Flavor Symmetry and Charm Decays

Bhubanjyoti Bhattacharya and Jonathan L. Rosner
Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, IL 60637

1. Introduction

The application of flavor symmetries, notably SU(3), to charmed particle decays can shed light on some fundamental questions. Often it is useful to know the strong phases of amplitudes in these decays. For example, the relative strong phase in \( D^0 \to K^-\pi^+ \) and \( \bar{D}^0 \to K^-\pi^+ \) is important in interpreting decays of B mesons to \( D^0X \) and \( \bar{D}^0X \) \([1, 2]\). Such strong phases are non-negligible even in B decays to pairs of pseudoscalar mesons (P) despite some perturbative QCD expectations to the contrary, and can be even more important in \( D \to PP \) decays. In the present report we shall illustrate the extraction of strong phases from charmed particle decays using SU(3) flavor symmetry, primarily the U-spin symmetry involving the interchange of s and d quarks.

We begin in Section 2 by discussing the overall diagrammatic approach to flavor symmetry. In Section 3 we treat Cabibbo-favored decays, turning to singly-Cabibbo-suppressed decays in Section 4 and doubly-Cabibbo-suppressed decays in Section 5. We note specific applications to \( D^0 \) and \( \bar{D}^0 \) decays to \( K^-\pi^+ \) in Section 6, mention some other theoretical approaches in Section 7, and conclude in Section 8.

2. Diagrammatic amplitude expansion

We use a flavor-topology language for charmed particle decays first introduced by Chau and Cheng \([3, 4]\). These topologies, corresponding to linear combinations of SU(3)-invariant amplitudes, are illustrated in Fig. 1. Cabibbo-favored (CF) amplitudes, proportional to the product \( V_{us}V_{cs}^* \) of Cabibbo-Kobayashi-Maskawa (CKM) factors, will be denoted by unprimed quantities; singly-Cabibbo-suppressed amplitudes proportional to \( V_{us}V_{cd}^* \) or \( V_{us}V_{ad}^* \) will be denoted by primed quantities; and doubly-Cabibbo-suppressed quantities proportional to \( V_{us}V_{cd}^* \) will be denoted by amplitudes with a tilde. The relative hierarchy of these amplitudes is \( 1 : \lambda : -\lambda : -\lambda^2 \), where \( \lambda = \tan \theta_C = 0.232\pm0.002 \) \([5]\). Here \( \theta_C \) is the Cabibbo angle.

3. Cabibbo-favored decays

A detailed discussion of amplitudes and their relative phases for Cabibbo-favored charm decays was given in Ref. \([6]\). The main conclusions of that analysis were large relative phases of the \( C \) and \( E \) amplitudes relative to the dominant \( T \) term, and an approximate relation \( A \simeq -E \). The present updated data confirm these results.

In Table I we show the results of extracting amplitudes \( A = M_B[8\pi B\hbar/(p^*\tau)]^{1/2} \) from the branching ratios \( B \) and lifetimes \( \tau \), all from Ref. \([6]\) unless otherwise noted. Here \( M_B \) is the mass of the decaying charmed particle, and \( p^* \) is the final c.m. 3-momentum.

The extracted amplitudes, with \( T \) defined to be real, are, in units of \( 10^{-6} \) GeV:

\[
T = 2.71 + 0i \quad (1)
\]
\[
C = -1.77 - 1.01i \quad \delta(CT) = -150^\circ \quad (2)
\]
\[
E = -0.71 + 1.49i \quad \delta(ET) = 115^\circ \quad (3)
\]
\[
A = 0.57 - 1.30i \quad \delta(AT) = -66^\circ \quad (4)
\]

These values update (and are consistent with) those quoted with less precision in Ref. \([6]\). New (mainly lower) preliminary branching ratios for many \( D_s \) decays reported at this Conference \([7]\) will change some of the results slightly once they are incorporated into averages.

