REVIEW OF D-MESON DALITZ PLOT ANALYSES

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This review will be revised for 2014 after recent papers on the subject have been added to the Particle Listings.

Weak nonleptonic decays of D and B mesons are expected to proceed dominantly through resonant two-body decays [1]; see Ref. 2 and Ref. 3 for a review of resonance phenomenology. The amplitudes are typically calculated with the Dalitz-plot analysis technique [4], which uses the minimum number of independent observable quantities. For three-body decays of a spin-0 particle to all pseudo-scalar final states, such as D or $B \to abc$, the decay rate [5] is

$$\Gamma = \frac{1}{(2\pi)^3 32\sqrt{s^3}} \left|\mathcal{M}\right|^2 dm_{ab}^2 \, dm_{bc}^2 \,, \qquad (1)$$

where m_{ij} is the invariant mass of particles i and j. Here the prefactor contains all kinematic factors, while $\left|\mathcal{M}\right|^2$ contains the dynamics. The scatter plot in m_{ab}^2 versus m_{bc}^2 is the Dalitz plot. If $\left|\mathcal{M}\right|^2$ is constant, the kinematically allowed region of the plot will be populated uniformly with events. Any variation in the population over the Dalitz plot is due to dynamic rather than kinematic effects.

Recent studies of multi-body decays of charm mesons probe a variety of physics, including γ/ϕ_3, D^0–$\overline{D}^0$ mixing, searches for CP violation, doubly Cabibbo-suppressed decays, and properties of S-wave $\pi\pi$, $K\pi$, and $K\bar{K}$ resonances. In the following, we discuss: (1) $D^0 \to K_S^0\pi^+\pi^-$; (2) doubly Cabibbo-suppressed decays; and (3) CP violation. The properties of the light meson resonances determined in D-meson Dalitz-plot analyses are reported in the light unflavored meson section of this *Review*.

$\boldsymbol{D^0 \to K_S^0\pi^+\pi^-}$: Several experiments have analyzed $D^0 \to K_S^0\pi^+\pi^-$ decay. A CLEO analysis [6] included ten resonances: $K_S^0\rho^0$, $K_S^0\omega$, $K_S^0 f_0(980)$, $K_S^0 f_2(1270)$, $K_S^0 f_0(1370)$, $K^*(892)^-\pi^+$, $K_0^*(1430)^-\pi^+$, $K_2^*(1430)^-\pi^+$, $K^*(1680)^-\pi^+$, and the doubly Cabibbo-suppressed (DCS) mode $K^*(892)^+\pi^-$.

The CLEO model does not provide a good description of higher-statistics BABAR and Belle data samples. An improved description is obtained in three ways: First, by adding more Breit-Wigner resonances. Second, following the methodology of FOCUS [7], by applying a K-matrix model [8–10] to the $\pi\pi$ S-wave [11,12]. Third, by adding a parameterization to the $K\pi$ S-wave motivated by the LASS experiment [13].

A BABAR analysis [12,14,15] added to the CLEO model the $K^*(1410)^-\pi^+$, $K^0_S\rho^0(1450)$, the DCS modes $K^*_0(1430)^+\pi^-$ and $K^*_2(1430)^+\pi^-$, and two Breit-Wigner $\pi\pi$ S-wave contributions. A Belle analysis [16–18] included all the components of BABAR and added two more DCS modes, $K^*(1410)^+\pi^-$ and $K^*(1680)^+\pi^-$. Recently, BABAR has modeled the $\pi\pi$ S-wave using a K-matrix model for the $\pi\pi$ and $K\pi$ S-waves [19].

The primary motivation for the analysis of the decay $D^0 \to K^0_S\pi^+\pi^-$ is to study $D^0 - \overline{D}^0$ oscillations and the CKM angles. The quasi-two-body intermediate states include both CP-even and CP-odd eigenstates as well as doubly Cabibbo-suppressed channels. Time-dependent analyses of the Dalitz plot from CLEO [20] and Belle [11] simultaneously determined the strong transition amplitudes and phases, the mixing parameters x and y without phase or sign ambiguity, and the CP-violating parameter $|q/p|$ and $\mathrm{Arg}(q/p)$. See the note on "$D^0 - \overline{D}^0$ Mixing" for a discussion.

