, the strength of the leptonic (j_l^2), hadronic (j_q^2), as well as semileptonic interactions (j_qj_l) are enhanced by a factor $A(1+1/x_1)$, $A(1+1/x_2)$, and A, respectively. The four-fermion coupling constant G_F in the model determining the pure leptonic processes such as μ decay, is given by

$$\sqrt{2}G_F=\frac{u^2+v_q^2}{u^2v^2+v_q^2v_l^2}\,. \tag{11}$$

From Eqs. (10) and (11) we obtain

$$\mathcal{H}_{\rm eff}^{\rm cc}=\sqrt{2}G_F\left[j_l^2+j_q^2\left(\frac{u^2+v_l^2}{u^2+v_q^2}\right)+2j_qj_l\left(\frac{u^2}{u^2+v_q^2}\right)\right]. \tag{12}$$

An analysis has been made in Ref. [14] in which the ratio u/v_q is constrained from the knowledge of the experimental values of the Kobayashi-Maskawa (KM) matrix elements $V'_{ud}=0.9747\pm0.001$, $V'_{us}=0.02196\pm0.0023$ along with the unitarity relation $|V_{ud}|^2_{\rm SM}+|V_{us}|^2_{SM}\le1$, and the analysis leads to the constraint relation

$$\frac{u}{v_q}>20\,. \tag{13}$$

Thus, from Eqs. (11) and (13), the value of G_F can be expressed approximately as

$$\sqrt{2}G_F\simeq\frac{1}{v_q^2+v_l^2}=\frac{1}{v^2}\,, \tag{14}$$

which is in accordance with the SM. In the extended PUM, the most appealing feature of the original ununified model [8,12,16], the universality between the strength of the leptonic and semileptonic interactions, is lost. The ratio of the strength of j_l^2 and j_qj_l in our present model is given by

$$\frac{j_l^2}{j_qj_l}=\frac{u^2+v_q^2}{u^2}=1+\frac{v_q^2}{u^2}\,. \tag{15}$$

Again, applying the constraint relation $u/v_q>20$, we find that the nonuniversality feature decreases as the value of u increases. Moreover, from preliminary $p\bar{p}$ data [17], another constraint relation has been obtained in Ref. [14], which is given by

$$0.2\le\frac{v_q^2}{v_q^2+v_l^2}=y\ (\text{say})\,. \tag{16}$$

Furthermore, we note

$$\text{(i)}\;\; v_l=0\;\;\text{for } y=1, \tag{17a}$$

$$\text{(ii)}\;\; v_q=v_l=0\;\;\text{for } y>1\,. \tag{17b}$$

Hence, for a realistic case, the constraint relation (16) has an upper bound as

$$0.2\le y<1\,. \tag{18}$$

Interestingly, with the present choice $v_q=v_l$ together with Eq. (13), Eq. (12) reduces to

$$\mathcal{H}_{\rm eff}^{\rm cc}=\frac{1}{v^2}\left[(j_q+j_l)^2\right], \tag{19}$$

which is in agreement with the SM. For our present choice $v_l=v_q$ together with $u>20v_q$, the mass of W' is well above 2 TeV. Although the semileptonic branching fraction of the B meson is enhanced from the experimental value, but, with this choice of VEV's $v_q=v_l=u/20=125\sqrt{2}$ GeV, the enhancement can be kept consistent with the SM value [16]. Similarly, the enhancement of neutral current interactions in our present model can also be made consistent with SM for the previous choice of VEV's along with the constraint relation given in Eq. (13). Our analysis remains the same for the FUM also.

IV. HIGGS POTENTIAL AND SCPV

The most general renormalizable and D-invariant Higgs potential in the extended PUM is given by

$$V = V_{\phi_{1q}} + V_{\phi_{2q}} + V_{\Sigma_1} + V_{\phi_{1q}\Sigma_1} + V_{\phi_{2q}\Sigma_1} + v_{\phi_{1q}\phi_{2q}} + V_{\phi_{1q}\phi_{2q}\phi_{1l}\phi_{2l}} + \text{terms replacing } \phi_{1q} \to \phi_{1l}, \phi_{2q} \to \phi_{2l} \ . \quad (20)$$

