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FCNC's in leptonic and semileptonic decays of *D* mesons in a general two-Higgs-doublet model

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Large long-distance standard model effects in flavor-changing neutral current (FCNC) semileptonic D decays can make observable these processes in future measurements. Eventual disagreements in this sector and/or the observation of lepton-family-violating (LFV) D decays would require an explanation beyond the standard model framework. In this paper we confront present experimental data on leptonic and semileptonic FCNC and LFV D meson decays with a version of the two-Higgs-doublet model that allows these effects to occur at the tree level. The stringent bounds on the parameters of the model are obtained from $D^0 \to l^+ l'^-$ and $D \to \pi l^+ l'^-$ decays. The consistency of the model requires that the branching fractions of $D \to V l^+ l'^-$ decays should be below the 10^{-9} level. [S0556-2821(98)06713-7]

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I. INTRODUCTION

Flavor-changing neutral currents (FCNC's) in leptonic and semileptonic decays of charmed mesons are higher order, very suppressed modes in the standard model (SM) of particle interactions [1–5]. The short-distance contributions to these processes in the SM are expected to give branching fractions at the 10^{-19} level for $D^0 \to \mu^+ \mu^-$ and 10^{-9} for $D \to \pi l^+ l^-$ processes, while long-distance effects can enhance these predictions up to 10^{-15} [4] and $10^{-7}-10^{-6}$ [5], respectively. Present experimental upper limits for these decays are in the range $10^{-6}-10^{-5}$ for $D^0 \to l^+ l'^-$ and $10^{-3}-10^{-5}$ for $D \to X l^+ l'^-$ [6–10] (X is a pseudoscalar or vector meson and $l, l' = e, \mu$). On the other hand, lepton-family-violating (LFV) processes, i.e., $l \neq l'$, are completely forbidden in the SM scenario with unmixed lepton generations. Thus, FCNC and/or LFV leptonic and semileptonic D decays can serve to test the mechanisms responsible for long-distance contributions or eventually would require an explanation beyond the SM framework. Yet another (unlikely) possibility is that nature places FCNC processes well below the SM expectations. This would force a revision of the estimates of long-distance effects or, again, invoke contributions beyond the SM contributions to explain the eventual destructive interference with the SM amplitudes.

Recently, the study of FCNC's in charm quark decays has attracted a renewed interest [2–11]. On the one hand, it has been pointed out that these rare decays in models of new physics can be enhanced over the SM predictions by several orders of magnitude [4]. On the other hand, the existing bounds on FCNC and LFV D decays have been improved recently at Fermilab E791, E771, and E687 experiments [7–9] and by the CLEO Collaboration [10]. In addition, some projects have been proposed with the aim of reconstructing the order of 10^9 charm decays during the Fermilab Tevatron Run II [11], which would increase the sensitivity to FCNC and LFV processes by almost three orders of magnitude with respect to present experiments. Therefore, it becomes timely to explore all possible scenarios of new physics that may give sizable contributions to these rare decays.

In this paper we consider the constraints imposed by FCNC and LFV D meson decays on a general two-Higgs-doublet model that allows these effects to contribute at the tree level [12]. The variant of the model considered here is built in such a way that tree-level FCNC interactions of neutral Higgs bosons do not spoil the good agreement between the SM predictions and experiment for the down-quark sector. The constraints on Yukawa interactions of the charged Higgs bosons of this model have been studied in previous works [13]. Here we consider the effects of Yukawa interactions of neutral Higgs bosons in FCNC and LFV decays of D mesons. To be more specific, we study the effects of the neutral Higgs bosons of this model in the $D^0 \to l^+ l'^-$, $D \to P l^+ l'^-$, and $D \to V l^+ l'^-$ decays [$P(V)$ stands for a pseudoscalar (vector) light meson and $l, l' = e$ or μ], which will provide a rather wide set of constraints on the effective Yukawa couplings of the model.

