Quark-Diagram Analysis of Two-Body Charm Decays

Ling-Lie Chau
Physics Department, Brookhaven National Laboratory, Upton, New York 11973
and
Hai-Yang Cheng
Physics Department, Indiana University, Bloomington, Indiana 47405
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Two-body decays of charm mesons are analyzed in the quark-diagram formulation, including effects of SU(3) breaking and final-state interactions. Interesting future experiments are also pointed out.

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In this Letter we analyze the experimental results for exclusive two-body decays of charmed mesons in a model-independent way within the framework of the quark-diagram formulation. We show that the recent measurements of two-body exclusive decays of charm mesons D^+, D^0, F^+ by Baltrusaitis *et al.*,[1] Chen *et al.*,[2] Darden *et al.* and Albrecht et al.,[3] Derrick *et al.*,[4] and Althoff *et al.*,[5] incorporating lifetime measurements,[6] can allow us to determine the magnitudes and even the signs of some of the quark-diagram amplitudes for $P_c \rightarrow VP$ decays. (Here, P_c represents D^+, D^0, F^+; V is the vector meson; and P is the pseudoscalar meson.) For $P_c \rightarrow PP$, we can also derive relations among various quark-diagram amplitudes. Using these experimentally determined quark amplitudes, we are able to make predictions for other charm decay channels and test various theoretical models.

It has been known for some time that all nonleptonic weak decays of mesons can be described in terms of six different quark diagrams[7,8]: the external W emission a, the internal W emission b, the W exchange c, the W annihilation d, the horizontal W-loop diagram e, and the vertical W-loop diagram f. This description is independent of the strong-interaction gluon effects, and hence can incorporate any specific strong-interaction model calculations. Such a scheme is most suitable for a systematic model-independent study of the numerous two-body decays of heavy-quark particles, such as charm and beauty. This scheme is greatly helped by the recent good determination of the quark-mixing matrix; it is especially helpful that $V_{us}^*/V_{ud} \simeq -V_{cd}^*/V_{cs} \simeq s_1c_1 \simeq 0.22$ (from the measured sup-

TABLE I. Charm meson decays into a vector boson and a pseudoscalar meson.

	Experimental branching ratio (%)	Amplitudes with SU(3) symmetry[f]	Amplitudes with SU(3) breaking and final-state interactions[g]
		D^+ decays	
$\bar{K}^{*0}\pi^+$	$3.0 \pm 1.9 \pm 1.7$[a]	$(c_1)^2\{a'+b'\}$	$(c_1)^2\{a'+b'\}\exp(i\delta_{3/2}^{\bar{K}^*\pi})$
$\rho^+\bar{K}^0$	$12.2 \pm 2.8 \pm 1.9$[a]	$(c_1)^2\{a+b\}$	$(c_1)^2\{a+b\}\exp(i\delta_{3/2}^{\rho\bar{K}})$
$\phi\pi^+$	$0.93 \pm 0.26 \pm 0.17$[a]	$(s_1c_1)\{b'\}$	$(s_1c_1)\{b'\}\exp(i\delta^{\phi\pi})$
$\bar{K}^{*0}K^+$	$0.53 \pm 0.24 \pm 0.14$[a]	$(s_1c_1)\{a'-\tilde{d}\}$	$(s_1c_1)\{a'-\tilde{d}+\delta e\}\exp(i\delta_1^{\bar{K}^*K})$
		D^0 decays	
$\phi\bar{K}^0$	1.4 ± 0.5[b]	$(c_1)^2\{\tilde{c}'\}$	$(c_1)^2\{\tilde{c}'\}\exp(i\delta^{\phi\bar{K}})$
$\omega\bar{K}^0$	$3.8 \pm 1.5 \pm 1.0$[a]	$(1/\sqrt{2})(c_1)^2\{b+c\}$	$(1/\sqrt{2})(c_1)^2\{b+c\}\exp(i\delta^{\omega\bar{K}})$
$K^{*-}\pi^+$	$7.8 \pm 1.2 \pm 0.9$[a] $7.1 \pm 1.6 \pm 1.3$	$(c_1)^2\{a'+c'\}$	$(c_1)^2\{(a'+c')-\frac{1}{3}(a'+b')[1-\exp(i\Delta_{\bar{K}^*\pi})]\}\exp(i\delta_{1/2}^{\bar{K}^*\pi})$
$\bar{K}^{*0}\pi^0$	$2.1 \pm 0.9 \pm 0.6$[a]	$(1/\sqrt{2})(c_1)^2\{b'-c'\}$	$(1/\sqrt{2})(c_1)^2\{(b'-c')-\frac{2}{3}(a'+b')[1-\exp(i\Delta_{\bar{K}^*\pi})]\}\exp(i\delta_{1/2}^{\bar{K}^*\pi})$
ρ^+K^-	$13.7 \pm 1.3 \pm 1.5$[a]	$(c_1)^2\{a+c\}$	$(c_1)^2\{(a+c)-\frac{1}{3}(a+b)[1-\exp(i\Delta_{\rho\bar{K}})]\}\exp(i\delta_{1/2}^{\rho\bar{K}\pi})$
$\rho^0\bar{K}^0$	$1.3 \pm 0.4 \pm 0.3$[a]	$(1/\sqrt{2})(c_1)^2\{b-c\}$	$(1/\sqrt{2})(c_1)^2\{(b-c)-\frac{2}{3}(a+b)[1-\exp(i\Delta_{\rho\bar{K}})]\}\exp(i\delta_{1/2}^{\rho\bar{K}\pi})$
		F^+ decays	
$\phi\pi^+$	3.3 ± 1.1[c]; 4.4[d] $13.0 \pm 3.0 \pm 4.0$[e]	$(c_1)^2\{a'\}$	$(c_1)^2\{a'\}\exp(i\delta^{\phi\pi})$

