$c \to u\gamma$ in Cabibbo suppressed D meson radiative weak decays

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We investigate Cabibbo suppressed D^0, D^+, and D_s^+ radiative weak decays in order to find the best mode to test $c \to u\gamma$ decay. Combining heavy quark effective theory and the chiral Lagrangian approach we determine the decay widths. We calculate $\Gamma(D^0 \to \rho^0/\omega\gamma)/\Gamma(D^0 \to \overline{K^{*0}}\gamma)$, previously proposed to search for possible new physics. However, we notice that there are large, unknown, corrections within the standard model. We propose a better alternative, the ratio $\Gamma(D_s^+ \to K^{*+}\gamma)/\Gamma(D_s^+ \to \rho^+\gamma)$, and show that it is less sensitive to the standard model. [S0556-2821(96)04721-2]

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According to the standard model, the physics of charm mesons is not as exciting as the physics of bottom mesons [1–3]: the relevant Cabibbo-Kobayashi-Maskawa (CKM) matrix elements V_{cs} and V_{cd} are well known, the D^0-$\overline{D^0}$ oscillations and CP asymmetries are small, weak decays of D mesons are difficult to investigate due to the strong final state interactions, and very small branching ratios are expected for rare decays. However, authors [1–3] have noticed that the D^0-$\overline{D^0}$ oscillation and $c \to u\gamma$ decays obtain contributions coming from nonminimal supersymmetry which are not present within the standard model. Therefore, these two phenomena might be guides for a signal of new physics. Namely, the authors of Ref. [1] showed that in $D^0 \to \rho^0(\omega)\gamma$ some nonminimal supersymmetric models give a contribution of the same order of magnitude as the long distance contribution within the standard model. The short distance contribution to $c \to u\gamma$ determined by the standard model is found to be negligible [4,5], so we will not take it into account. But, as observed in Ref. [2], new physics can generate $c \to u\gamma$ transitions leading to a deviation from the standard model prediction (for the long distance contributions only) in the chiral limit

$$R_{\rho/\omega} \equiv \frac{\Gamma(D^0 \to \rho^0/\omega\gamma)}{\Gamma(D^0 \to \overline{K^{*0}}\gamma)} = \frac{\tan^2\theta_C}{2} \tag{1}$$

(the factor 1/2 was overlooked in Refs. [1,2]). However, in order to distinguish a hypothetical new physics signal from the standard model background, one must make it sure that the standard model chiral symmetry-breaking terms do not cause too large deviations from Eq. (1). The purpose of this paper is to check how sensitive the ratio (1) is and how similar it is with chiral symmetry breaking. As a theoretical framework we use a hybrid theory: a combination of heavy quark effective theory (HQET) and chiral Lagrangians (CHL's) [6–10]. This approach, accompanied by the factorization hypothesis, enables us to use the standard model results for electroweak processes. It is possible to apply other approaches such as, for example [4], but the result which indicates the deviation from $\tan^2\theta_c$ cannot be very different from ours obtained with HQET + CHL's. In fact, our results agree with [4] within the uncertainties.

We calculate the ratios between various Cabibbo suppressed and Cabibbo allowed charm meson radiative weak decays, as predicted by the standard model. Analyzing them we notice that the relation (1) can be badly violated already in the standard model framework, while a similar relation for D_s^+ radiative decays, i.e.,

$$R_K \equiv \frac{\Gamma(D_s^+ \to K^{*+}\gamma)}{\Gamma(D_s^+ \to \rho^+\gamma)} = \tan^2\theta_C \tag{2}$$

offers a much better test for $c \to u\gamma$.

Experimentally, radiative decays of D mesons have not yet been measured, while the known branching ratios of D^* radiative decays [11,12] can be described using the combination HQET + CHL's [10,13,14].

The initial HQET ideas [15,16] were implemented with the chiral Lagrangian formalism for light pseudoscalar mesons first in [6–8], and the electromagnetic interaction included in [13,14,17]. Subsequently, the light vector mesons were introduced [9], following the hidden symmetry approach [18]. We will follow the model described in [10], where in addition to [9], the electromagnetic (EM) interaction was introduced.