II. MODEL

The variant of the two-Higgs-doublet model needed in our work has been described elsewhere [13]. The general form of the Yukawa interactions that allows tree-level FCNC processes is given by [12]

$$\mathcal{L}_Y=\overline{Q_L^0}(F\tilde{\Phi}_1+\xi F'\tilde{\Phi}_2)U_R^0+\overline{Q_L^0}(G\Phi_2+\xi G'\Phi_1)D_R^0 + \overline{\Psi_L^0}(K\Phi_2+\xi K'\Phi_1)l_R^0+\text{H.c.}, \tag{1}$$

where F, F', G, G', K, and K' are dimensionless 3×3 matrices, $\overline{Q_L^0}=(\overline{U_L^0},\overline{D_L^0})$ with U_L^0 (D_L^0) the triplet of left-handed up (down) quarks, and $\overline{\Psi_L^0}=(\overline{\nu_L^0},\overline{l_L^0})$ has a similar definition in terms of leptonic fields. ξ parametrizes the small breaking of the discrete symmetry that forbids FCNC's at the tree level. The superscript 0 in fermion fields stands for weak eigenstates.

Since we are interested in having FCNC contributions only in the up-quark sector, we shall drop the term proportional to G' in Eq. (1) [13]. Notice that the Yukawa interactions for leptons are built to allow FCNC's in the charged leptons and keep massless neutrinos. After spontaneous symmetry breaking, with $\langle\Phi_1\rangle^T=(0,v_1/\sqrt{2})$ and $\langle\Phi_2\rangle^T=(0,v_2e^{-i\alpha'}/\sqrt{2})$, the model contains five physical Higgs bosons; the mass matrices for quarks and charged leptons become

$$M_U=\frac{1}{\sqrt{2}}(Fv_1+\xi F'v_2e^{-i\alpha'}), \tag{2}$$

$$M_D=\frac{1}{\sqrt{2}}Gv_2, \tag{3}$$

$$M_l=\frac{1}{\sqrt{2}}(Kv_2+\xi K'v_1e^{-i\alpha'}). \tag{4}$$

For simplicity we choose to work in a basis where M_U and M_l are diagonal. Notice that, unlike the case where $\xi=0$, F and F' (respectively, K and K') are not diagonal matrices and can allow for (unsuppressed by fermion masses) FCNC interactions in the up-quark sector.

The Yukawa interactions between mass eigenstates of neutral Higgs scalars (H_0 and h_0), the Higgs pseudoscalar (A_0) and fermions $[U=(u,c,t)$ and $l=(e,\mu,\tau)]$ are given by (we do not write the interactions of down quarks because we are interested in FCNC's in the up sector)

$$\begin{aligned}\mathcal{L}_N=&\frac{1}{\sqrt{2}}\bar{U}\{(F\cos\alpha+\xi F'\sin\alpha)H_0\\&+(-F\sin\alpha+\xi F'\cos\alpha)h_0\\&+i(F\sin\beta-\xi F'\cos\beta)A_0\gamma_5\}U\\&+\frac{1}{\sqrt{2}}\bar{l}\{(K\sin\alpha+\xi K'\cos\alpha)H_0\\&+(K\cos\alpha-\xi K'\sin\alpha)h_0\\&+i(K\cos\beta-\xi K'\sin\beta)A_0\gamma_5\}l.\end{aligned} \tag{5}$$

In these expressions, α is the angle that appears in the diagonalization of the neutral scalar Higgs bosons and $\tan\beta\equiv v_2/v_1$.

Because of the low energy scales involved in charm meson decays, it becomes convenient to write out an effective four-fermion interaction Hamiltonian to describe the tree-level processes of our interest. The form of this Hamiltonian is

$$\mathcal{H}_{eff}=\frac{G_F}{\sqrt{2}}\{\bar{U}\Lambda_{H_0}U\cdot\bar{l}L_{H_0}l+\bar{U}\Lambda_{h_0}U\cdot\bar{l}L_{h_0}l + \bar{U}\Lambda_{A_0}\gamma^5U\cdot\bar{l}L_{A_0}\gamma_5 l\}. \tag{6}$$