[a]Reference 1.
[b]Reference 3; see also Refs. 1 and 2.
[c]Reference 4.
[d]Reference 2.
[e]Reference 5.
[f]$V_{us}V_{cs}^* \simeq -V_{ud}V_{cd}^* \simeq s_1c_1$ used.
[g]$\delta e \equiv \tilde{e} - e$; $\delta f \equiv f - f$; $\delta c \equiv \tilde{c} - c$; the amplitudes with tildes have $s\bar{s}$.

pression[9] of V_{cb}, V_{ub}) provides a simplification of the quark-diagram description for charm decays and more importantly gives the result that only the SU(3)-breaking parts of the W-loop graphs contribute to charm decays, thus sharpening the test for SU(3)-breaking effects.[10] For example, the experimental observation[11] of $\bar{\Gamma}(D^0 \to \bar{K}K) > \bar{\Gamma}(D^0 \to \pi^+\pi^-)$ indicates clearly the importance of SU(3) breaking and/or final-state interactions. Chau and Cheng[12] give the quark-diagram formulation, including SU(3)-breaking and final-state–interaction effects, for all charm two-body decays, $P_c \to PV$, $P_c \to PP$. We have listed those relevant for our discussions here in Tables I and II.

Recently, many two-body decays of charm particles have been beautifully measured,[1–5] which we list in Tables I and II. Here we shall put the quark-diagram formalism to use, analyzing all existing charm two-body decay data and discussing their implications for various theoretical model calculations.

We begin with the PV decays because of the relative simplicity in presenting the discussion, though the data of PV decays are not yet as good as those for some of the PP decays. The simplicity in discussing the PV decays comes from the purity of the quark contents in ϕ and ω. Many PV decays are given by one type of amplitude, as shown in Table I: e.g., $F^+ \to \phi\pi^+$ ($\propto a'$), $D^+ \to \phi\pi^+$ ($\propto b'$), $D^0 \to \phi\bar{K}^0$ ($\propto \tilde{c}'$), respectively. Thus from the decay rates, using the known lifetime measurements,[6] we can determine their absolute values:

$$|a'| = (2.50 \pm 0.42)\times 10^{-6},$$
$$|b'| = (3.67 \pm 0.51)\times 10^{-6}, \qquad (1)$$
$$|\tilde{c}'| = (1.68\text{–}2.10)\times 10^{-6}.$$

The only theoretical assumption used here is that $|\exp(i\delta^{\phi\pi})| = 1 = |\exp(i\delta^{\phi\bar{K}})|$. Note here that neither amplitude b' nor amplitude $\tilde{c}'$ is negligible, as preferred by some model calculations.