The terms in the potential can be written explicitly as

$$V_{\phi_{1q}} = -m_1^2 \phi_{1q}^\dagger \phi_{1q} + \mu_1 (\phi_{1q}^\dagger \phi_{1q})^2 \ , \quad (21)$$

$$V_{\phi_{2q}} = -m_2^2 \phi_{2q}^\dagger \phi_{2q} + \mu_2 (\phi_{2q}^\dagger \phi_{2q})^2 \ , \quad (22)$$

$$V_{\Sigma_1} = -m_3^2 \mathrm{Tr}(\Sigma_1^\dagger \Sigma_1) + \mu_3 \mathrm{Tr}(\Sigma_1^\dagger \Sigma_1)^2 \ , \quad (23)$$

$$\begin{aligned} V_{\phi_{1q}\Sigma_1} &= \mu_4 \phi_{1q}^\dagger \phi_{1q} \mathrm{Tr}(\Sigma_1^\dagger \Sigma_1) + \mu_5 \tilde{\phi}_{1q}^\dagger \tilde{\phi}_{1q} \mathrm{Tr}(\tilde{\Sigma}_1^\dagger \tilde{\Sigma}_1) \\ &\quad + \mu_6 \tilde{\phi}_{1q}^\dagger \tilde{\phi}_{1q} \mathrm{Tr}(\Sigma_1^\dagger \Sigma_1) + \mu_7 \phi_{1q}^\dagger \phi_{1q} \mathrm{Tr}(\tilde{\Sigma}_1^\dagger \tilde{\Sigma}_1) \ , \end{aligned} \quad (24)$$

$$\begin{aligned} V_{\phi_{2q}\Sigma_1} &= \mu_8 \phi_{2q}^\dagger \phi_{2q} \mathrm{Tr}(\Sigma_1^\dagger \Sigma_1) + \mu_9 \tilde{\phi}_{2q}^\dagger \tilde{\phi}_{2q} \mathrm{Tr}(\tilde{\Sigma}_1^\dagger \tilde{\Sigma}_1) \\ &\quad + \mu_{10} \tilde{\phi}_{2q}^\dagger \tilde{\phi}_{2q} \mathrm{Tr}(\Sigma_1^\dagger \Sigma_1) + \mu_{11} \phi_{2q}^\dagger \phi_{2q} \mathrm{Tr}(\tilde{\Sigma}_1^\dagger \tilde{\Sigma}_1) \ , \end{aligned} \quad (25)$$

$$\begin{aligned} V_{\phi_{1q}\phi_{2q}} &= \lambda_1 (\phi_{1q}^\dagger \phi_{1q})(\phi_{2q}^\dagger \phi_{2q}) + \lambda_2 (\phi_{1q}^\dagger \phi_{2q})(\phi_{2q}^\dagger \phi_{1q}) + \lambda_3 \left[(\phi_{1q}^\dagger \phi_{2q})^2 + (\phi_{2q}^\dagger \phi_{1q})^2 \right] + \lambda_4 (\phi_{1q}^\dagger \phi_{1q} + \phi_{2q}^\dagger \phi_{2q})^2 \\ &\quad + \lambda_5 (\phi_{1q}^\dagger \phi_{2q} + \phi_{2q}^\dagger \phi_{1q})^2 + \lambda_6 (\phi_{1q}^\dagger \phi_{2q} - \phi_{2q}^\dagger \phi_{1q})^2 \ , \end{aligned} \quad (26)$$

$$V_{\phi_{1q}\phi_{2q}\phi_{1l}\phi_{2l}} = \mu_{11}' (\phi_{1q}^\dagger \phi_{2q} + \phi_{2q}^\dagger \phi_{1q})(\phi_{1l}^\dagger \phi_{2l} + \phi_{2l}^\dagger \phi_{1q}) + \mu_{12} (\phi_{1q}^\dagger \phi_{1q} + \phi_{2q}^\dagger \phi_{2q})(\phi_{1l}^\dagger \phi_{1l} + \phi_{2l}^\dagger \phi_{2l}) \ . \quad (27)$$