Using Eqs. (2) and (4), the effective couplings Λ_i and L_i can be written as

$$\Lambda_{H_0}=\frac{2m_W}{gm_{H_0}}\xi F'(\sin\alpha-\tan\beta\cos\alpha e^{-i\alpha'}), \tag{7}$$

$$\Lambda_{h_0}=\frac{2m_W}{gm_{h_0}}\xi F'(\cos\alpha+\tan\beta\sin\alpha e^{-i\alpha'}), \tag{8}$$

$$\Lambda_{A_0}=-\frac{2m_W}{gm_{A_0}}\xi F'(\cos\beta+\tan\beta\sin\beta e^{-i\alpha'}), \tag{9}$$

$$L_{H_0}=\frac{\sqrt{2}M_l}{m_{H_0}}\frac{\sin\alpha}{\sin\beta} + \frac{2m_W}{gm_{H_0}}\xi K'(\cos\alpha-\cot\beta\sin\alpha e^{-i\alpha'}), \tag{10}$$

$$L_{h_0}=\frac{\sqrt{2}M_l}{m_{h_0}}\frac{\cos\alpha}{\sin\beta} - \frac{2m_W}{gm_{h_0}}\xi K'(\sin\alpha+\cot\beta\cos\alpha e^{-i\alpha'}), \tag{11}$$

$$L_{A_0}=\frac{\sqrt{2}M_l}{m_{A_0}}\cot\beta - \frac{2m_W}{gm_{A_0}}\xi K'(\sin\beta+\cot\beta\cos\beta e^{-i\alpha'}). \tag{12}$$

As already anticipated, the leptonic couplings contain a (diagonal) piece proportional to fermion masses[1] and another (nondiagonal) piece which is not *a priori* suppressed by fermion masses and will induce FCNC interactions.

If we assume a specific ansatz for the Yukawa couplings F' and K', we can use the experimental data on D decays to

[1]Since we are interested in $c\to u$ transitions, we do not write a corresponding diagonal mass term in the quark couplings.

get bounds on the remaining parameters of the model. Instead, in the following we choose to use the available data to constrain the effective couplings given in Eqs. (6)–(12).

III. CONSTRAINTS FROM LEPTONIC AND SEMILEPTONIC *D* DECAYS

The relevant hadronic matrix elements of the $\overline{u}c$ and $\overline{u}\gamma_5 c$ currents can be computed from the divergence of the $c\to d$ vector and axial vector charged currents and using isospin symmetry. Thus, we obtain

$$\langle 0|\overline{u}\gamma_5 c|D^0(p)\rangle = i f_D \frac{m_D^2}{m_c+m_u}, \tag{13}$$

$$\langle \pi^+(p')|\overline{u}c|D^+(p)\rangle = \sqrt{2}\langle \pi^0(p')|\overline{u}c|D^0(p)\rangle, \tag{14}$$

$$= \left(\frac{m_D^2-m_\pi^2}{m_c-m_u}\right) F_0^{D^0\to\pi^-}(q^2), \tag{15}$$

$$\langle V(p',\varepsilon^*)|\overline{u}c|D(p)\rangle = 0, \tag{16}$$

$$\langle \rho^+(p',\varepsilon^*)|\overline{u}\gamma_5 c|D^+(p)\rangle = \sqrt{2}\langle \rho^0(p',\varepsilon^*)|\overline{u}\gamma_5 c|D^0(p)\rangle, \tag{17}$$

$$= -\frac{2im_\rho}{m_c+m_u} q\cdot\varepsilon^* A_0^{D^0\to\pi^-}(q^2), \tag{18}$$

where $q=p-p'$ is the momentum transfer to the lepton pair and ε^* is the polarization four-vector of the outgoing vector meson. In Eq. (16), V is a vector meson. Notice that the matrix elements for the $D\to P$ and $D\to V$ transitions depend on only one form factor at a time. This happens because only the relative waves $l=0$ and $l=1$ of the P-Higgs and V-Higgs systems contribute to these transitions, respectively.

For the D meson decay constant we take the value $f_D = 217$ MeV which is obtained from the relation $f_D/f_{D_s}\approx 0.9$ [14] and $f_{D_s}=241$ MeV from [15]. The q^2 dependences of the scalar and pseudoscalar form factors appearing in Eqs. (14)–(18) are chosen to be monopolar:

$$F_0(q^2) = \frac{F_0(0)}{1-q^2/m_{0^+}^2}, \quad A_0(q^2) = \frac{A_0(0)}{1-q^2/m_{0^-}^2}, \tag{19}$$

where m_{0^+} and m_{0^-} are the masses of the scalar and pseudoscalar neutral D mesons, respectively. The normalizations of these form factors at $q^2=0$ are taken from the relativistic quark model of Wirbel, Stech, and Bauer [16].

