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Final State Gluon Effects in Charmed Meson Decays

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ABSTRACT

In the valence-quark c-decay-scheme the decay $D^0 \to \overline{K}^0 \pi^0$ is expected to be strongly suppressed. We suggest that final state soft gluon exchange may account for the rather large branching ratio recently measured for this process, and study two body decays of charmed mesons in our new scheme.

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In the past few years a fair understanding of the nonleptonic decays of kaons, hyperons and the Ω^- has emerged.[1] The description of these decay processes is based on the following three elements:

a). The weak currents which induce the nonleptonic transitions are given by the standard $SU(2) \times U(1)$ model.[2]

b). The effective Hamiltonian H_{eff} is determined by the short distance behavior of strong interactions and may be calculated within Quantum Chromodynamics.[3,4]

c). In order to evaluate matrix elements of H_{eff} between hadronic states one assumes a valence quark model for the hadron wave function.

Encouraged by the rather satisfactory description of the nonleptonic decays of strange particles,[1] one is tempted to extend the same procedure to the hadronic decays of charmed particles.[5,6] In fact one expects the approximation in c) to be better satisfied for the latter processes. Also, some of the still controversial aspects of step b) related to the so called "penguin operator",[7] are eliminated by considering in particular the dominant (Cabibbo allowed) $\Delta C = \Delta S = \pm 1$ decays of charmed particles. It is therefore at first sight quite disturbing to find that a recent measurement of the ratio of branching ratios for $D^0 \to K^- \pi^+$ and $D^0 \to \overline{K}^0 \pi^0$ shows a large discrepancy from the predictions of this scheme.

It is the purpose of this note to reexamine the above scheme. We will relax somewhat assumption c), the most naive and therefore the most questionable of the above three assumptions. The predictions of this new scheme for the charmed meson decay into two pseudoscalars ($P_c \rightarrow PP$) will be presented. We also reexamine the degree to which the success of the simple valence quark approximation in strange particle decays is affected in our scheme.

The effective nonleptonic $\Delta C = \Delta S = -1$ weak interaction, including the short distance renormalization effects due to hard gluon exchange (i.e. based on a) and b)) is

$$H_{eff} = (G/\sqrt{2})\, V_{ud} V_{cs} \left(\frac{1}{2} (f_+ + f_-)(\bar{u}d)(\bar{s}c) + \frac{1}{2} (f_+ - f_-)(\bar{s}d)(\bar{u}c) \right) . \tag{1}$$

We have suppressed the Lorentz (μ) and color (a) indices and V_{ij} stand for the mixing angles in the Kobayashi-Maskawa[2] matrix:

$$(\bar{u}d) \equiv \bar{u}^a \gamma_\mu (1 - \gamma_5) d_a$$

$$V_{ud} V_{cs} \equiv c_1 (c_1 c_2 c_3 - s_2 s_3 e^{i\delta}) . \tag{2}$$

The coefficients $f_\pm$ were computed in Ref. 3 and 5:

$$f_\pm = \left(\frac{\alpha_s(m_c^2)}{\alpha_s(M_W^2)} \right)^{\gamma_\pm} (1 + \alpha_s(m_c^2))$$

$$\gamma_- = -2\gamma_+ = \frac{12}{33 - 2F} \tag{3}$$

$$\frac{\alpha_s(m_c^2)}{\alpha_s(M_W^2)} = 1 + \frac{\pi}{\gamma_-} \alpha_s(m_c^2) \ln \left(\frac{M_W^2}{m_c^2} \right) .$$

With $F = 6$, $m_c \sim 1.5$ GeV, $\alpha_s(m_c^2) \sim 0.7$ one finds the values

$$f_- \sim 2.15 \qquad\qquad f_+ \sim 0.68 \ . \tag{4}$$

In order to evaluate the decay matrix elements of H_{eff} between a charmed meson ($D^{\overset{+}{0}}$, F^+) and two pseudoscalars, one conventionally[1,5,6] adopts the following assumptions, which are in the spirit of the parton model and are sometimes referred to as the valence quark approximation:

(c1) The hard interaction induced by H_{eff} is the one in which the c quark in the charmed meson decays into $su\bar{d}$ (Fig. 1(a)) rather than annihilates the antiquark in the initial state to produce a quark-antiquark pair (Fig. 1(b)).

