Review of Charm Meson Hadronic Decays and Lifetimes

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Recent progress in the experimental study of charm meson hadronic decays and lifetimes is reviewed. New high-precision branching fractions and amplitude analyses improve noticeably upon previous world averages.

1. INTRODUCTION

In addition to being probes of final state interactions and SU(3) symmetry breaking, hadronic decays of $D_{(s)}$ mesons are widely used in the study of $B_{(s)}$ mesons. As a result, improved measurements of $D_{(s)}$ branching fractions and strong phases leads directly to the reduction of systematic uncertainties in $B_{(s)}$ analyses, thus allowing tighter constraints on the CKM matrix to be made. The recent results reviewed in this article come both from incoherently produced charm (at the B factories, the Tevatron, and fixed target experiments) and from coherent $D\bar{D}$ pairs (produced by charm factories running near threshold).

2. CABIBBO-FAVORED BRANCHING FRACTIONS

Using a double tagging technique pioneered by MARK III [1,2], CLEO-c measures [3] several charge-averaged branching fractions listed in Table 1. Included in these measurements are the reference modes $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$. Essentially all other D^0 and D^+ branching fractions have been determined from ratios to one of these two branching fractions. For D_s^+, the reference mode $D_s^+ \to \phi\pi^+$ is one component of $D_s^+ \to K^+K^-\pi^+$, which also contains an overlapping contribution from $D_s^+ \to f_0(980)\pi^+$. Previous experiments neglected this subtlety, but it becomes important with the current precision. A Dalitz analysis is needed to disentangle the various contributions to $D_s^+ \to K^+K^-\pi^+$.

BES and CLEO-c also measure inclusive D^0, D^+, and D_s^+ branching fractions using pair-produced meson pairs, with one of the two mesons fully reconstructed. Then, they search for charged and neutral $K^{(*)}$ (BES) or η, η', and ϕ (CLEO-c) in the remainder of the event to obtain the results shown in Tables 2 and 3. Previous measurements [4] exist only for $\mathcal{B}(D^0 \to \overset{(-)}{K}{}^0 X)$ $[(42 \pm 5)\%]$ and $\mathcal{B}(D^+ \to \overset{(-)}{K}{}^0 X)$ $[(59 \pm 7)\%]$.

The $D \to K_S^0 K_S^0 K^+\pi^-$ final state is observed by FOCUS [6] to have a charge-averaged branching fraction of $(6.1 \pm 1.1 \pm 0.7) \times 10^{-4}$. They also detect both Cabibbo-favored modes, $D^0 \to$

Table 1
Absolute branching fraction measurements from CLEO-c, compared to the 2004 PDG [4] fit results, which do not include the CLEO-c measurements. Uncertainties are statistical and systematic, respectively. The D_s^+ measurements are preliminary.

Mode	$\mathcal{B}$ (%)	PDG $\mathcal{B}$ (%)
$D^0 \to$		
$K^-\pi^+$	$3.91 \pm 0.08 \pm 0.09$	3.80 ± 0.09
$K^-\pi^+\pi^0$	$14.9 \pm 0.3 \pm 0.5$	13.0 ± 0.8
$K^-\pi^+\pi^+\pi^-$	$8.3 \pm 0.2 \pm 0.3$	7.46 ± 0.31
$D^+ \to$		
$K^-\pi^+\pi^+$	$9.5 \pm 0.2 \pm 0.3$	9.2 ± 0.6
$K^-\pi^+\pi^+\pi^0$	$6.0 \pm 0.2 \pm 0.2$	6.5 ± 1.1
$K_S^0\pi^+$	$1.55 \pm 0.05 \pm 0.06$	1.41 ± 0.10
$K_S^0\pi^+\pi^0$	$7.2 \pm 0.2 \pm 0.4$	4.9 ± 1.5
$K_S^0\pi^+\pi^+\pi^-$	$3.2 \pm 0.1 \pm 0.2$	3.6 ± 0.5
$K^+K^-\pi^+$	$0.97 \pm 0.04 \pm 0.04$	0.89 ± 0.08
$D_s^+ \to$		
$K_S^0K^+$	$1.28^{+0.13}_{-0.12} \pm 0.07$	1.80 ± 0.55
$K^+K^-\pi^+$	$4.54^{+0.44}_{-0.42} \pm 0.25$	4.3 ± 1.2
$K^+K^-\pi^+\pi^0$	$4.83^{+0.49}_{-0.47} \pm 0.46$	—
$\pi^+\pi^-\pi^+$	$1.02^{+0.11}_{-0.10} \pm 0.05$	1.00 ± 0.28