The Cabibbo-favored amplitudes are shown on an Argand diagram in Fig. 2. Here A was extracted from \( D_s \to \pi^+\eta \) and \( D_s \to \pi^+\eta' \); the amplitude \( A \) for \( D_s \to \bar{K}^0K^+ \) is then predicted to be \( 2.60 \times 10^{-6} \) GeV vs. \( (2.60 \pm 0.25) \times 10^{-6} \) GeV observed. Note the importance of the \( E \) and \( A \simeq -E \) amplitudes.

4. Singly-Cabibbo-suppressed decays

4.1. SCS decays involving pions and kaons

We show in Table II the branching ratios, amplitudes, and representations in terms of reduced amplitudes for singly-Cabibbo-suppressed (SCS) charm decays involving pions and kaons. The ratio of primed (SCS) to unprimed (CF) amplitudes is expected to be \( \tan \theta_C \simeq 0.232 \).

A wealth of new data in charmed particle decays allows the testing of flavor symmetry and the extraction of key amplitudes. Information on relative strong phases is obtained.
The deviations from flavor SU(3) implicit in Table III are well known. We shall discuss amplitudes in units of $10^{-7}$ GeV. If one rescales the CF amplitudes by the factor of $\tan \theta_C$, one predicts that for $D^+ \rightarrow K^- \pi^+$, $|A| (10^{-6} \text{ GeV})$ = 2.94$ \pm$ 0.12, which may be described in terms of a connected “singlet” exchange amplitude for $D^+ \rightarrow K^- \pi^+$. In Table III we write amplitudes multiplied by factors so that they involve unit coefficients of an amplitude $SE'$ describing a disconnected “singlet” exchange amplitude for $D^0$ decays. Similarly the decays $D^+ \rightarrow (\pi^+ \eta, \pi^+ \eta')$ and $D^+_s \rightarrow (K^+ \eta, K^+ \eta')$ may be described in terms of the new unit coefficient.

4.2. SCS decays involving $\eta, \eta'$

The amplitudes $C$ and $E$ extracted from Cabibbo-favored charm decays imply values of $C' = \lambda C$ and $E' = \lambda E$ which may be used in constructing amplitudes for singly-Cabibbo-suppressed $D^0$ decays involving $\eta$ and $\eta'$. In Table III we write amplitudes multiplied by factors so that they involve unit coefficient of an amplitude $SE'$ describing a disconnected “singlet” exchange amplitude for $D^0$ decays. Similarly the decays $D^+ \rightarrow (\pi^+ \eta, \pi^+ \eta')$ and $D^+_s \rightarrow (K^+ \eta, K^+ \eta')$ may be described in terms of a
Table II Branching ratios, amplitudes, and decomposition in terms of reduced amplitudes for singly-Cabibbo-suppressed (SCS) charm decays involving pions and kaons.

| Meson mode | Decay mode | \( B \) \((10^{-3})\) | \( \rho^* \) \( (\text{MeV}) \) | \( |A| \) \((10^{-7} \text{ GeV})\) | Rep. |
|------------|------------|------------------|------------------|------------------|------|
| \( D^0 \) | \( \pi^+\pi^- \) | 1.37±0.03 | 922 | 4.57±0.05 | \( -(T' + E') \) |
| \( D^0 \) | \( \pi^0\pi^0 \) | 0.79±0.08 | 923 | 3.46±0.18 | \( -(C' - E')/\sqrt{2} \) |
| \( K^+K^- \) | 3.85±0.09 | 791 | 8.26±0.10 | \( (T' + E') \) |
| \( K^0\bar{K}^0 \) | 0.72±0.14 | 789 | 3.58±0.35 | 0 |
| \( D^+ \) | \( \pi^+\pi^0 \) | 1.28±0.08 | 925 | 2.77±0.09 | \( -(T' + C')/\sqrt{2} \) |
| \( K^+\bar{K}^0 \) | 5.90±0.38 | 793 | 6.43±0.21 | \( T' - A' \) |
| \( D^+_s \) | \( \pi^0K^+ \) | 2.46±0.40 | 916 | 5.87±0.48 | \( -(T' - A') \) |
| \( \pi^0K^+ \) | 0.75±0.28 | 917 | 3.24±0.60 | \( -(C' + A')/\sqrt{2} \) |

Figure 2: Construction of Cabibbo-favored amplitudes from observed processes. Here the sides \( C + T \), \( C + A \), and \( E + T \) correspond to measured processes; the magnitudes of other amplitudes listed in Table I are also needed to specify the reduced amplitudes \( T \), \( C \), \( E \), and \( A \).