$D^+ \to \bar{K}^{*0}\pi^+$ [$\propto (a'+b')$] is an exotic channel which implies elastic and small $\delta_{3/2}^{\bar{K}^*\pi}$. Therefore, the rate gives

$$|a'+b'| = (1.16 \pm 0.37)\times 10^{-6}. \qquad (2)$$

Combining Eqs. (1) and (2), we obtain

$$a' = (2.50 \pm 0.42)\times 10^{-6},$$
$$b' = -(3.67 \pm 0.51)\times 10^{-6}. \qquad (3)$$

From $D^0 \to K^{*-}\pi^+, \bar{K}^{*0}\pi^0$ measurements we obtain the following two solutions:

$$(a'+c')/(a'+b') = 2.36 \pm 0.67 \to c' = -(5.25 \pm 0.39)\times 10^{-6}, \quad \Delta_{\bar{K}^*\pi} = (52^{+30}_{-52})^\circ, \qquad (4a)$$

$$(a'+c')/(a'+b') = -1.70 \pm 0.67 \to c' = -(0.53 \pm 0.39)\times 10^{-6}, \quad \Delta_{\bar{K}^*\pi} = 180^\circ - (52^{+30}_{-52})^\circ. \qquad (4b)$$

We note that the errors on $\Delta_{\bar{K}^*\pi}$ are so large that the data can be accommodated by real amplitudes without final-state interactions. The amplitude c' is quite different from $\tilde{c}'$ in Eq. (1). (Amplitudes with tildes involve strange-quark and -antiquark pair production.) To make definite conclusions, we need better measurements.

TABLE II. Charm meson decays into two pseudoscalars. The same notations a to f are used for amplitudes, but in general they have no relations to those in the PV decays in Table I.

	Experimental branching ratio (%) (Ref. 1)	Amplitudes with SU(3) symmetry[a]	Amplitudes with SU(3) breaking and final-state interactions[b]
		D^+ decays	
$\bar{K}^0\pi^+$	$3.5 \pm 0.5 \pm 0.4$	$(c_1)^2\{a+b\}$	$(c_1)^2\{a+b\}\exp(i\delta_{3/2}^{\bar{K}\pi})$
$\bar{K}^0K^+$	$1.11 \pm 0.34 \pm 0.21$	$(s_1c_1)\{a-d\}$	$(s_1c_1)\{a-\tilde{d}+\delta e\}\exp(i\delta_1^{\bar{K}K})$
$\pi^0\pi^+$	$\leqslant 0.53$	$(1/\sqrt{2})(s_1c_1)\{a+b\}$	$(1/\sqrt{2})(s_1c_1)\{a+b\}\exp(i\delta_2^{\pi\pi})$
		D^0 decays	
$K^-\pi^+$	$4.9 \pm 0.4 \pm 0.4$	$(c_1)^2\{a+c\}$	$(c_1)^2\{(a+c)-(a+b)\frac{1}{3}[1-\exp(i\Delta_{\bar{K}\pi})]\}\exp(i\delta_{1/2}^{\bar{K}\pi})$
$\bar{K}^0\pi^0$	$2.2 \pm 0.4 \pm 0.2$	$(1/\sqrt{2})(c_1)^2\{b-c\}$	$(1/\sqrt{2})(c_1)^2\{(b-c)-(a+\tilde{b})\frac{2}{3}[1-\exp(i\Delta_{\bar{K}\pi})]\}\exp(i\delta_{1/2}^{\bar{K}\pi})$
$\bar{K}^0\eta$	$1.8 \pm 0.8 \pm 0.3$	$\cos\theta A(D^0 \to \bar{K}^0\eta_8) + \sin\theta A(D^0 \to \bar{K}^0\eta_0)$	
$K^0\bar{K}^0$	$\leqslant 0.62$	$(s_1c_1)\,0$	$(s_1c_1)\{(-\delta e-2\delta f)+(a+\tilde{c}-\delta e)\frac{1}{2}[1-\exp(\Delta_{\bar{K}K})]\}\exp(i\delta_0^{K\bar{K}})$
K^-K^+	$0.60 \pm 0.10 \pm 0.08$	$(s_1c_1)\{a+c\}$	$(s_1c_1)\{(a+c)+(\delta e+2\delta f)-(a+\tilde{c}-\delta e)\frac{1}{2}[1-\exp(i\Delta_{\bar{K}K})]\}\exp(i\delta_0^{\bar{K}K})$
$\pi^+\pi^-$	$0.16 \pm 0.09 \pm 0.03$	$-(s_1c_1)\{a+c\}$	$-(s_1c_1)\{(a+c)+(\delta e+2\delta f)-(a+b)\frac{1}{3}[1-\exp(i\Delta_{\pi\pi})]\}\exp(i\delta_0^{\pi\pi})$
$\pi^0\pi^0$		$\frac{1}{2}\sqrt{2}(s_1c_1)\{b-c\}$	$\frac{1}{2}\sqrt{2}(s_1c_1)\{(b-c)+(\delta e+2\delta f)-(a+b)\frac{2}{3}[1-\exp(i\Delta_{\pi\pi})]\}\exp(i\delta_0^{\pi\pi})$