Table 2
Inclusive D^0 and D^+ branching fractions to kaons, measured by BES. Except for the K^{*0} and $\bar{K}^{*0}$ measurements [5], these results are preliminary. Uncertainties are statistical and systematic, respectively. Upper limits are given at the 90% C.L.

Mode	$\mathcal{B}$ (%)
$D^0 \to \bar{K}^{*0} X$	$8.7 \pm 4.0 \pm 1.2$
$D^+ \to \bar{K}^{*0} X$	$23.2 \pm 4.5 \pm 3.0$
$D^0 \to K^{*0} X$	$2.8 \pm 1.2 \pm 0.4$
$D^+ \to K^{*0} X$	< 6.6
$D^0 \to K^{*-} X$	$15.3 \pm 8.3 \pm 1.9$
$D^+ \to K^{*-} X$	$5.7 \pm 5.2 \pm 0.1$
$D^0 \to K^{*+} X$	< 3.6
$D^+ \to K^{*+} X$	< 20.3
$D^0 \to \overset{(-)}{K}{}^0 X$	$47.6 \pm 4.8 \pm 3.0$
$D^+ \to \overset{(-)}{K}{}^0 X$	$62.5 \pm 5.6 \pm 3.4$

$\bar{K}^0\bar{K}^0K^+\pi^-$ and $D^0 \to \bar{K}^0K^0K^-\pi^+$, which are distinguished with a D^{*+} tag. No evidence of substructure is found.

3. SINGLY-CABIBBO-SUPPRESSED BRANCHING FRACTIONS

Cabibbo-suppressed branching fractions are usually measured with respect to reference branching fractions, even at the charm factories, where limited statistics reduces the utility of the double tagging technique. Recent measurements of pionic and kaonic decay modes of D^0 and D^+ are summarized in Tables 4 and 5.

For the three $D \to \pi\pi$ modes, CLEO-c [7] also finds the ratio of the $\Delta I = 3/2$ to $\Delta I = 1/2$ isospin amplitudes to be $A_2/A_0 = 0.420 \pm 0.014(\text{stat.}) \pm 0.010(\text{syst.})$ and the relative strong phase to be $\delta_I = (86.4 \pm 2.8 \pm 3.3)^\circ$, which indicates a substantial contribution from final state interactions. There is no corresponding SU(3) triangle for $D \to K\bar{K}$, as $D^0 \to K^0\bar{K}^0$ vanishes in the SU(3) limit; this mode only receives contributions from SU(3) breaking effects.

Table 3
Preliminary inclusive D^0, D^+, and D_s^+ branching fractions to η, η', and ϕ, measured by CLEO-c. Uncertainties are statistical and systematic, respectively.

Mode	$\mathcal{B}$ (%)
$D^0 \to \eta X$	$9.4 \pm 0.4 \pm 0.6$
$D^0 \to \eta' X$	$2.6 \pm 0.2 \pm 0.2$
$D^0 \to \phi X$	$1.0 \pm 0.1 \pm 0.1$
$D^+ \to \eta X$	$5.7 \pm 0.5 \pm 0.5$
$D^+ \to \eta' X$	$1.0 \pm 0.2 \pm 0.1$
$D^+ \to \phi X$	$1.1 \pm 0.1 \pm 0.2$
$D_s^+ \to \eta X$	$32.0 \pm 5.6 \pm 4.7$
$D_s^+ \to \eta' X$	$11.9 \pm 3.3 \pm 1.2$
$D_s^+ \to \phi X$	$15.1 \pm 2.1 \pm 1.5$