Let us briefly describe the relevant terms (for the charm meson radiative weak decays) of the Lagrangian [10]. The main contribution comes from the odd-parity Lagrangian

$$\begin{aligned}\mathcal{L}_{\rm odd} = &-4e\sqrt{2}\frac{C_{V\pi\gamma}}{f}\epsilon^{\mu\nu\alpha\beta}\mathrm{Tr}(\{\partial_\mu\rho_\nu,\Pi\}Q\partial_\alpha B_\beta)\\ &-4\frac{C_{VV\Pi}}{f}\epsilon^{\mu\nu\alpha\beta}\mathrm{Tr}(\partial_\mu\rho_\nu\partial_\alpha\rho_\beta\Pi)\\ &-\lambda' e\mathrm{Tr}[H_a\sigma_{\mu\nu}F^{\mu\nu}(B)\overline{H_a}]\\ &+i\lambda\mathrm{Tr}[H_a\sigma_{\mu\nu}F^{\mu\nu}(\hat{\rho})_{ab}\overline{H_b}],\end{aligned} \tag{3}$$

where $C_{VV\Pi} = 0.423$, $C_{V\Pi\gamma} = -3.26 \times 10^{-2}$ [19,20], $f = 132$ MeV is the pseudoscalar decay constant, while the phenomenological parameters λ and λ' are constrained by the analysis [10]:

$$|\lambda' + \tfrac{2}{3}\lambda| = (0.50 \pm 0.15)\ \ \mathrm{GeV}^{-1}, \tag{4}$$

$$|\lambda' - \frac{\lambda}{3}| < 0.19\ \ \mathrm{GeV}^{-1}. \tag{5}$$

In Eq. (3) Π and ρ_μ are the usual pseudoscalar and vector Hermitian matrices

$$\Pi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}}+\frac{\eta_8}{\sqrt{6}}+\frac{\eta_0}{\sqrt{3}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}}+\frac{\eta_8}{\sqrt{6}}+\frac{\eta_0}{\sqrt{3}} & K^0 \\ K^- & \overline{K^0} & -2\frac{\eta_8}{\sqrt{6}}+\frac{\eta_0}{\sqrt{3}} \end{pmatrix}, \tag{6}$$

$$\rho_\mu = \begin{pmatrix} \frac{\rho^0_\mu+\omega_\mu}{\sqrt{2}} & \rho^+_\mu & K^{*+}_\mu \\ \rho^-_\mu & \frac{-\rho^0_\mu+\omega_\mu}{\sqrt{2}} & K^{*0}_\mu \\ K^{*-}_\mu & \overline{K^{*0}}_\mu & \phi_\mu \end{pmatrix} \tag{7}$$

with $\eta=\eta_8\cos\theta-\eta_0\sin\theta$, $\eta'=\eta_8\sin\theta+\eta_0\cos\theta$ and $\theta=-23°$ [11] is the η-η' mixing angle. $Q=\mathrm{diag}(2/3,-1/3,-1/3)$ is the light quark sector charge matrix,

$$H_a=\tfrac{1}{2}(1+\not{v})(\sqrt{m_{D^{a*}}}D^{a*}_\mu\gamma^\mu-\sqrt{m_{D^a}}D^a\gamma_5), \tag{8}$$

where D^{a*}_μ and D^a annihilate, respectively, a spin-one and spin-zero meson $c\overline{q^a}$ ($q^a=u$, d or s) of velocity v_μ and $\overline{H}_a\equiv\gamma^0H^\dagger_a\gamma^0$. Finally, $F_{\mu\nu}(\hat\rho)=\partial_\mu\hat\rho_\nu-\partial_\nu\hat\rho_\mu+[\hat\rho_\mu,\hat\rho_\nu]$, $\hat\rho_\mu=ig_V\rho_\mu/\sqrt{2}$ with $g_V=5.8$ [9], and $F_{\mu\nu}(B)=\partial_\mu B_\nu-\partial_\nu B_\mu$ with B_μ being the photon field with the EM coupling constant e.