Figure 3: Graphical construction to obtain the disconnected singlet annihilation amplitude \( SA' \), written with unit coefficient in Table III. For experimental values we have used new CLEO measurements as reported in Ref. [9]. (See Table IV.)

We show in Fig. 3 the construction proposed in Ref. [8] to obtain the amplitude \( SA' \). Two solutions are found. In one, \( |SA'| \) is uncomfortably large in comparison with the “connected” amplitudes, while in the other \( |SA'| \) is smaller, but nonzero. Corresponding studies of the \( D^0 \) decays listed in Table III, which await further analysis by the CLEO Collaboration, will permit determination of the corresponding amplitude \( SE' \) if one or more consistent solutions are found.

5. Doubly-Cabibbo-suppressed decays

In Table V we expand amplitudes for doubly-Cabibbo-suppressed decays in terms of the reduced amplitudes \( \bar{T} \equiv -\tan^2\theta_C T \), \( \bar{C} \equiv -\tan^2\theta_C C \), \( \bar{E} \equiv \)
Table III Real and imaginary parts of amplitudes for SCS charm decays involving \( \eta \) and \( \eta' \), in units of \( 10^{-3} \) GeV as predicted in Ref. [8].

| Amplitude | Expression | Re | Im | \( A_{\text{exp}} \) |
|-----------|------------|----|----|----------------|
| \(-\sqrt{3} A(D^0 \to \pi^0 \eta)\) | \(2E' - C + SE'\) | 0.82 | 9.24 |
| \(-\sqrt{3} A(D^0 \to \pi^0 \eta')\) | \(\frac{1}{2}(C' + E') + SE'\) | -0.91 | 9.24 |
| \(\sqrt{3} A(D^0 \to \eta \eta)\) | \(C' + SE'\) | -10.06 | 9.24 |
| \(-\sqrt{3} A(D^0 \to \eta' \eta)\) | \(-\frac{1}{2}(C' + 6E') + SE'\) | 0.21 | 9.24 |
| \(\sqrt{3} A(D^0 \to \pi^+ \eta)\) | \(T' + 2C' + 2A' + SA'\) | 0.21 | 9.24 |
| \(-\sqrt{3} A(D^0 \to \pi^+ \eta')\) | \(-\frac{1}{2}(T' - C' + 2A') + SA'\) | 0.21 | 9.24 |
| \(\sqrt{3} A(D^0 \to \eta K^+)\) | \(-T' + 2C'\) + SA' | 0.21 | 9.24 |

Table IV Branching ratios and amplitudes for \( D^+ \) and \( D_s^+ \) SCS decays involving \( \eta \) and \( \eta' \).

| Meson | Decay mode | \( B \) (10^{-3}) | \( p^* \) (MeV) | \( A \) (10^{-7} GeV) |
|-------|------------|--------------------|----------------|------------------|
| \( D^+ \) | \( \pi^0 \eta \) | 3.50±0.32 | 848 | 4.79±0.22 |
| \( \pi^0 \eta' \) | 5.31±1.1 | 681 | 6.58±0.68 |
| \( D_s^+ \) | \( K^+ \eta \) | 1.92±0.43 | 835 | 5.43±0.61 |
| \( K^+ \eta' \) | 2.02±0.69 | 646 | 6.33±1.08 |

\(-\tan^2 \theta_CE\), and \( \tilde{A} \equiv -\tan^2 \theta_C A\).