4. DOUBLY-CABIBBO-SUPPRESSED BRANCHING FRACTIONS

For D^0, doubly-Cabibbo-suppressed (DCS) final states are conjugate to Cabibbo-favored (CF) final states. As a result, the DCS transition amplitude may interfere with the mixing amplitude (followed by a CF transition), thus altering the apparent "wrong-sign" rate. For the results shown in Table 6, DCS decays are isolated from CF decays by reconstructing $D^{*+} \to D^0\pi^+$, in which the charge of the slow pion tags the flavor of the D meson. These results assume no mixing or CP violation.

The DCS decay $D^+ \to K^+\pi^0$ has no CF counterpart and was recently observed by BABAR [10] and confirmed by CLEO-c [16] with branching fractions of $(2.52 \pm 0.47 \pm 0.26) \times 10^{-4}$ and $(2.28 \pm 0.36 \pm 0.17) \times 10^{-4}$, respectively.

5. AMPLITUDE ANALYSES

In a typical Dalitz plot analysis, the resonant contributions are modeled as sums of interfering Breit-Wigner amplitudes. CLEO has studied the low-mass $\pi^+\pi^-$ S-wave resonance (known as the σ) in two different three-body final states, $D^0 \to \pi^+\pi^-\pi^0$ (CLEO II.V [17]) and $D^+ \to \pi^+\pi^-\pi^+$ (CLEO-c, preliminary). In the former analysis, the σ was modeled both by a Breit-Wigner and with the K-matrix formalism, and

Table 4
Recent measurements of Cabibbo-suppressed D^0 and D^+ branching fractions to pionic final states, compared to the 2004 PDG [4] fit results, which do not include the new measurements. Uncertainties are statistical and systematic, respectively.

Mode	$\mathcal{B}$ (10^{-3})	PDG
$\pi^+\pi^-$	$1.39 \pm 0.04 \pm 0.05$ [7]	1.38 ± 0.05
	$1.31 \pm 0.27 \pm 0.04$ [8]	
$\pi^0\pi^0$	$0.79 \pm 0.05 \pm 0.06$ [7]	0.84 ± 0.22
$\pi^+\pi^-\pi^0$	$13.2 \pm 0.2 \pm 0.5$ [7]	11 ± 4
	$14.93 \pm 0.08 \pm 0.56$ [9]	
$\pi^0\pi^0\pi^0$	< 0.35 (90% C.L.) [7]	
$2(\pi^+\pi^-)$	$7.3 \pm 0.1 \pm 0.3$ [7]	7.3 ± 0.5
	$6.4 \pm 1.5 \pm 0.4$ [8]	
$\pi^+\pi^-\pi^0\pi^0$	$9.9 \pm 0.6 \pm 0.7$ [7]	
$2(\pi^+\pi^-)\pi^0$	$4.1 \pm 0.5 \pm 0.2$ [7]	
$\omega\pi^+\pi^-$	$1.7 \pm 0.5 \pm 0.2$ [7]	
$\eta\pi^0$	$0.62 \pm 0.14 \pm 0.05$ [7]	
$\omega\pi^0$	< 0.26 (90% C.L.) [7]	
$\eta\pi^+\pi^-$	< 1.9 (90% C.L.) [7]	
$\pi^+\pi^0$	$1.25 \pm 0.06 \pm 0.08$ [7]	1.33 ± 0.22
	$1.25 \pm 0.10 \pm 0.10$ [10]	
$\pi^+\pi^+\pi^-$	$3.35 \pm 0.10 \pm 0.20$ [7]	3.1 ± 0.4
	$3.9 \pm 1.0 \pm 0.3$ [8]	
$\pi^+\pi^0\pi^0$	$4.8 \pm 0.3 \pm 0.4$ [7]	
$\pi^+\pi^+\pi^-\pi^0$	$11.6 \pm 0.4 \pm 0.7$ [7]	
$2(\pi^+\pi^-)\pi^+$	$1.60 \pm 0.18 \pm 0.17$ [7]	1.73 ± 0.23
$\eta\pi^+$	$3.61 \pm 0.25 \pm 0.26$ [7]	3.0 ± 0.6
$\omega\pi^+$	< 0.34 (90% C.L.) [7]	