[a] $V_{us}V_{cs}^* \simeq -V_{ud}V_{cd}^* \simeq s_1c_1$ used.

[b] $\delta e \equiv \tilde{e} - e$; $\delta f \equiv \tilde{f} - f$; $\delta c \equiv \tilde{c} - c$; the amplitudes with tildes have $s\bar{s}$.

One nice prediction from this analysis is $B(D^0 \to \phi\pi^0) \simeq 0.21\%$, from $D^0 \to \phi\pi^0$ ($\propto b'$). This will be an important measurement if we are to test this scheme.

We next proceed to determine the unprimed amplitudes from $D \to \rho\bar{K}$ and $D^0 \to \omega\bar{K}$ decays. From Table I it follows that $D^+ \to \rho^+\bar{K}^0$, $D^0 \to \omega\bar{K}^0$ determine

$$|a+b| = (2.18 \pm 0.25)\times 10^{-6},\quad |b+c| = (2.57 \pm 0.51)\times 10^{-6}. \tag{5}$$

From the measurements of $D^0 \to \rho^0\bar{K}^0, \rho^+K^-$, we find two solutions for $(a+c)/(a+b)$. Combining all those results we obtain the following three possible solutions for amplitudes a, b, and c: two for $\Delta_{\rho\bar{K}} = (24^{+25}_{-24})°$,

$$a = (4.06 \pm 0.38)\times 10^{-6},\quad b = -(1.88 \pm 0.28)\times 10^{-6},\quad c = -(0.68 \pm 0.28)\times 10^{-6}, \tag{6a}$$

$$a = (1.50 \pm 0.38)\times 10^{-6},\quad b = (0.68 \pm 0.28)\times 10^{-6},\quad c = (1.89 \pm 0.28)\times 10^{-6}, \tag{6b}$$

and one for $\Delta_{\rho\bar{K}} = 180° - (24^{+21}_{-24})°$,

$$a = (1.41 \pm 0.38)\times 10^{-6},\quad b = (0.77 \pm 0.28)\times 10^{-6},\quad c = -(3.34 \pm 0.28)\times 10^{-6}. \tag{6c}$$

The measurement of $D^+ \to \bar{K}^{*0}K^+$, Table I, gives us $|a' - \tilde{d} + \delta_e| = (2.70 \pm 0.61)\times 10^{-6}$.

Future measurements of $\bar{K}^{*0}\eta_8$ [$\propto (b'+c'-2\tilde{c})$] and $\bar{K}^{*0}\eta_0$ [$\propto (b'+c'+\tilde{c})$], can help to determine amplitudes $\tilde{c}$ and $(b'+c')$, and then c', since b' is known. From future measurements of $D^0 \to \bar{K}^{*0}K^0$, $K^{*0}\bar{K}^0$ [$\propto (c-c')$], and the known information on c' we can determine the amplitude c. Then we can check which solution of Eq. (6) will be picked, and thus determine a and b individually. From $F^+ \to \rho^+\pi^0$ [$\propto (d-d')$], $F^+ \to \omega\pi^+$ [$\propto (d+d')$], we can determine d and d'. We then known all the amplitudes a, b, c, d, and a', b', c', d', and their relative signs. The rest of the PV decays are predictable, up to SU(3) breaking and final-state interactions. These results must be conformed to by any theoretical calculations.