With \( \tan \theta_C \approx 0.23 \) one predicts \( |A(D^0 \to K^+ \pi^-)| = 1.32 \times 10^{-7} \) GeV and \( |A[D^+ \to K^+(\pi^0, \eta, \eta')]| = (0.93, 0.83, 1.27) \times 10^{-7} \) GeV, in qualitative agreement with experiment.

5.2. \( D^+ \to (K^0 \pi^+, \bar{K}^0 \pi^+) \) interference

In contrast to the case of \( D^0 \to (K^0 \pi^0, \bar{K}^0 \pi^0) \), the decays \( D^+ \to (K^0 \pi^+, \bar{K}^0 \pi^+) \) are not related to one another by a simple U-spin transformation. Amplitudes contributing to these processes are shown in Fig. [9]. Although both processes receive color-suppressed (\( C \) or \( \bar{C} \)) contributions, the Cabibbo-favored process receives a color-favored tree (\( T \)) contribution, while the doubly-Cabibbo-suppressed process receives an annihilation (\( \bar{T} \)) contribution. In order to calculate the asymmetry between \( K_S \) and \( K_L \) production in these decays due to interference between CF and DCS amplitudes, one can use the determination of the CF amplitudes discussed previously and the relation between them and DCS amplitudes. Thus, we define

\[
R(D^+) \equiv \frac{\Gamma(D^+ \to K_S \pi^+) - \Gamma(D^+ \to K_L \pi^+)}{\Gamma(D^+ \to K_S \pi^+) + \Gamma(D^+ \to K_L \pi^+)}
\]

and predict

\[
R(D^+) = -2 \Re \frac{\bar{C} + \bar{A}}{\bar{T} + \bar{C}} = 2 \tan^2 \theta_C \Re \frac{C + A}{T + C} = 0.068 \pm 0.007.
\]

This is consistent with (though slightly larger in central value than) the observed value \( R(D^+) = 0.026 \pm 0.016 \pm 0.018 \) [10]. The relative phase of \( C + A \) and \( T + C \) is about 70°, as can be seen from Fig. [2]. The real part of their ratio hence is small. A similar exercise can be applied to the decays \( D_s^+ \to K^+ K^0 \) and \( D_s^+ \to K^+ \bar{K}^0 \), which are related by U-spin to the \( D^+ \) decays discussed here. The corresponding ratio

\[
R(D_s^+) \equiv \frac{\Gamma(D_s^+ \to K_S K^+) - \Gamma(D_s^+ \to K_L K^+)}{\Gamma(D_s^+ \to K_S K^+) + \Gamma(D_s^+ \to K_L K^+)}
\]

is predicted to be

\[
R(D_s^+) = -2 \Re \frac{\bar{C} + \bar{T}}{\bar{A} + \bar{C}}
\]

5.1. \( D^0 \to (K^0 \pi^0, \bar{K}^0 \pi^0) \) interference

The decays \( D^0 \to K^0 \pi^0 \) and \( D^0 \to \bar{K}^0 \pi^0 \) are related to one another by the U-spin interchange \( s \leftrightarrow d \), and SU(3) symmetry breaking is expected to be extremely small in this relation [11]. Graphs contributing to these processes are shown in Fig. [1].

The CLEO Collaboration [12] has reported the asymmetry

\[
R(D^0) \equiv \frac{\Gamma(D^0 \to K_S \pi^0) - \Gamma(D^0 \to K_L \pi^0)}{\Gamma(D^0 \to K_S \pi^0) + \Gamma(D^0 \to K_L \pi^0)}
\]

