REVIEW OF D-MESON DALITZ PLOT ANALYSES

Revised April 2010 by D. Asner (Pacific Northwest National Laboratory)

The formalism of Dalitz-plot analysis is reviewed in the preceding note. 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) $D^0 \to K^0_S\pi^+\pi^-$; (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*.

$\boldsymbol{D^0 \to K^0_S\pi^+\pi^-}$: Several experiments have analyzed $D^0 \to K^0_S\pi^+\pi^-$ decay. A CLEO analysis [1] included ten resonances: $K^0_S\rho^0$, $K^0_S\omega$, $K^0_S f_0(980)$, $K^0_S f_2(1270)$, $K^0_S f_0(1370)$, $K^*(892)^-\pi^+$, $K^*_0(1430)^-\pi^+$, $K^*_2(1430)^-\pi^+$, $K^*(1680)^-\pi^+$, 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 [2], by applying a K-matrix model [3–5] to the $\pi\pi$ S-wave [6,7]. Third, by adding a parameterization to the $K\pi$ S-wave motivated by the LASS experiment [8].

A BABAR analysis [7,9,10] 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 [11–13] 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 [14].

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 [15] and Belle [6] 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 Arg(q/p). See the note on "$D^0 - \overline{D}^0$ Mixing" for a discussion.

The CKM angle γ/ϕ_3 [16] and the quark-mixing parameter $\cos 2\beta/\phi_1$ [17] 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 [11–13] and BABAR [7,9,10,14,18] and $\cos 2\beta/\phi_1$ (Belle [19], BABAR [20]) . 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 [21,22] provides sensivity to the cosine of the relative phase, while studying double-tagged Dalitz plots [22] probes both the cosine and sine of the $D^0/\overline{D}^0$ phase difference. CLEO analyzed [23] 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 [1] and Belle [6] 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 [6] 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 [7] 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 [14] has used a K-matrix formalism to describe the $\pi\pi$ S-wave in $K_S^0\pi^+\pi^-$. 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 $K_S^0K^+\pi^-$, or to $K_S^0K^-\pi^+$. 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

$$\mathcal{A}_{CP} = \int \left(\frac{|\mathcal{M}|^2 - |\overline{\mathcal{M}}|^2}{|\mathcal{M}|^2 + |\overline{\mathcal{M}}|^2} \right) dm_{ab}^2 \, dm_{bc}^2 \Bigg/ \int dm_{ab}^2 \, dm_{bc}^2 \,, \quad (1)$$

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,

$$\mathcal{A}_{CP} = \frac{N_{D^0} - N_{\overline{D}^0}}{N_{D^0} + N_{\overline{D}^0}}\,. \qquad (2)$$

These expressions are less sensitive to CP violation than are the individual resonant submodes [24–26]. 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 $D^0 \to K_S^0\pi^+\pi^-$ range from 3.5×10^{-4} to 28.4×10^{-4} at 95% confidence level [24]. A similar analysis has been performed by CLEO [25] 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 $D^0 \to \pi^+\pi^-\pi^0$ [26].

References

1. H. Muramatsu *et al.* (CLEO Collab.), Phys. Rev. Lett. **89**, 251802 (2002).
2. J.M. Link *et al.* (FOCUS Collab.), Phys. Lett. **B585**, 200 (2004).
3. E. P. Wigner, Phys. Rev. **70**, 15 (1946).
4. S. U. Chung *et al.*, Annalen Phys. **4**, 404 (1995).
5. I. J. R. Aitchison, Nucl. Phys. **A189**, 417 (1972).
6. L.M. Zhang *et al.* (Belle Collab.), Phys. Rev. Lett. **99**, 131803 (2007).
7. B. Aubert *et al.* (BABAR Collab.), Phys. Rev. Lett. **95**, 121802 (2005).
8. D. Aston *et al.* (LASS Collab.), Nucl. Phys. **B296**, 493 (1988).
9. B. Aubert *et al.* (BABAR Collab.), `hep-ex/0507101`.
10. B. Aubert *et al.* (BABAR Collab.), `arXiv:hep-ex/0607104`.

11. A. Poluektov *et al.* (Belle Collab.), Phys. Rev. **D70**, 072003 (2004).
12. K. Abe *et al.* (Belle Collab.), `hep-ex/0411049`.
13. A. Poluektov *et al.* (Belle Collab.), Phys. Rev. **D73**, 112009 (2006).
14. B. Aubert *et al.* (BABAR Collab.), Phys. Rev. **D78**, 034023 (2008).
15. D.M. Asner *et al.* (CLEO Collab.), Phys. Rev. **D72**, 012001 (2005).
16. A. Giri *et al.*, Phys. Rev. **D68**, 054018 (2003).
17. A. Bondar, T. Gershon, and P. Krokovny, Phys. Lett. **B624**, 1 (2005).
18. B. Aubert *et al.*(BABAR Collab.), Phys. Rev. **D79**, 072003 (2009).
19. P. Krokovny *et al.* (Belle Collab.), Phys. Rev. Lett. **97**, 081801 (2006).
20. B. Aubert *et al.* (BABAR Collab.), `arXiv:hep-ex/0607105`.
21. A. Bondar and A. Poluektov, Eur. Phys. J. **C47**, 347 (2006).
22. A. Bondar and A. Poluektov, `arXiv:hep-ph/0703267`.
23. R. A. Briere *et al.*(CLEO Collab.), Phys. Rev. **D80**, 032002 (2009).
24. D.M. Asner *et al.* (CLEO Collab.), Phys. Rev. **D70**, 091101R (2004).
25. P. Rubin *et al.* (CLEO Collab.), Phys. Rev. **D78**, 072003 (2008).
26. B. Aubert *et al.* (BABAR Collab.), Phys. Rev. **D78**, 051102 (2008).