The first (third) term in Eq. (3) describes the anomalous direct emission of the photon by the light (heavy) meson, while the second (fourth) term, together with the vector meson dominance (VMD) coupling

$$\mathcal{L}_{V-\gamma}=-m_V^2\frac{e}{g_V}B_\mu\left(\rho^{0\mu}+\frac{1}{3}\omega^\mu-\sqrt{\frac{2}{3}}\phi^\mu\right), \tag{9}$$

describes a two-step photon emission, with an intermediate neutral vector meson with mass m_V which transforms to the final photon.

A charged charm meson can emit a real photon also through the usual electromagnetic coupling

$$\mathcal{L}_{\mathrm{EM}}=-ev^\mu B_\mu\mathrm{Tr}[H_a(Q-2/3)_{ab}\overline{H_b}], \tag{10}$$

while a charged light vector meson can produce through

$$\mathcal{L}_{VVV}=\frac{1}{2g_V^2}\mathrm{Tr}[F_{\mu\nu}(\hat\rho)F^{\mu\nu}(\hat\rho)] \tag{11}$$

first a neutral vector meson, which subsequently transforms via VMD (9) to a photon.

The weak Lagrangian is approximated by the current-current-type interaction

$$\mathcal{L}^{\mathrm{eff}}_W(\Delta c=1)=-\frac{G_F}{\sqrt{2}}[a_1(\overline{u}d')^\mu(\overline{s'}c)_\mu+a_2(\overline{s'}d')^\mu(\overline{u}c)_\mu], \tag{12}$$

where $(\overline{q_1}q_2)^\mu\equiv\overline{q_1}\gamma^\mu(1-\gamma^5)q_2$, G_F is the Fermi constant, and $a_{1,2}$ are the QCD Wilson coefficients, which depend on the energy scale μ. One expects the scale to be the heavy quark mass and we take $\mu\simeq1.5$ GeV which gives $a_1=1.2$ and $a_2=-0.5$, with an approximate 20% error. Since we are interested only in the physics of the first two generations, we can express the weak eigenstates d', s' with the mass eigenstates d, s using the Cabibbo angle instead of the CKM matrix:

$$\begin{pmatrix} d' \\ s' \end{pmatrix}=\begin{pmatrix} \cos\theta_C & -\sin\theta_C \\ \sin\theta_C & \cos\theta_C \end{pmatrix}\begin{pmatrix} d \\ s \end{pmatrix} \tag{13}$$

with $\sin\theta_C=0.222$. Possible contributions caused by the penguin-type diagrams are found to be very small [4].

Many heavy meson weak nonleptonic amplitudes [21–23] have been calculated using the factorization approximation. In this approach the quark currents are approximated by the ‘‘bosonized’’ currents [6,9,10], of which only

$$(\overline{q^a}c)_\mu=i(m_{D^{*a}}f_{D^{*a}}D^{*a}_\mu-m_{D^a}f_{D^a}v_\mu D^a), \tag{14}$$

$$(\overline{q_b}q_a)^\mu=-f\partial^\mu\Pi_{ab}+m_Vf_V\rho^\mu_{ab} \tag{15}$$

will contribute to our amplitudes. The numerical values for the masses will be taken from [11] and for the decay constants from [23].

It is now straightforward to calculate the decay widths. The result, of course, depends on the numerical values we take for $(\lambda'+2\lambda/3)$ and $(\lambda'-\lambda/3)$.

Apart from the Cabibbo allowed decays $D^0\to\overline{K^{*0}}\gamma$ and $D^+_s\to\rho^+\gamma$, five once Cabibbo suppressed ($D^0\to\rho^0\gamma$, $D^0\to\omega\gamma$, $D^0\to\phi\gamma$, $D^+\to\rho^+\gamma$, $D^+_s\to K^{*+}\gamma$) and two doubly Cabibbo suppressed ($D^0\to K^{*0}\gamma$ and $D^+\to K^{*+}\gamma$) decays are possible.

In the quark picture the neutral charmed meson decays can be viewed as a W exchange in the $t(u)$ channel, resulting in the amplitude proportional to a_2, while the charged charmed mesons decay via an s-channel W exchange and are proportional to a_1. We assume for the moment that none of the high-lying mesons contributes as an intermediate state to our decays. We will come back to this point after presenting the results.