(5)

to have the value \( R(D^0) = 0.122 \pm 0.024 \pm 0.030 \), consistent with the expected value [11, 13] : \( R(D^0) = 2 \tan^2 \theta_C \approx 0.108 \). One expects the same \( R(D^0) \) if \( \pi^0 \) is replaced by \( \eta \) or \( \eta' \) [11]. Moreover, by similar arguments, one expects \( \Delta A(D^0 \to K^0(\rho^0, f_0, \ldots)) / \Delta A(D^0 \to \bar{K}^0(\rho^0, f_0, \ldots)) = -\tan^2 \theta_C \).
Table V Branching ratios, amplitudes, and representations in terms of reduced amplitudes for doubly-Cabibbo-suppressed decays. Amplitudes denoted by (a) involve interference between the doubly-Cabibbo-suppressed process shown and the corresponding Cabibbo-favored decay to $\bar{K} + X$.

| Meson  | Decay mode | $\mathcal{B}$ | $p^*$ | |Rep. |
|--------|------------|---------------|-------|---|-----|
| $D^+$  | $K^+\pi^-$ | 1.45±0.04 | 1.54±0.02 | (a) | $\bar{T} + \bar{E}$ |
|        | $K^0\pi^0$ (a) | 861 | (a) | $\bar{C}/\sqrt{2}$ |
| $K^0\eta$ (a) | 772 | (a) | $\bar{C}/\sqrt{2}$ |
| $K^0\eta'$ (a) | 565 | (a) | $-\bar{C}/\sqrt{2}$ |
| $D^+$  | $K^+\pi^+$ | 2.28±0.39 | 1.21±0.10 | (a) | $C + \bar{A}$ |
| $K^+\pi^0$ | 864 | (a) | $(\bar{T} - \bar{A})/\sqrt{2}$ |
| $K^+\eta$ | 1.01±0.37 | 776 | 0.85±0.16 | $-\bar{T}/\sqrt{2}$ |
| $K^+\eta'$ | < 1.2 | 571 | < 1.08 | $(\bar{T} + 3\bar{A})/\sqrt{6}$ |
| $D_{s}^+$ | $K^0K^+$ (a) | 850 | (a) | $T + C$ |

\[
\langle K^-\pi^+|D^0\rangle \equiv A e^{i\delta_R}, \quad \langle K^-\pi^+|\bar{D}^0\rangle \equiv A e^{i\delta_W}. \quad (10)
\]

The difference $\delta = \delta_R - \delta_W$ of strong phases would vanish in the SU(3) limit. At $\psi(3770)$ with $K^-\pi^+$ produced opposite a state $S_C$ with CP eigenvalue $\zeta$, one would have

$$
\Gamma(K^-\pi^+, S_C) \approx A^2 S_C^2 (1 + 2\zeta r \cos \delta), \quad (11)
$$

so by choosing states with $\zeta = \pm 1$ one can measure $(1 + 2r \cos \delta)/(1 - 2r \cos \delta)$, where $r = |A/A| = 0.057 \approx \tan^2 \theta_C$.

6. Strong phases in $D^0, \bar{D}^0 \rightarrow K^-\pi^+$

The relative strong phase in the CF decay $D^0 \rightarrow K^-\pi^+$ and the DCS decay $\bar{D}^0 \rightarrow K^-\pi^+$ is of interest in studying $B$ decays involving neutral $D$ mesons, where these two processes often can interfere. It was shown in Ref. [1] that one could measure this phase by producing a CP eigenstate $D_{CP}^0$, for example by tagging on a state of opposite CP at the $\psi(3770)$. Define decay amplitudes as

$$
\langle K^-\pi^+|D^0\rangle \equiv A e^{i\delta_R}, \quad \langle K^-\pi^+|\bar{D}^0\rangle \equiv A e^{i\delta_W}. \quad (10)
$$

The difference $\delta = \delta_R - \delta_W$ of strong phases would vanish in the SU(3) limit. At $\psi(3770)$ with $K^-\pi^+$ produced opposite a state $S_C$ with CP eigenvalue $\zeta$, one would have

$$
\Gamma(K^-\pi^+, S_C) \approx A^2 S_C^2 (1 + 2\zeta r \cos \delta), \quad (11)
$$

so by choosing states with $\zeta = \pm 1$ one can measure $(1 + 2r \cos \delta)/(1 - 2r \cos \delta)$, where $r = |A/A| = 0.057 \approx \tan^2 \theta_C$.