(c2) In the soft process, in which the final quark state evolves into the observed hadrons one neglects final state soft gluon exchange. This implies saturating the matrix element of the product of the two quark bilinears with the vacuum intermediate state.

Thus the process $D^0 \to K^-\pi^+$ for instance is represented by Fig. 1(a). To form a π^+ the u and $\bar{d}$ quarks must be in a color singlet state. The contribution of the first term in Eq.(1) to the decay process may be written as $(f_+ + f_-)A$. Using the Fierz identity

$$(\bar{s}d)(\bar{u}c) = \frac{1}{3}(\bar{u}d)(\bar{s}c) + \frac{1}{2}(\bar{u}\lambda^a d)(\bar{s}\lambda^a c) \ , \tag{5}$$

the contribution of the second term in Eq. (1) is found to be $\frac{1}{3}(f_+ - f_-)A$. The second term in Eq. (5) which would create a $u\bar{d}$ pair in a color octet state does not contribute to the process. Finally one obtains:

$$M(D^0 \to K^-\pi^+) = 2X_+ A\,, \tag{6}$$

with $X_+ \equiv \frac{1}{3}(2f_+ + f_-) \simeq 1.17$. Similarly

$$M(D^0 \to \bar{K}^0\pi^0) = \sqrt{2}X_- A\,, \tag{7}$$

with $X_- \equiv \frac{1}{3}(2f_+ - f_-) = -0.26$.

In general all the $P_c \to PP$ decays may be expressed in terms of the single free parameter A.[6] All the ratios of decay widths are predicted in this scheme. In particular one predicts

$$\frac{\Gamma(D^0 \to K^-\pi^+)}{\Gamma(D^0 \to \bar{K}^0\pi^0)} \approx 2\left(\frac{X_+}{X_-}\right)^2 \approx 40\,. \tag{8}$$

Recent experiments definitely indicate that the decay $D^0 \to \bar{K}^0\pi^0$ is not suppressed as strongly as predicted in this scheme. The measurements yield[8] B. R. $(D^0 \to K^-\pi^+) = (2.8 \pm 0.6)\%$ and B. R. $(D^0 \to \bar{K}^0\pi^0) = (2.0 \pm 0.9)\%$ and are in obvious disagreement with Eq. (8).

Guided by this discrepancy we are led to reexamine briefly the valence quark approximation. Assumption (c1) may be reasonably justified by the observation that the annihilation diagram in Fig. 1(b) leads to a vanishing amplitude in the SU(3) conserved-vector-current limit. We now turn to the second approximation (c2). The apparent justification here is perhaps that soft gluon exchange between the two pairs of quarks $(u\bar{d})$ and $(s\bar{u})$ (Fig. 1(a)) may be neglected, due to the large relative momentum between the two pairs. (Soft gluon exchange between the quark and antiquark in a pair would not alter the predictions of the scheme.) We note, however, that soft multiple gluon exchange, such as illustrated in Fig. 1(c) are definitely possible.

The other rationale for this oversimplifying approximation is the quite reasonable prediction which is obtained within this scheme for the $\Delta I = 3/2$ amplitudes of strange particle decays. We will return and clarify this point later.

In the following we will use (c1) but abandon (c2), while allowing in the soft process the exchange of soft gluons[9] as illustrated by Fig. 1(c). When considering now the amplitude for $D^0 \to K^- \pi^+$ one obtains a new contribution from the second term in Eq. (5), in which the two quark-antiquark pairs interact via color octet currents. We may denote this contribution by $\frac{1}{2}(f_+ - f_-)\epsilon A$, where the complex parameter ϵ measures the ratio of the contributions of Fig. 1(c) to the operator $(\bar{u}\lambda^a d)(\bar{s}\lambda^a c)$ and of Figs. 1(a),(c) to $(\bar{u}d)(\bar{s}c)$. Note that ϵ is independent of the particular $P_c \to PP$ process under consideration.