In the case of the FUM the Σ_1 field will be replaced by Δ and some other terms due to the Σ_2 field will appear. It is to be noted that although the phase-dependent part of the Higgs potential in the PUM and the FUM are given by the same equations, the representation contents of the Higgs fields, as discussed earlier, are different in these models. All the coefficients in the potential are assumed to be real so that the model has a CP-invariant potential to start with. After substitution of VEV's, the potential V in both the models (PUM and FUM) can be expressed as sum of the phase-independent terms V_0 and phase-dependent term V':

$$V = V_0 + V' \ . \quad (28)$$

After minimization of the potential with respect to θ we obtain a nontrivial phase which is given by

$$\cos\theta = -\frac{\mu_{11}'}{\lambda_3 + \lambda_5 + \lambda_6} \left(\frac{v_1}{v_2} \right) \left(\frac{v_4}{v_3} \right) \ . \quad (29)$$

It is to be noted that, unlike the two Higgs doublet models [6,14], this nontrivial phase which contributes to SCPV in the present ununified models arises without considering D-symmetry-violating terms due to the choice of transformations of the Higgs fields under D symmetry. It is easily seen that the minimum value of the Higgs potential is obtained if

$$(\lambda_3 + \lambda_5 + \lambda_6) > 0 \ . \quad (30)$$

The existence of a nontrivial phase θ, between the flavor-changing neutral Higgs fields ϕ_{1q}^0 and ϕ_{2q}^0 mediating the K^0-$\bar{K}^0$ transition is a necessary but not sufficient condition in order to have CP and T spontaneously broken [18]. Denoting $\psi_1 = \phi_{1q}^0$, $\psi_2 = \phi_{2q}^0$, $\psi_3 = \phi_{1l}^0$, and $\psi_4 = \phi_{2l}^0$, we assume that the most general T transformation is defined by

$$T\psi_i T^{-1} = U_{ij}\psi_i \quad (i,j = 1, \ldots, 4) \ . \quad (31)$$

Given a particular set of VEV's, the vacuum is T invariant (hence CP invariant assuming CPT theorem) if the following relations are satisfied:

$$U_{ij}^* \langle 0|\psi_j|0\rangle^* = \langle 0|\psi_i|0\rangle \ , \quad (32a)$$

$$\mathcal{L}(U\psi) = \mathcal{L}(\psi) \ . \quad (32b)$$

The Higgs potential is also invariant under the discrete symmetry such that

$$\psi_i \to G_{ij}\psi_j \ , \quad (33a)$$

where

$$G = \begin{pmatrix} 1 & 0 & 1 & 0 \\ 0 & -1 & 0 & -1 \\ 1 & 0 & 1 & 0 \\ 0 & -1 & 0 & -1 \end{pmatrix} \ . \quad (33b)$$

Combining Eqs. (32a) and (33a) we get the U matrix as

$$U = \begin{pmatrix} 1 & 0 & c & 0 \\ 0 & -b & 0 & -d \\ \frac{1}{c} & 0 & 1 & 0 \\ 0 & -e & 0 & -1 \end{pmatrix} , \quad (33c)$$

where $b = e^{-2i\theta}$, $c = v_2/v_1$, $d = (v_3/v_4)e^{-i\theta}$, $e = (v_4/v_3)e^{-i\theta}$ with $\det U = 0$. Thus the unitary matrix U is singular and does not exist and, hence, SCPV is ensured in our present models.

V. MASS MATRICES AND CP PHENOMENOLOGY

We consider that the D-symmetry breaking in the quark-Higgs Lagrangian in the models is achieved through a parameter $\xi \ll 1$ [15] so that the SCPV associated with the D symmetry can be treated as perturbation. The quark-Higgs Lagrangian in these models is given by

$$-\mathcal{L}_y = (f_{ij}\bar{Q}^0_{iL}u^0_{jR}\tilde{\phi}_{1q} + g_{ij}\bar{Q}^0_{iL}d^0_{jR}\phi_{2q}) \\ +\xi(f'_{ij}\bar{Q}^0_{iL}u^0_{jR}\tilde{\phi}_{2q} + g'_{ij}\bar{Q}^0_{iL}d^0_{jR}\phi_{1q}) + \text{H.c.}\ , \quad (34)$$

where f_{ij}, g_{ij}, f'_{ij}, g'_{ij} are assumed to be real in order to ensure that L_Y is CP invariant to start with. Substituting the VEV's of the Higgs fields the mass matrices M_u and M_d for the up- and down-type quarks are given by

$$M_u = \hat{f}v_2 + \xi\hat{f}'v_3e^{-i\theta}\ , \quad (35)$$

$$M_d = \hat{g}v_3e^{i\theta} + \xi\hat{g}'v_2\ , \quad (36)$$

where $\hat{f}$, $\hat{g}$, $\hat{f}'$, $\hat{g}'$ are the 3×3 real matrices. Neglecting the second term of M_u (which is the flavor-changing part of the up-type quark) for simplicity and redefining $d_{jR} - e^{-i\theta}d_{jR}$, the up- and down-type quark mass matrices can be rewritten as

$$M_u \approx \hat{f}v_2\ , \\ M_d = M^0_d + \xi e^{-i\theta}\frac{v_2}{v_3}M'_d\ . \quad (37)$$