In an analysis of 281 pb$^{-1}$ of CLEO data [5], the error on $\cos \delta$ is not yet conclusively determined, as a result of uncertainty in fits to $D^0, \bar{D}^0$ mixing. For an eventual integrated luminosity at CLEO of 750 pb$^{-1}$ and a cross section of $\sigma(e^+e^+ \rightarrow \psi(3770) \rightarrow D\bar{D}) = 6$ nb, one can estimate by rescaling the calculation in Ref. [1] an eventual error of $\Delta \cos \delta < 0.2$.

7. Other theoretical approaches

One can invoke effects of final state interactions to explain arbitrarily large SU(3) violations (if, for example, a resonance with SU(3)-violating couplings dominates a decay such as $D^0 \rightarrow \pi^+\pi^-$ or $D^0 \rightarrow K^+K^-$).

As one example of this approach [16], both resonant and nonresonant scattering can account for the observed ratio $\Gamma(D^0 \rightarrow K^+K^-)/\Gamma(D^0 \rightarrow \pi^+\pi^-) = 2.8 \pm 0.1$. This same approach predicted $B(D^0 \rightarrow K^0\bar{K}^0) = 9.8 \times 10^{-4}$, a level of SU(3) violation consistent with the world average of Ref. [9] but far in excess of the recent CLEO value [8]. The paper of Ref. [16] may be consulted for many predictions for $PV$ and $PS$ final states in charm decays, where $V$ denotes a vector meson and $S$ denotes a scalar meson. Results for $PV$ decays also may be found in Refs.
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Figure 5: Amplitudes $T$ and $C$ contributing to $D^+ \to K^- \pi^+$; amplitudes $\tilde{C}$ and $\hat{A}$ contributing to $D^+ \to K^0 \pi^+$.

The recent discussion of Ref. [19] entails a prediction $A \simeq -0.4E$ (recall we were finding $A \simeq -E$), essentially as a consequence of a Fierz identity and QCD corrections. Tree amplitudes are obtained from factorization and semileptonic $D \to \pi$ and $D \to K$ form factors. The main source of SU(3) breaking in $|T|$ is assumed to come from $f_K/f_\pi = 1.22$. Predictions include asymmetries $R(D^0,\mp) = (2 \tan^2 \theta_C, 0.068 \pm 0.007)$, and - via a sum rule for $D^0 \to K^\mp \pi^\pm$ and $D^+ \to K^+ \pi^0$ - and expectation of $|\delta| \simeq 7-20^\circ$ (to be compared with 0 in exact SU(3) symmetry).

8. Summary

We have shown that the relative magnitudes and phases of amplitudes contributing to charm decays into two pseudoscalar mesons are describable by flavor symmetry. We have verified that there are large relative phases between the color-favored tree amplitude $T$ and the color-suppressed amplitude $C$, as well as between $T$ and $E \simeq -A$.

The largest symmetry-breaking effects are visible in singly-Cabibbo-suppressed (SCS) decays, particularly in the $D^0 \to (\pi^+\pi^-/K^+K^-)$ ratio which are at least in part understandable through form factor and decay constant effects. Decays involving $\eta, \eta'$ are mostly describable with small “disconnected” amplitudes, a possible exception being in SCS $D^+$ and $D^+_s$ decays.

One sees evidence for the expected interference between Cabibbo-favored (CF) and doubly-Cabibbo-suppressed decays in $D^{0,+,\mp} \to K_{S,L}\pi^{0,+,\mp}$ decays. As a result of CLEO’s present data on $(D^0, \overline{D}^0) \to K^- \pi^+$, limits are being placed on the relative strong phase $\delta$ between these amplitudes, and the full CLEO data sample is expected to result in an error equal to or better than $\Delta\cos \delta = 0.2$.

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