The other hadronic matrix elements needed in our calculation are fixed either by identifying the $\overline{u}u$ content of final state isosinglet mesons: namely,

TABLE I. Bounds on Yukawa couplings from FCNC and LFV D meson decays.

Channel	Expt. branching ratio	Upper bound
$D^0\to e^+e^-$	$<1.3\times10^{-5}$	$\alpha^{ee}<4.0\times10^{-3}$
$D^0\to\mu^+\mu^-$	$<4.2\times10^{-6}$	$\alpha^{\mu\mu}<2.3\times10^{-3}$
$D^0\to\mu^\pm e^\mp$	$<1.9\times10^{-5}$	$\alpha^{\mu e}<4.9\times10^{-3}$
$D^0\to\pi^0 e^+e^-$	$<4.5\times10^{-5}$	$\sigma^{ee}<4.2\times10^{-2}$
$D^0\to\pi^0\mu^+\mu^-$	$<1.8\times10^{-4}$	$\sigma^{\mu\mu}<8.6\times10^{-2}$
$D^0\to\pi^0\mu^\pm e^\mp$	$<8.6\times10^{-5}$	$\sigma^{\mu e}<5.8\times10^{-2}$
$D^0\to\eta e^+e^-$	$<1.1\times10^{-4}$	$\sigma^{ee}<0.16$
$D^0\to\eta\mu^+\mu^-$	$<5.3\times10^{-4}$	$\sigma^{\mu\mu}<0.38$
$D^0\to\eta\mu^\pm e^\mp$	$<1.0\times10^{-4}$	$\sigma^{\mu e}<0.16$
$D^+\to\pi^+e^+e^-$	$<6.6\times10^{-5}$	$\sigma^{ee}<2.2\times10^{-2}$
$D^+\to\pi^+\mu^+\mu^-$	$<1.8\times10^{-5}$	$\sigma^{\mu\mu}<1.2\times10^{-2}$
$D^+\to\pi^+\mu^-e^+$	$<1.1\times10^{-4}$	$\sigma^{\mu e}<2.9\times10^{-2}$
$D_s^+\to K^+\mu^+\mu^-$	$<5.9\times10^{-4}$	$\sigma^{\mu\mu}<0.15$
$D^0\to\rho^0e^+e^-$	$<1.0\times10^{-4}$	$\alpha^{ee}<0.35$
$D^0\to\rho^0\mu^+\mu^-$	$<2.3\times10^{-4}$	$\alpha^{\mu\mu}<0.57$
$D^0\to\rho^0\mu^\pm e^\mp$	$<4.9\times10^{-5}$	$\alpha^{\mu e}<0.25$
$D^0\to\omega e^+e^-$	$<1.8\times10^{-4}$	$\alpha^{ee}<0.48$
$D^0\to\omega\mu^+\mu^-$	$<8.3\times10^{-4}$	$\alpha^{\mu\mu}<1.14$
$D^0\to\omega\mu^\pm e^\mp$	$<1.2\times10^{-4}$	$\alpha^{\mu e}<0.40$
$D^+\to\rho^+\mu^+\mu^-$	$<5.6\times10^{-4}$	$\alpha^{\mu\mu}<0.39$
$D_s^+\to K^{*+}\mu^+\mu^-$	$<1.4\times10^{-3}$	$\alpha^{\mu\mu}<0.96$

$$\langle \eta|\overline{u}c|D^0\rangle = \frac{1}{\sqrt{3}}\langle \pi^0|\overline{u}c|D^0\rangle(\cos\,\theta_P - \sqrt{2}\,\sin\,\theta_P), \tag{20}$$

$$\langle \omega|\overline{u}\gamma_5 c|D^0\rangle = \langle \rho^0|\overline{u}\gamma_5 c|D^0\rangle \tag{21}$$

or, using SU(3) flavor symmetry,

$$\langle K^+|\overline{u}c|D_s^+\rangle = \langle \pi^+|\overline{u}c|D^+\rangle, \tag{22}$$

$$\langle K^{*+}|\overline{u}\gamma_5 c|D_s^+\rangle = \langle \rho^+|\overline{u}\gamma_5 c|D^+\rangle. \tag{23}$$

Notice that we assume ideal ω-ϕ mixing and we use $\theta_P = -20°$ in Eqs. (20) and (21).