M^0_d is the flavor-conserving part and M'_d is the flavor-changing part of the down-type mass matrices. This complex nature of the down-type mass matrix leads to the usual contribution to the CP-violation parameter ε due to complex couplings of the quark fields with the gauge bosons through box diagrams [19] due to exchange of charged gauge bosons.

Another CP-violating contribution ε_H to ε comes from the mixing of the real and imaginary parts of the neutral Higgs fields ϕ^0_{1q} and ϕ^0_{2q} at the tree level through imaginary terms [20] such as $\langle\phi^0_{1q},\phi^{0*}_{2q}\rangle, \langle\phi^0_{2q},\phi^{0*}_{1q}\rangle$. Using the conventional procedure [3,6,15] we expand these Higgs fields around their VEV's:

$$\phi^0_{1q} = (v_2 + \phi^{0\prime}_{1q}) = (v_2 + R_1 + iI_1)\ , \quad (38)$$

$$\phi^0_{2q} = (v_3 + \phi^{0\prime}_{2q})e^{i\theta} = (v_3 + R_2 + iI_2)e^{i\theta}\ . \quad (39)$$

In general, the physical scalar H_j's ($j = 1,\ldots, 10$) for the PUM ($j = 1,\ldots,11$ for FUM) are related to the R_k's and I_k's ($k = 1,\ldots,6$ for PUM, $k = 1,\ldots, 7$ for FUM) of weak Higgs fields by a unitary matrix U_H:

$$\begin{pmatrix} R_K \\ I_K \end{pmatrix} = U_H \begin{pmatrix} G_i \\ H_j \end{pmatrix} \quad (40)$$

($i = 1,2$ for PUM, $i = 1,2,3$ for FUM). G_i's are Goldstone bosons which are absorbed by the massless neutral gauge bosons to make Z, Z' massive in the PUM and Z, Z', Z'' massive in the FUM. The exchange of H_j's can lead to CP violation through R-I mixing if the Higgs mass matrix in the weak basis is complex. It is customary to define the relevant neutral Higgs fields for the K^0-$\bar{K}^0$ transition as

$$G = I_1\cos\alpha + I_2\sin\alpha\ , \\ I = -I_1\sin\alpha + I_2\cos\alpha\ , \\ R' = R_1\cos\alpha + R_2\sin\alpha\ , \\ R = -R_1\sin\alpha + R_2\cos\alpha\ , \quad (41)$$

with $\tan\alpha = v_3/v_2$, where G is the Goldstone boson. The coefficient of the mixing of the R and I fields is given by

$$M^2_{R\text{-}I} = A'\sin2\theta\ , \quad (42)$$

where

$$A' \simeq 4(\lambda_3 + \lambda_5 + \lambda_6)(v_2^2\cos^2\alpha - v_3^2\sin^2\alpha)\ . \quad (43)$$

It is interesting to note that, if $v_2 = v_3$, the mixing between real and imaginary parts of the FCNH fields will vanish but still $\theta \neq 0$ as in the two Higgs doublet model [3,6,15]. In this situation, however, the contribution to the CP-violation parameters can come from the box diagrams due to the exchange of W, W' and $H^\pm$. From Eqs. (34), (38), (39), and (41) one obtains the relevant Yukawa Lagrangian responsible for CP violation in the K^0-$\overline{K^0}$ transition, which is given by