It is interesting to note that in an approach to D decays which adopts the $1/N_c$ expansion, the contributions from the two operators of Eq. (5), respectively $\frac{1}{3}(f_+ - f_-)A$ and $\frac{1}{2}(f_+ - f_-)\epsilon A$, are of the same order.[10] In such an approach one would evidently maintain the second term as well as the first one.

Within our scheme we find:

$$M(D^0 \to K^- \pi^+) = A_+$$
$$M(D^0 \to \overline{K}^0 \pi^0) = \frac{1}{\sqrt{2}} A_- , \tag{9}$$

where

$$A_+ \equiv \left[X_+ + \frac{\epsilon}{4}(f_+ - f_-)\right] 2A$$
$$A_- \equiv \left[X_- + \frac{\epsilon}{4}(f_+ + f_-)\right] 2A . \tag{10}$$

It is obviously possible to account for the measured value of $\Gamma(D^0 \to K^- \pi^+)/\Gamma(D^0 \to \overline{K}^0 \pi^0)$ with the additional free parameter ϵ. An attempt to determine bounds on ϵ by this measurement would be premature in view of the rather large uncertainty in the latter.

Our new scheme allows the prediction of all other amplitudes for decay processes of the type $P_c \to PP$ in terms of the processes $D^0 \to K^- \pi^+$ and $D^0 \to \overline{K}^0 \pi^0$:

$$M(D^0 \to K^- \pi^+) = -\sqrt{\frac{3}{2}}\, M(F^+ \to \pi^+ \eta) = \sqrt{3}\, M(F^+ \to \pi^+ \eta') \tag{11a}$$

$$\sqrt{2}\, M(D^0 \to \overline{K}^0 \pi^0) = \sqrt{6}\, M(D^0 \to \overline{K}^0 \eta) = \sqrt{3}\, M(D^0 \to \overline{K}^0 \eta') = M(F^+ \to \overline{K}^0 K^+) \tag{11b}$$

$$M(D^+ \to \overline{K}^0 \pi^+) = M(D^0 \to K^- \pi^+) + \sqrt{2}\, M(D^0 \to \overline{K}^0 \pi^0) . \tag{11c}$$

In the above η and η' were assumed to be the SU(3) octet and singlet states respectively. The triangle relation, Eq. (11c), is the immediate consequence of the very general $\Delta I = 1$ property of the $\Delta C = \Delta S = -1$ weak

Hamiltonian. The first equality of Eq. (11b) is a straight-forward prediction of SU(3). All the other relations are the predictions of our specific scheme.

We have introduced in our scheme a new element due to final state gluon exchanges, which was absent in the more simplified conventional version of the valence quark approximation. It is of crucial importance to find out whether this new element alters in any essential way the successes of the latter scheme in the nonleptonic decays of strange particles.[1]

The $\Delta I = 1/2$ amplitudes for these processes are supposed to be dominated by the "penguin operator," which has enhanced matrix elements when two of the four fermion lines are attached to an external pion. This enhancement is not altered in our scheme. We expect final state gluon corrections to alter the numerical estimate of the matrix elements, however we consider this as part of the uncertainty in the numerical evaluation of these matrix elements.[7]

Turning next to the $\Delta I = 3/2$ transitions we note that the predictions for these amplitudes within the valence quark approximation agree with experiment in both sign and magnitude up to a common factor of 1.6.[1,11] When applying our modified scheme to these transitions one expects corrections due to multigluon exchange in the final state. Thus, in $K^+ \to \pi^+ \pi^0$ for instance, in addition to the traditional diagrams of Fig. 2(a), one has also diagrams such as in Fig. 2(b). The amplitude for this process was calculated using Fig. 2(a) and found to be[5,11]

$$|M(K^+ \to \pi^+\pi^0)| = 0.4\, c_1 s_1 c_3\, G M_K^2 f_\pi \simeq 2.9 \times 10^{-8}\ \text{GeV}\,, \qquad (12)$$

which is larger by a factor 1.6 than the experimental value 1.8×10^{-8} GeV. Denote by ϵ' the ratio of the contributions of Fig. 2(b) to the operator $(\bar{u}\lambda^a d)(\bar{s}\lambda^a u)$ and of Figs. 2(a), (b) to $(\bar{u}d)(\bar{s}u)$. Then in our new scheme one expects

$$|M(K^+ \to \pi^+\pi^0)| \simeq 2.9 \times 10^{-8} \left|1 + \frac{3}{8}\epsilon'\right| \text{GeV}. \qquad (13)$$