The CKM angle γ/ϕ_3 [21] and the quark-mixing parameter $\cos 2\beta/\phi_1$ [22] can be determined using the decays $B^- \to D^{(*)}K^{(*)-}$ and $\overline{B}^0 \to Dh^0$, respectively, followed by the decay $D \to K^0_S\pi^+\pi^-$. The Belle and BABAR experiments measured γ/ϕ_3 (Belle [16–18] and BABAR [12,14,15,19,23] and $\cos 2\beta/\phi_1$ (Belle [24], BABAR [25]) . In these analyses, a large systematic uncertainty in the relative phase between the D^0 and $\overline{D}^0$ amplitudes point by point across the Dalitz plot remains to be fully understood.

The quantum entangled production of $D^0\overline{D}^0$ pairs from $\psi(3770)$ enables a model-independent determination of the $D^0/\overline{D}^0$ relative phase. Studying CP-tagged Dalitz plots [26,27] provides sensivity to the cosine of the relative phase, while studying double-tagged Dalitz plots [27] probes both the cosine and sine of the $D^0/\overline{D}^0$ phase difference. CLEO analyzed [28] the $D^0 \to K^0_S\pi^+\pi^-$ and $D^0 \to K^0_L\pi^+\pi^-$ samples using the CP-even tag modes K^+K^-, $\pi^+\pi^-$, $K^0_L\pi^0$ (vs. $K^0_S\pi^+\pi^-$ only), the CP-odd tag modes $K^0_S\pi^0$, $K^0_S\eta$, and the double-tag modes $(K^0_S\pi^+\pi^-)^2$ and $(K^0_S\pi^+\pi^-)(K^0_L\pi^+\pi^-)$. These measurements can reduce the model uncertainty on γ/ϕ_3 to about 3°.

Doubly Cabibbo-Suppressed Decays: There are two classes of multibody doubly Cabibbo-suppressed (DCS) decays of D mesons. The first consists of those in which the DCS and corresponding Cabbibo-favored (CF) decays populate distinct Dalitz plots; the pairs $D^0 \to K^+\pi^-\pi^0$ and $D^0 \to K^-\pi^+\pi^0$, or $D^+ \to K^+\pi^+\pi^-$ and $D^+ \to K^-\pi^+\pi^+$, are examples. Our average of three measurements of $\Gamma(D^0 \to K^+\pi^-\pi^0)/\Gamma(D^0 \to K^-\pi^+\pi^0)$ is $(2.20 \pm 0.10) \times 10^{-3}$. Our average of four measurements of $\Gamma(D^+ \to K^+\pi^-\pi^+)/\Gamma(D^+ \to K^-\pi^+\pi^+)$ is $(5.77 \pm 0.22) \times 10^{-3}$; see the Particle Listings.

The second class consists of decays in which the DCS and CF modes populate the same Dalitz plot; for example, $D^0 \to K^{*-}\pi^+$ and $D^0 \to K^{*+}\pi^-$ both contribute to $D^0 \to K^0_S\pi^+\pi^-$. In this class, the potential for interference of DCS and CF amplitudes increases the sensitivity to the DCS amplitude and allows direct measurement of the relative strong phases between amplitudes. CLEO [6] and Belle [11] have measured the relative phase between $D^0 \to K^*(892)^+\pi^-$ and $D^0 \to K^*(892)^-\pi^+$ to be $(189 \pm 10 \pm 3^{+15}_{-5})^\circ$ and $(171.9 \pm 1.3)^\circ$ (statistical error only). These results are close to the 180° expected from Cabibbo factors and a small strong phase.