$$\mathcal{L}'_y = \sqrt{\sqrt{2}G_F}\left(\frac{v_q}{v_3}\right)^2 \xi(R\{[e^{-i\theta}(U_LM'_dU_R^\dagger)_{12} + e^{i\theta}(U_LM'_dU_R^\dagger)_{21}]\bar{d}s + [e^{-i\theta}(U_LM'_dU_R^\dagger)_{12} - e^{i\theta}(U_LM'_dU_R^\dagger)_{21}]\bar{d}\gamma_5 s\} \\ +iI\{[e^{-i\theta}(U_LM'_dU_R^\dagger)_{12} - e^{i\theta}(U_LM'_dU_R^\dagger)_{21}]\bar{d}s + [e^{-i\theta}(U_LM'_dU_R^\dagger)_{12} + e^{i\theta}(U_LM'_dU_R^\dagger)_{21}]\bar{d}\gamma_5 s\}) + \text{H.c.}\ , \quad (44)$$

where higher-order terms of ξ are neglected. U_L and U_R are the diagonalization matrices for the down-type quark. It can be seen that the CP violation in the K^0-$\overline{K^0}$ transition arises at the tree level (Fig. 1) due to the mixing of real (CP even) and imaginary (CP odd) parts of the Higgs fields.

The contribution to Δm_k arises from the box diagrams due to the exchange of W, W', and $H^\pm$ through charged current vertices as shown in Fig. 2 and the tree-level diagrams through FCNC vertices as shown in Fig. 1. Thus, Δm_k receives contributions in principle from all four terms:

$$\Delta m_K = \Delta m_{W,W'-W,W'} + \Delta m_{W,W'-H^\pm} + \Delta m_{H^\pm-H^\pm} + \Delta m_{H_0} \,. \tag{45}$$

Estimation of first term with the standard W of the SM has been discussed in Ref. [19]. The contribution coming from the box diagrams due to the exchange of W' and $H^\pm$ is much smaller than that due to the exchange of the neutral Higgs at the tree level. The lowest-order contribution to Δm_k due to FCNH is given by (neglecting the top-quark contribution)

$$(\Delta m_K)_{H_0} \approx \left\{ \frac{G_F}{\sqrt{2}} \left(1 + \frac{v_l^2}{v_q^2}\right) \left(\frac{v_q}{v_3}\right)^4 (\xi m_s \sin\theta_C)^2 \right\} \times \left\{ \frac{4}{3} \frac{f_K^2 m_K^3}{m_s^2} \left[\frac{1}{m_I^2} - \frac{B}{m_R^2}\right] \right\} . \tag{46}$$

The bag factor B contains the uncertainties of the hadron dynamics. This parameter has been estimated by vacuum insertion, bag model, and current algebra methods. The value of B is in between $0.33 < B < 3$. We use $B = 1$ in the vacuum saturation approximation. As the dominant contribution to $(\Delta m_k)_{\rm expt}$ comes from the W sectors, the contribution to the K_L-K_S mass difference arising from the neutral Higgs should not exceed [21]

$$(\Delta m_k)_{\rm expt}[= (3.522 \pm 0.016) \times 10^{-12} \text{MeV}] \,.$$

For $v_l = v_q$, $v_2 = 2v_3$, $\xi = 7.6 \times 10^{-2}$, $m_I = 2m_R$, $m_R = 1$ TeV, $\frac{4}{3}(f_k^2 m_k^3/m_s^2) \simeq (0.15)$ GeV^3, we get $(\Delta m_k)_{H_0} < [0.04(\Delta m_k)]_{\rm expt}$, so that the total contribution to (Δm_k) from different sectors agrees with $(\Delta m_k)_{\rm expt}$. Although, the values of the parameters such as v_q/v_l, v_2/v_3, m_I, m_R, ξ can be varied in the same manner as in the two-Higgs-doublet model [15], the $K_L - K_S$ mass difference will not differ much for other values of the parameters quoted above and in this respect quoted parameters are typical.

The CP-violating parameter ε is defined by

$$\varepsilon = \frac{1}{\sqrt{2}} \frac{\text{Im}\langle \bar{K}^0 | H_{\rm eff}^{\Delta s=2} | k^0 \rangle}{\text{Re}\langle \bar{K}^0 | H_{\rm eff}^{\Delta s=2} | k^0 \rangle} = \frac{1}{2} \frac{\text{Im} M_{12}}{\text{Re} M_{12}} = \frac{m'}{2\Delta m_k} \,. \tag{47}$$

Several contributions to ε come from

$$\varepsilon = \varepsilon_{W,W'-W,W'} + \varepsilon_{W,W'-H^\pm} + \varepsilon_{H^\pm-H^\pm} + \varepsilon_{H_0} \,. \tag{48}$$