Due to the reasonable initial prediction Eq. (12), only not too large values of $|\epsilon'|$ may be considered acceptable, i.e. $|\epsilon'| \lesssim 2$ and preferably $\epsilon' \sim -1$. It seems to us encouraging that with $\epsilon = -1$* one finds from Eqs. (4), (9) and (10), $M(D^0 \to K^-\pi^+)/M(D^0 \to \bar{K}^0\pi^0) = -2.2$, which is not excluded by present measurements. With the same value of ϵ one also finds, $M(D^0 \to K^-\pi^+)/M(D^+ \to \bar{K}^0\pi^+) = 2.7$, which is not inconsistent with the measurement of $B.R.(D^+ \to \bar{K}^0\pi^+) = (2.1 \pm 0.4)\%$[8] and with the possibility that $\tau_{D^+} \sim 6\tau_{D^0}$.[12]

Our scheme may also be applied to the charmed meson decay into a pseudoscalar and a vector meson ($P_c \to PV$).[6] In general we do not

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*We use $\epsilon \sim \epsilon'$ for no deep reason but simplicity. As an educated guess one would expect final state soft gluon effects to be stronger in K decays than in D decays, so that probably $|\epsilon'| > |\epsilon|$.

expect $\epsilon_{PP} = \epsilon_{PV}$. The D^0 to D^+ ratio of amplitudes is very sensitive to the value of ϵ in the vicinity of $\epsilon = -1$. Therefore even when assuming approximately equal normalization for $D^0 \to PP$ and $D^0 \to PV$ ($A \sim B$, $z \sim 1$ in Ref. 6), our scheme does not necessarily predict even approximately equal branching ratios for $D^+ \to \overline{K}^0 \pi^+$ and $D^+ \to \overline{K}^{0*} \pi^+$.

In our scheme, proposed as a minimal modification of the over-simplified but rather successful valence quark model, we argued that it was reasonable to neglect the annihilation diagram (Fig. 1(b)). To the extent that such diagrams contribute to the charmed meson decays (we may view these contributions as coming from a gluon in the initial wave function which creates the final quark-antiquark pair), it is of interest to see which of our predictions (Eq. (11)) are particularly sensitive to such corrections. We find that these new contributions appear with opposite signs in decay modes which involve η and η' in the final state, and therefore expect the corrections to the corresponding ratios of amplitudes to be somewhat enhanced.* The role played by the annihilation diagram would be clarified by measuring the branching ratios for the processes $D^0 \to \phi \overline{K}^0$ and $F^+ \to \omega \pi^+$, which in our scheme are absolutely prohibited by assumption (c1). Note also that by isospin the annihilation diagram does not contribute to $K^+ \to \pi^+ \pi^0$.

*These and other points such as the application of our scheme to charmed baryon and heavier flavor decay will be discussed elsewhere.

Recent measurements of the Cabibbo suppressed decays $D^0 \to K^- K^+$ and $D^0 \to \pi^- \pi^+$ [8] indicate a gross deviation from equal rates, which is a strict consequence of SU(3) in a four quark model. It has been argued by a few authors that this large deviation may be accounted for by a combined effect of possible large Kobayashi-Maskawa mixing angles,[13,14] SU(3) breaking due to $f_K \neq f_\pi$ [13] and the possible contribution of the "penguin operator."[15*] We would like to emphasize that our predictions Eqs. (11a) and (11b), which we suggest as tests for our scheme, are unaffected by the above.

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*Another possible source for this deviation may be due to final state interactions enhanced by nearby lying resonance states. See Ref. 16.

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FIGURE CAPTIONS

Fig. 1: (a) The c-decay diagram for $D^0 \to K^- \pi^+$.