Next we discuss the case of charm meson decay into two pseudoscalars, $P_c \to PP$. (Note that the amplitudes a to f here for PP decays have no relation to those for the PV decays. When needed for clarity, we use subscript PP to denote the distinction.) Here, the data are of greater accuracy than for the $P_c \to PV$ case, Table II. From $D^+ \to \pi^+\bar{K}^0$, $D^0 \to K^-\pi^+, \bar{K}^0\pi^0$, we can conclude definitely that real amplitudes $(a,b,c)_{PP}$ (without effects like final-state interactions included) cannot fit the data.[12,13] From $D^+ \to \pi^+\bar{K}^0$, we obtain

$$|a+b|_{PP} = (1.66 \pm 0.11)\times 10^{-6}\ \text{GeV}. \tag{7}$$

Then from $D^0 \to K^-\pi^+, \bar{K}^0\pi^0$, we obtain the following two solutions:

$$[(a+c)/(a+b)]_{PP} = 1.95 \pm 0.14,\quad \Delta_{\bar{K}\pi} = (79^{+10}_{-14})°, \tag{8a}$$

or

$$[(a+c)/(a+b)]_{PP} = -1.28 \pm 0.14,\quad \Delta_{\bar{K}\pi} = 180 - (79^{+10}_{-14})°. \tag{8b}$$

We want to caution about the interpretation of the phase shift obtained here. Its relation to the hadronic scattering phase shifts is complicated by the other competing channels, e.g., $\pi\pi\bar{K}$, $\pi\pi\pi\bar{K}$ (not including $\rho\bar{K}$, $\pi\bar{K}^*$, which do not communicate with $\bar{K}\pi$ through strong interactions).

Unlike the PV decays, it is much harder here to determine individual amplitudes, since none of the decays is given by a single amplitude. It is interesting to point out that the nonspectator-diagram amplitudes $\tilde{c}$ and d can be measured in a model-independent way by observation of the following decay modes:

$$\frac{\Gamma(D^0 \to K^0\eta_8)}{\Gamma(D^0 \to K^0\eta_0)} = \frac{1}{2}\left|\frac{(b+c-2\tilde{c})}{(b+c+\tilde{c})}\right|^2_{PP},\quad \frac{\Gamma(F^+ \to \eta_8\pi^+)}{(F^+ \to \eta_0\pi^+)} = 2\left|\frac{(a-d)}{(a+2d)}\right|^2_{PP}. \tag{9}$$

From the absolute rates of these decays we can determine $[(b+c),\tilde{c};$ and $a,d]_{PP}$. Combining these with the solutions Eq. (7) and (8), we shall determine all amplitudes $(a, b, c, \text{and } d)_{PP}$ and their relative signs.

Next we go to the mixing-matrix singly suppressed measurement of $\Gamma(D^0 \to K^+K^-)/\Gamma(D^0 \to \pi^+\pi^-) \neq 1$. From Table II, we see that such differences can be attributed to the SU(3)-breaking effect of $(\delta e + 2\delta f)_{PP}$, which contributes with opposite sign to $D^0 \to K^+K^-, \pi^+\pi^-$ and/or to the final-state–interaction effect (e.g., $\delta_0^{\pi\pi}$ has a larger absorptive part than $\delta_0^{K\bar{K}}$). To clarify these mechanisms it is of paramount importance to measure $D^0 \to \pi^0\pi^0$ (see Table II), since the same unknowns, $(\delta e + 2\delta f)_{PP}$, $\delta_0^{\pi\pi}$, are present, but the rest of the amplitudes, $(b-c)_{PP}$, $(a+b)_{PP}$, are known [from Eqs. (7) and (8)].