The information on the experimental data about the FCNC and LFV D decays is taken from the 1997 update of Ref. [6], which already incorporates some recent results of Refs. [7–10].

In Table I we show the upper bounds for the products of couplings constants that can be constrained from the experimental data considered. We have introduced in Table I a short notation for coupling constants. First, we express the bounds from leptonic D^0 decays and $D\to Vl^+l'^-$ decays in terms of $\alpha^{ll'}\equiv\Lambda_{A_0}^{uc}L_{A_0}^{ll'}$. Since both neutral Higgs scalars contribute to $D\to Pl^+l'^-$ we have expressed the upper bounds in terms of the quantity $\sigma^{ll'}\equiv\Lambda_{H_0}^{uc}L_{H_0}^{ll'}+\Lambda_{h_0}^{uc}L_{h_0}^{ll'}$.

Despite the fact that all the upper limits on branching ratios are at the $10^{-4}-10^{-5}$ level, the different bounds on the effective couplings spread over two orders of magnitude. From Table I we conclude that the stronger bounds on the $\alpha^{ll'}$ couplings come from purely leptonic D^0 decays, while the same bounds from $D\to Vl^+l'^-$ decays are rather weak. Therefore, in the context of the present model, the leptonic D^0 decays imply that branching ratios of three-body decays of D's involving vector mesons should be below the 10^{-9} level. On the other hand, the best constraints on the $\sigma^{ll'}$ couplings are obtained from the $D\to\pi l^+l'^-$ mainly because of the phase space suppression in the decays involving the η meson. Finally, since the V-Higgs system in $D\to Vl^+l'^-$ decays is in a $l=1$ relative wave, this gives a further phase space suppression and the absolute numerical bounds on the $\alpha^{ll'}$'s become weaker than the limits on the $\sigma^{ll'}$'s (obtained from $D\to P$ transitions).

In order to draw any information on the Yukawa couplings of our interest let us make some considerations. To start, let us neglect the first term[2] in Eqs. (10)–(12) and set $\alpha'=0$. In this case we obtain the following expressions for $\alpha^{ll'}$ and $\sigma^{ll'}$:

$$\alpha^{ll'}=\frac{1}{\sqrt{2}G_F m_{A_0}^2}\frac{(\xi F')^{uc}(\xi K')^{ll'}}{\sin\beta\cos\beta}, \tag{24}$$

$$\sigma^{ll'}=-\frac{1}{\sqrt{2}G_F}\frac{(\xi F')^{uc}(\xi K')^{ll'}}{\sin\beta\cos\beta}\times\left\{\frac{\sin^2(\alpha-\beta)}{m_{H_0}^2}+\frac{\cos^2(\alpha-\beta)}{m_{h_0}^2}\right\}, \tag{25}$$

or the relationship

$$\sigma^{ll'}\leqslant -m_{A_0}^2\left\{\frac{1}{m_{H_0}^2}+\frac{1}{m_{h_0}^2}\right\}\alpha^{ll'}. \tag{26}$$

[2]Notice that this approximation is not necessary in the case of LFV decays.

In the absence of information regarding the parameters of this model we will assume $\tan\beta\approx 1$, $m_{h_0}=130$ GeV, and $m_{H_0}=m_{A_0}=300$ GeV. From Eq. (24) and the bounds on $\alpha^{ll'}$ obtained from leptonic D^0 decays (see Table I) we derive

$$(\xi F')^{uc}(\xi K')^{ee}\leqslant 2.9\times 10^{-3}, \tag{27}$$

$$(\xi F')^{uc}(\xi K')^{\mu\mu}\leqslant 1.7\times 10^{-3}, \tag{28}$$

$$(\xi F')^{uc}(\xi K')^{\mu e}\leqslant 3.6\times 10^{-3}. \tag{29}$$

Therefore, one may conclude that present experimental data on FCNC and LFV D decays only mildly constrain the strength of products of the relevant Yukawa couplings of this model. Since the (diagonal) terms proportional to fermion masses in Eqs. (10)–(12) are of $O(10^{-4})$ for the $D\to X\mu^+\mu^-$ modes, the approximation done to derive Eqs. (24) and (25) is justified in view of the present experimental upper limits.