(b) The $c\bar{u}$ annihilation diagram for $D^0 \to K^- \pi^+$.

(c) A multiple soft gluon exchange diagram for $D^0 \to K^- \pi^+$, which obtains a contribution from the operator $(\bar{u}\lambda^a d)(\bar{s}\lambda^a c)$.

Fig. 2: (a) The $\bar{s}$ decay diagram for $K^+ \to \pi^+ \pi^0$.

(b) A multiple soft gluon exchange diagram for $K^+ \to \pi^+ \pi^0$.

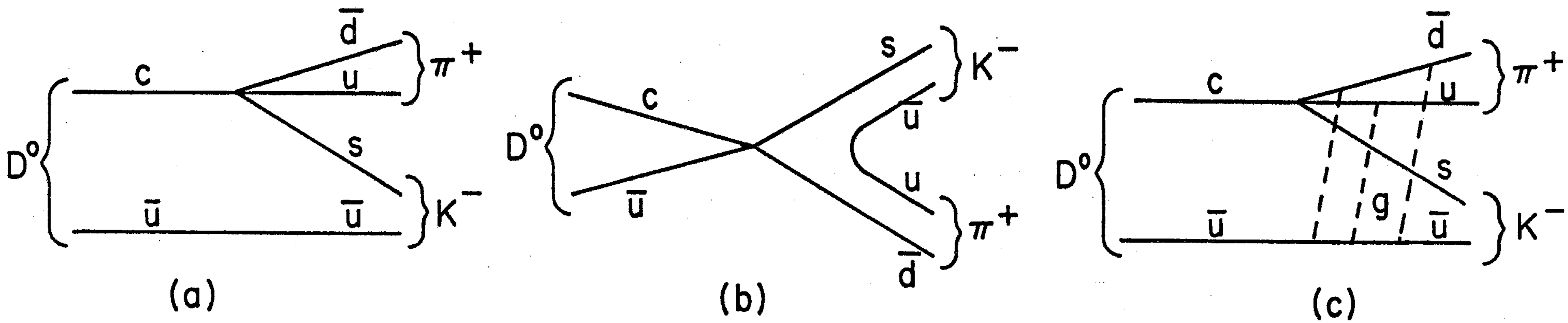

Fig. 1

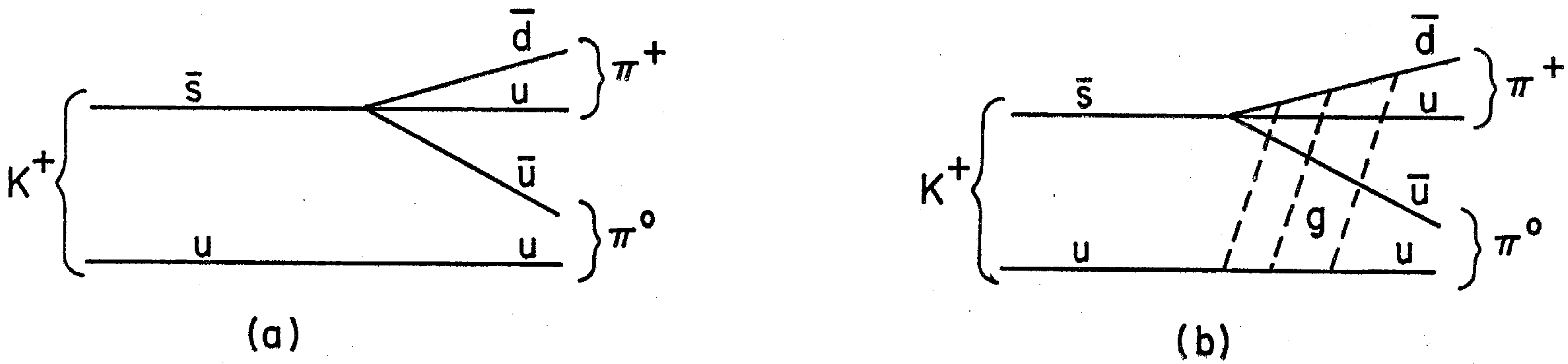

Fig. 2