We write the amplitude for the $D^q\to V^q\gamma$, where q stands for the charge of D meson ($q=1$ stands for + charge, while $q=0$ is for the neutral D mesons)

$$A(D^q\to V^q\gamma)=e\frac{G_F}{\sqrt{2}}K_ca(q)\left[C^{(1)}_{DV\gamma}\epsilon_{\mu\nu\alpha\beta}k^\mu\epsilon^{\nu*}_\gamma v^\alpha\epsilon^{\beta*}_V+iC^{(2)}_{DV\gamma}m_V\left(\epsilon^*_\gamma\cdot\epsilon^*_V-\frac{\epsilon^*_\gamma\cdot p_V\epsilon^*_V\cdot k}{p_V\cdot k}\right)\right] \tag{16}$$

with $a(+1)=a_1$ and $a(0)=a_2$. (k,ϵ_γ) and (p_V,ϵ_V) are the four-momenta and polarization vectors of the photon and vector meson, respectively, while v is the four-velocity of the heavy meson.

TABLE I. The b^{VP_i} coefficients defined in relation (19), where $s=\sin\theta$, $c=\cos\theta$, and θ is the η-η' mixing angle.

	π^0	η	η'
ρ^0	$\frac{1}{3\sqrt{2}}$	$-\frac{1}{\sqrt{2}}c(c-\sqrt{2}s)$	$-\frac{1}{\sqrt{2}}s(\sqrt{2}c+s)$
ω	$\frac{1}{\sqrt{2}}$	$-\frac{1}{3\sqrt{2}}c(c-\sqrt{2}s)$	$-\frac{1}{3\sqrt{2}}s(\sqrt{2}c+s)$
ϕ	0	$\frac{\sqrt{2}}{3}c(\sqrt{2}c+s)$	$-\frac{\sqrt{2}}{3}s(c-\sqrt{2}s)$

The overall factor K_c contains the Cabibbo angle and is equal to $\cos\theta_C{}^2$ for allowed decays, to $+\sin\theta_C\cos\theta_C$ (when there is no s quark or antiquark in the final V) or $-\sin\theta_C\cos\theta_C$ (when there is at least one s quark or antiquark in the final V) for once suppressed decays and to $-\sin\theta_C{}^2$ for double suppressed decays. The coefficients $C^{(i)}$ in Eq. (16) can be written as

$$C^{(1)}_{DV\gamma}=\left(C_{VV\Pi}\frac{1}{g_V}+C_{V\Pi\gamma}\right)4\sqrt{2}f_D m_D^3 b^V+4[\lambda' +(\tfrac{2}{3}-q)\lambda]f_{D^*}f_V\frac{m_{D^*}m_V}{m_{D^*}^2-m_V^2}\sqrt{m_D m_{D^*}}b_0^V, \quad (17)$$

$$C^{(2)}_{DV\gamma}=qf_Df_V. \quad (18)$$

The coefficient b^V is equal to $(2/3-q)/(m_D^2-m_P^2)$ for $V=(\overline{K^{*0}}, K^{*0}, \rho^+, K^{*+})$, for which $P=(\overline{K^0}, K^0, \pi^+, K^+)$. For the remaining final state vector mesons this coefficient is expressed as

$$b^V=\sum_{i=1}^{3}\frac{b^{VP_i}}{m_D^2-m_{P_i}^2}, \quad (19)$$

where the pole coefficients b^{VP_i} are given in Table I. Furthermore, we have $b_0^V=-1/\sqrt{2}$ for $V=\rho^0$, $b_0^V=1/\sqrt{2}$ for $V=\omega$, and $b_0^V=1$ otherwise.