In addition, Belle [11] has results for both the relative phase (statistical errors only) and ratio R (central values only) of the DCS fit fraction relative to the CF fit fractions for $K^*(892)^+\pi^-$, $K^*_0(1430)^+\pi^-$, $K^*_2(1430)^+\pi^-$, $K^*(1410)^+\pi^-$, and $K^*(1680)^+\pi^-$. The systematic uncertainties on R must be evaluated. The values for R in units of $\tan^4\theta_c$ are 2.94 ± 0.12, 22.0 ± 1.6, 34 ± 4, 87 ± 13, and 500 ± 500. For $K^+\pi^-$, the corresponding value for R_D is $(1.28 \pm 0.02) \times \tan^4\theta_c$. Similarly, BABAR [12] has reported central values for R for $K^*(892)^+\pi^-$, $K^*_0(1430)^+\pi^-$, and $K^*_2(1430)^+\pi^-$. The values for R in units of

$\tan^4\theta_c$ are 3.45 ± 0.31, 7.7 ± 3.0, and 1.7 ± 1.7, respectively. Recently, BABAR [19] has used a K-matrix formalism to describe the $\pi\pi$ S-wave in $K^0_S\pi^+\pi^-$. The reported values for R in units of $\tan^4\theta_c$ are 2.78 ± 0.11, 0.5 ± 0.2, and 1.4 ± 0.5, respectively. The large differences in R among these final states could point to an interesting role for hadronic effects.

There are other ways, not involving DCS decays, in which D^0 and $\overline{D}^0$ singly Cabibbo-suppressed decays can populate the same Dalitz plot. Examples are D^0 and $\overline{D}^0$ decays to $K^0_S K^+\pi^-$, or to $K^0_S K^-\pi^+$. These final states can be used to study D^0–$\overline{D}^0$ mixing and the CKM angle γ/ϕ_3.

***CP* Violation**: In the limit of CP conservation, charge conjugate decays will have the same Dalitz-plot distribution. The $D^{*\pm}$ tag enables the discrimination between D^0 and $\overline{D}^0$. The integrated CP violation across the Dalitz plot is determined in two ways. The first uses

$$\mathcal{A}_{CP} = \int \left(\frac{|\mathcal{M}|^2 - |\overline{\mathcal{M}}|^2}{|\mathcal{M}|^2 + |\overline{\mathcal{M}}|^2} \right) dm^2_{ab}\, dm^2_{bc} \Big/ \int dm^2_{ab}\, dm^2_{bc} \,, \quad (2)$$

where $\mathcal{M}$ and $\overline{\mathcal{M}}$ have the same normalization and represent the D^0 and $\overline{D}^0$ Dalitz-plot amplitudes for the three-body decay $D \to abc$, and m_{ab} (m_{bc}) is the invariant mass of ab (bc). The second uses the asymmetry in the efficiency-corrected D^0 and $\overline{D}^0$ yields,

$$\mathcal{A}_{CP} = \frac{N_{D^0} - N_{\overline{D}^0}}{N_{D^0} + N_{\overline{D}^0}} \,. \quad (3)$$

These expressions are less sensitive to CP violation than are the individual resonant submodes [29–31]. Our Particle Listings give limits on CP violation for 12 D^+, 52 D^0, and 13 D^+_S decay modes. No evidence of CP violation has been observed in D-meson decays.

The possibility of interference between CP–conserving and CP–violating amplitudes provides a more sensitive probe of CP violation. The constraints on the square of the CP–violating amplitudes obtained in the resonant submodes of $D^0 \to K^0_S\pi^+\pi^-$ range from 3.5×10^{-4} to 28.4×10^{-4} at 95% confidence level [29]. A similar analysis has been performed by CLEO [30] searching for CP violation in $D^+ \to K^+K^-\pi^+$. The constraints on the square of the CP–violating amplitudes in the resonant submodes range from 4×10^{-4} to 51×10^{-4} at 95%. BABAR finds no evidence for CP–violating amplitudes in the resonant submodes of $D^0 \to K^+K^-\pi^0$ and $D^0 \to \pi^+\pi^-\pi^0$ [31].

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