Note that if a specific ansatz is assumed for these Yukawa couplings [17], then Eq. (24) can furnish the allowed region for m_{A_0} as a function of β. Let us notice, however, that Eq. (25) does not provide additional constraints on the Yukawa couplings unless, in addition, some information on the mixing angle α is introduced by hand.

In summary, in this work we have studied the constraints imposed by FCNC and LFV leptonic and semileptonic D decays on a version of the two-Higgs-doublet model that contains these effects at the tree level. The stringent bounds on the relevant Yukawa couplings are obtained from two-body leptonic D^0 decays which are mediated by the pseudoscalar Higgs boson of the model. The best constraints on the Higgs scalar interactions are obtained from $D\to\pi l^+l'^-$ decays. The three-body D decays involving vector mesons provide only very weak bounds and their measurements would have to be improved by five orders of magnitude in order to furnish similar constraints on the model as obtained from purely leptonic decays.

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[1] K. S. Babu, X-G. He, X-Q. Li, and S. Pakvasa, Phys. Lett. B **205**, 540 (1988).
[2] A. J. Schwartz, Mod. Phys. Lett. A **8**, 967 (1993).
[3] G. Eilam, J. L. Hewett, and A. Soni, Phys. Rev. D **44**, 1473 (1991).
[4] S. Pakvasa, in *FCNC97*, Proceedings of the Symposium on Flavor Changing Neutral Currents: Present and Future Studies, Santa Monica, California, edited by B. Cline (World Scientific, Singapore, 1997), p. 49, hep-ph/9705397 and references cited therein.
[5] P. Singer and D.-X. Zhang, Phys. Rev. D **55**, R1127 (1997).
[6] Particle Data Group, R. M. Barnett *et al.*, Phys. Rev. D **54**, 1 (1996). See also the 1997 update available at http://pdg.lbl.gov/.
[7] E791 Collaboration, E. M. Aitala *et al.*, Phys. Rev. Lett. **76**, 364 (1996).
[8] E771 Collaboration, T. Alexopoulos *et al.*, Phys. Rev. Lett. **77**, 2380 (1996).
[9] E687 Collaboration, P. L. Fabretti *et al.*, Phys. Lett. B **398**, 239 (1997).
[10] CLEO Collaboration, A. Freyberger *et al.*, Phys. Rev. Lett. **76**, 3065 (1996).
[11] D. Kaplan, in *FCNC 97*, Proceedings of the Symposium on Flavor Changing Neutral Currents: Present and Future Studies,

Santa Monica, California, edited by B. Cline (World Scientific, Singapore, 1997), p. 81, hep-ex/9705002.

[12] J. Liu and L. Wolfenstein, Nucl. Phys. **B289**, 1 (1987); G. C. Branco and M. N. Rebelo, Phys. Lett. **160B**, 117 (1985).

[13] J. L. Díaz-Cruz and G. López Castro, Phys. Lett. B **301**, 405 (1993); J. L.Díaz-Cruz, J. J. Godina Nava, and G. López Castro, Phys. Rev. D **51**, 5263 (1995).

[14] C. W. Bernard, J. N. Labrenz, and A. Soni, Phys. Rev. D **49**, 2536 (1994).

[15] J. D. Richman, in *ICHEP 96*, Proceedings of the 28th International Conference on High-Energy Physics, Warsaw, Poland, edited by Z. Ajduk and A. K. Wroblewski (World Scientific, Singapore, 1997), p. 143.

[16] M. Wirbel, B. Stech, and M. Bauer, Z. Phys. C **29**, 637 (1985).

[17] T. P. Cheng and M. Sher, Phys. Rev. D **35**, 3484 (1987); **44**, 461 (1991); A. Antaramian, L. J. Hall, and A. Rasin, Phys. Rev. Lett. **69**, 1871 (1992).