In Ref. [1,2] it was noticed that a nice bonus can be obtained by measuring the charm meson decay width $D\to\rho/\omega\gamma$ which is generated by $c\to u\gamma$ transitions. Namely, the authors claim that observing the violation of Eq. (1) would then eventually signal new physics [1]. Using our model, which describes low energy meson physics within the standard model, we find that this relation does not exactly hold due to U(3) breaking. We assume that the leading effect of this breaking is to change the values of the masses and decay constants for different members of the same multiplets and between octet and singlet. However, one would naively expect deviations from this limit in the standard model of the order of 20–30%. We will see that this is not true for the $D^0\to\rho^0/\omega\gamma$ decay, but is correct for D_s^+ Cabibbo suppressed radiative weak decay.

Within our framework λ and λ' are the most important parameters for charm meson radiative decays [10], and therefore, we present the ratios of the decay widths as functions of combinations of λ and λ'. Our result for R_ρ (1) is shown in Fig. 1. If the combination of $(\lambda'+\frac{2}{3}\lambda)$ turns out to be negative, the ratio R_ρ can approach 0. As is known from $D^0\to\overline{K^{*0}}\gamma$ [10], the negative values $(\lambda'+2/3\lambda)$ cause a destructive interference between the photon emission by the heavy meson and that by the light meson. A similar effect is possible also in the decay $D^0\to\rho^0\gamma$, only that the zero is achieved at a different value of $(\lambda'+2/3\lambda)$, because the model parameters are here slightly different due to U(3) breaking. It is obvious that such a large sensitivity to the model parameters does not allow us to conclude anything about new physics. If $(\lambda'+2/3\lambda)$ turns out to be positive, the decays are much easier to detect experimentally, and also the theoretical situation is clearer, since the curve is approaching the ideal theoretical value. A large disagreement with the theoretical prediction (1) would give in this case some sign of new physics. It is easy to find that a similarly defined R_ω is almost identical to R_ρ, which shows that the singlet-octet mixing in the light pseudoscalar sector is unimportant. The reason for this is the strong off shellness of these light pseudoscalars, which makes the mass differences negligible.

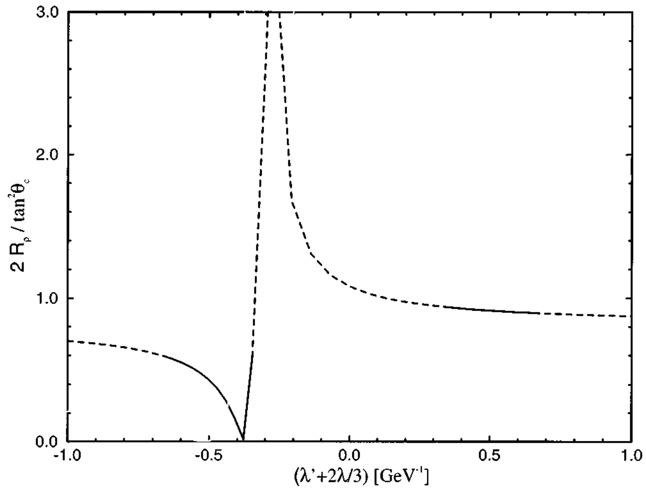

FIG. 1. The ratio $2R_\rho/\tan\theta_C{}^2$ as a function of the combination $\lambda'+2\lambda/3$. The full (dashed) lines denote the experimentally allowed (forbidden) values for this combination. In the U(3) symmetry limit of the standard model this ratio is equal to 1.

As mentioned earlier, a fair description of these decays should involve the contribution of high-lying resonances with pion or kaon quantum numbers to the annihilation-type diagrams. If such states exist close to the D^0 mass, they could even dominate, being enhanced by a factor a_1/a_2 with respect to the considered direct annihilation diagram [22]. However, this would not improve the prediction of the ratio (1), since such high-lying states are not definitely confirmed by experiment, and not much is known about their properties. So, even if such states are important, which is not clear, we cannot predict reliably the ratio (1).

The ratio $\Gamma(D^0\to\phi\gamma)/\Gamma(D^0\to\overline{K^{*0}}\gamma)$ would indicate the deviation from $\tan\theta_C{}^2$ instead of $\tan\theta_C{}^2/2$ such as for the ρ,ω case. However, our calculations show that it behaves similarly to $D^0\to\rho\gamma$, and therefore, it is not very useful for investigating $c\to u\gamma$ physics.