The first three terms due to the exchange of $W^\pm$ and $H^\pm$ have been discussed in Ref. [15]. The contribution to ε from the extra W' gauge boson can be neglected compared to that due to W boson as the value of M'_W is well above 2 TeV. The neutral Higgs contribution due to the mixing of real and imaginary parts of the neutral Higgs fields at the tree level is given by (for $\theta = \pi/2$)

$$\varepsilon_{H_0} \sim \frac{G_F}{4} B \left(1 + \frac{v_l^2}{v_q^2}\right) \left(\frac{v_q}{v_3}\right)^4 \left(\xi m_s \sin\theta_C\right)^2 \frac{4}{3} \frac{m_K^3}{m_s^2} \frac{f_K^2}{(\Delta m_K)} \times \left\{ \left(\frac{1}{m_R^2} - \frac{1}{m_I^2}\right) \xi \frac{v_2}{v_3} \right\} . \tag{49}$$

For $\xi \sim 7.6 \times 10^{-2}$, and $m_I = 2m_R$ with $m_R = 1$ TeV and $v_2 = 2v_3$, $v_l = v_q$, one obtains [21]

$$\varepsilon \sim \varepsilon_{\rm expt}[= (2.268 \pm 0.623) \times 10^{-3}] \,.$$

It is to be mentioned that although there are not typical parameter values, many possible parameter values give the same typical value of ε.

It is to be noted that if $\xi = 0$ then D symmetry prohibits the couplings of ϕ_{1q} and $\tilde{\phi}_{2q}$ with up- and down-type quarks, respectively, leading to flavor diagonal mass matrices and NFC at the tree level. The phase appearing in M_d can be rotated away by redefining the down-type quark fields. Thus, in order to obtain CP-violation effects, it is necessary to go to two-loop diagrams [22].

The model also admits contributions to ε'/ε arising from the $W^\pm$, $W'^\pm$, $H^\pm$, and H^0 propagators. Interestingly, ε is suppressed by a factor of ξ^3 but ε' is suppressed by ξ and, hence, as discussed in Ref. [15], the value of ε'/ε arising from the neutral Higgs fields is in the range from 10^{-6} to 10^{-4} which is larger than the superweak model. Similarly, the neutron electric dipole moment (D_n) receives the dominant contribution from the charged Higgs sector at the one-loop level and it is possible to obtain $D_n \sim 10^{-26}$–10^{-28} $e\,$cm from the charged Higgs sector like the two-Higgs-doublet model. The same phenomenology can be reproduced for the FUM also. The contribution to the CP-violation parameter arises from the tree level due to the mixing of real and imaginary parts of the neutral Higgs fields of mass around 1 TeV as well as from the box diagrams due to the exchange of W of mass around 100 GeV and W' of mass around 2 TeV for the PUM and FUM.

VI. CONCLUSIONS

We have achieved spontaneous CP violation in some ununified models based on the gauge groups $SU(2)_{qL} \times SU(2)_{lL} \times U(1)_Y$ and $SU(2)_{qL} \times SU(2)_{lL} \times U(1)_{Yq} \times U(1)_{Yl}$ through the appropriate extension of the Higgs sectors of the models and incorporation of a discrete D symmetry. With hard breaking of the D symmetry the models lead to superweak-type CP violation and admit a FCNC which is suppressed by the D-symmetry-breaking parameter ξ and Higgs mass $M_H \sim 1$ TeV. The VEV's of the Higgs fields in the present models are primarily constrained by the universality between the leptonic and semileptonic weak interactions. The contributions to Δm_k and ε come from different sectors of the gauge fields and Higgs fields. The large number of parameters in the model can be adjusted suitably to satisfy the experimental values of Δm_k and ε. The dominant contribution to ε'/ε comes from the neutral Higgs boson exchange and is of the order of 10^{-4}–10^{-6} unlike the superweak model. The neutron electric dipole moment comes from the charged Higgs exchange at the one-loop level and gives rise to $D_n \sim 10^{-26}$–10^{-28} $e\,$cm. Besides the electroweak symmetry-breaking scale at $M_{W_L} \sim 100$ GeV, the present PUM and FUM admit two other CP-violating mass scales at $M'_W \sim 2$ TeV and $M_H \sim 1$ TeV.

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