With the known relation between η, η' and η_8, η_0 (here the mixing angle of $-10°$ is used; in the analysis of future measurements of decays involving η', care should be taken to subtract any component in η' that is not η_0 or η_8), the current measurement of $D^0 \to \bar{K}^0\eta$, Table II, gives $|1.23b - 0.49c|_{PP} = (4.57 \pm 1.01)\times 10^{-6}$ GeV, if there is no SU(3) breaking, i.e., $\tilde{c} = c$; or it gives $|b+c|_{PP} = (3.71 \pm 0.83)\times 10^{-6}$ GeV, if SU(3) breaking is maximal, i.e., $\tilde{c} = 0$. Future measurements of $D^0 \to \bar{K}^0\eta_8$ [$\propto (b+c-2\tilde{c})$], or $\bar{K}^0\eta'$, will help to determine amplitudes $[(b+c),\tilde{c}$; thus $b,c]_{PP}$ individually when combined with the results of Eqs. (7) and (8). The measurement of $D^+ \to \bar{K}^0 K^+$ gives $|a-\tilde{d}+\delta e|_{PP} = (4.29 \pm 0.66)\times 10^{-6}$ GeV. Future measurements of $F^+ \to \pi^+ \eta_8$ [$\propto (a-d)_{PP}$], and $\pi^+ \eta_0$ [$\propto (a+2d)_{PP}$], can give $(a,d)_{PP}$; $\bar{\Gamma}(D^+ \to \bar{K}^0 K^+)$ is predicted to be equal to $(s_1/c_1)^2 \times \bar{\Gamma}(F^+ \to \pi^+ \eta_8)$ if there is no SU(3) breaking. The measurements of $D^0 \to K^0 \bar{K}^0, \eta_0 \eta_0$, which are nonzero only from SU(3) breaking, can give a direct modification of SU(3)-breaking effects. The long-predicted relation

$$\bar{\Gamma}(D^+ \to \pi^+ \pi^0)/\bar{\Gamma}(D^+ \to \bar{K}^0 \pi^+) = \tfrac{1}{2} |V_{cd}/V_{cs}|^2$$

should be checked by experiments.

We next turn to the theoretical aspect. It has been established that the vacuum insertion calculations do not agree with the two-body exclusive decays.[12] To improve the comparison with the data attempts have been made to enhance either the W-exchange diagram c, or the internal W-emission diagram b. Now we know from $D^+ \to \phi \pi^+$ and $D \to \bar{K}^* \pi$ data that the amplitude b' is very important. From the measurement of $D^0 \to \phi \bar{K}^0$ decay[1-3] we know that amplitude $\tilde{c}'$ is nonnegligible. Therefore enhancement of either the W-exchange or the internal W-emission amplitudes in model calculations is not sufficient to fit the data consistently. Current data on $D \to \bar{K}\rho$ and $\bar{K}\pi$ decays have not yet provided enough information about how important the individual amplitudes are. As discussed in the previous sections future measurements of $\bar{K}^{*0}\eta_8$, $\bar{K}^{*0}\eta_0$, $D^0 \to \bar{K}^{*0} K^0, K^{*0}\bar{K}^0$, $F^+ \to \rho^+ \pi^0, \omega \pi^+$ and $D^0 \to \bar{K}^0 \eta_8$, $\bar{K}^0 \eta_0$, $F^+ \to \pi^+ \eta_8, \pi^+ \eta_0$, will give definite and model-independent results about individual amplitudes, to which theoretical calculations must conform.

No theoretical calculations have so far addressed the question of how to calculate the final-state–interaction effects, as established here in $D^+ \to \bar{K}^0 \pi^+$, $D^0 \to K^- \pi^+, \bar{K}^0 \pi^0$, Eq. (8); or those to be determined, Eqs. (4) and (6). Actually it is not so straightforward even to relate the phase shifts in hadronic scattering to those determined in charm decays because of the communicating multichannels available in the decays.

In summary, we have demonstrated here that the quark-diagram approach provides a framework in which experimental results can be analyzed in a model-independent way. The current experimental measurements have already provided much information on nonleptonic decays in terms of quark-diagram amplitudes. Much progress in theory is needed in order to understand these results. The quark-diagram scheme and the analyses done here provide information for theoretical development, and for pointing out interesting measurements to be done in the future.

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