The decay $D^+\to\rho^+\gamma$ is also not very useful for the purposes of finding new physics, since the D^+ does not have Cabibbo allowed decays.

Contrary to the above cases we find that the decay $D_s^+\to K^{*+}\gamma$ offers a much better chance to test new physics.

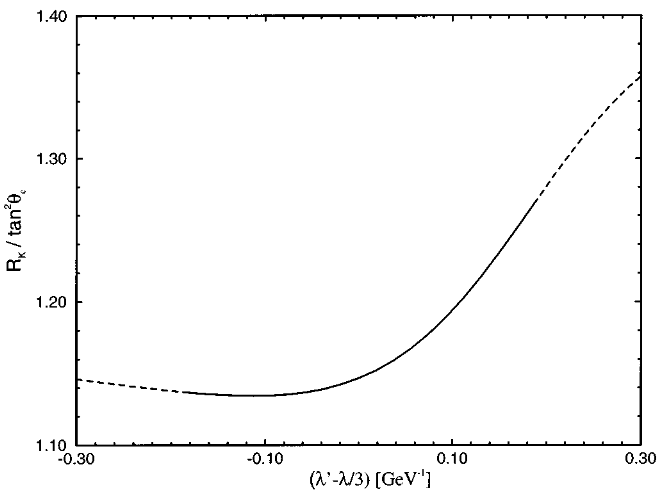

FIG. 2. The ratio $R_K/\tan\theta_C^2$ as a function of the combination $\lambda' - \lambda/3$. The full (dashed) lines denote the experimentally allowed (forbidden) values for this combination. In the U(3) symmetry limit of the standard model this ratio is equal to 1.

Using the general formulas for the amplitudes (16) it is easy to derive a deviation from Eq. (2), which is exactly correct only in the U(3) limit. The result for R_K as a function of $(\lambda' - 1/3\lambda)$ is presented in Fig. 2 (note the different scale relative to Fig. 1). We notice that the result is rather stable within the allowed region for $(\lambda' - 1/3\lambda)$. The deviation from relation (2) is due to U(3) breaking and is of order 30%, as one expects. Also, contrary to the D^0 case, the contribution of high-lying resonances close to the D_s^+ mass, assuming that these states exist, is suppressed by a factor a_2/a_1 [22]. Thus, if the experimental data are found to lie far off the curve in Fig. 2, one can interpret this as a possible sign of new physics.

It is important to stress that our proposal to search for new physics in the charged D decays instead of the neutral ones, is not a direct consequence of only our model. The same conclusion would also be reached in other models. The main point is that the charged D meson decays have a contribution from the direct photon emission diagram. This contribution does not mix with the anomalous contributions, causing the results to be more stable against small SU(3)-breaking differences.

We point out that it is difficult to observe all these decays. In fact, the Cabibbo allowed decays are already rare: the branching ratio for $D^0 \to \overline{K^{*0}}\gamma$ is smaller than 0.3×10^{-4} for $(\lambda' + 2\lambda/3) < 0$ and around $(2\text{–}4)\times10^{-4}$ for $(\lambda' + 2\lambda/3) > 0$, while for $D_s^+ \to \rho^+\gamma$ the branching ratio is around $(2\text{–}7)\times10^{-4}$ [10].

We determined the amplitudes of Cabibbo suppressed radiative decays using the combination of heavy quark symmetry and chiral symmetry, which constructs an effective strong, weak, and electromagnetic Lagrangian. This theoretical framework simply illustrates the characterictics of these amplitudes in the standard model. In our framework two parameters λ and λ', are not well known. We calculated the dependence of the ratio between the Cabibbo suppressed and Cabibbo allowed decay widths on these parameters λ and λ'. We found that it is better to search for a signal of new physics coming from $c \to u\gamma$ decays in the ratio $\Gamma(D_s^+ \to K^{*+}\gamma)/\Gamma(D_s^+ \to \underline{\rho}^+\gamma)$ instead of the proposed ratio $\Gamma(D^0 \to \rho^0/\omega\gamma)/\Gamma(D^0 \to \overline{K^{*0}}\gamma)$ [1–3], as the former is less sensitive to the standard model parameters.

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