Table 5
Recent measurements of Cabibbo-suppressed D^0 and D^+ branching fractions to kaonic final states, compared to the 2004 PDG [4] fit results, which do not include the new measurements. Uncertainties are statistical and systematic, respectively.

Mode	$\mathcal{B}$ (10^{-3})	PDG
K^+K^-	$4.68 \pm 0.42 \pm 0.18$ [8]	3.90 ± 0.12
$K^0\bar{K}^0$	$0.84 \pm 0.19 \pm 0.11$ [6]	0.74 ± 0.14
$K^+K^-\pi^0$	$3.34 \pm 0.04 \pm 0.13$ [9]	
$K^+K^-\pi^+\pi^-$	$2.39 \pm 0.09 \pm 0.09$ [22]	2.49 ± 0.23
	$3.6 \pm 1.5 \pm 0.4$ [8]	
$K^0_SK^0_S\pi^+\pi^-$	$1.2 \pm 0.2 \pm 0.2$ [6]	1.27 ± 0.24
$K^+\bar{K}^0$	$6.64 \pm 1.11 \pm 0.41$ [8]	5.7 ± 0.5
$K^+K^-\pi^+$	$11.0 \pm 1.2 \pm 0.7$ [8]	8.9 ± 0.8
	$9.7 \pm 0.4 \pm 0.4$ [3]	

Table 6
Recent measurements of DCS-to-CF rate ratios ($\mathcal{R}$) in D^0 decays, assuming no mixing or CP violation, compared to the 2004 PDG [4] fit results, which do not include the new measurements. Uncertainties are statistical and systematic, respectively.

Mode	$\mathcal{R}$ (10^{-3})	PDG
$K^+\pi^-$	$3.77 \pm 0.08 \pm 0.05$ [11]	3.62 ± 0.29
	$4.29^{+0.63}_{-0.61} \pm 0.27$ [12]	
	$4.05 \pm 0.21 \pm 0.11$ [13]	
$K^+\pi^-\pi^0$	$2.29 \pm 0.15^{+0.13}_{-0.09}$ [14]	$4.3^{+1.1}_{-1.0} \pm 0.7$
	$2.14 \pm 0.08 \pm 0.08$ [15]	
$K^+\pi^-\pi^+\pi^-$	$3.20 \pm 0.18^{+0.18}_{-0.13}$ [14]	4.2 ± 1.3

no evidence for it was found. However, the latter analysis observes a significant S-wave contribution, parametrized by a complex pole of the form $1/[(0.47 - 0.22i)\ \mathrm{GeV}^2 - m^2(\pi^+\pi^-)]$, with a fit fraction of $(41.8 \pm 1.4 \pm 2.5)\%$, which is consistent with that found previously by E791 [18] and FOCUS [19].

CLEO also analyzes the $D^0 \to K^+K^-\pi^0$ Dalitz plot to extract the relative amplitude and phase of the K^{*-} and K^{*+} contributions. These measurements are needed to reduce the systematic uncertainty in one method of determining the CKM parameter γ/ϕ_3 at the B factories [20]. CLEO finds [21] the amplitude ratio $A(D^0 \to K^{*-}K^+)/A(D^0 \to K^{*+}K^-)$ to have a magnitude of $0.52 \pm 0.05 \pm 0.04$ and a phase of $(332 \pm 8 \pm 11)^\circ$, which corresponds to nearly maximal destructive interference between the two amplitudes.

A related D^0 final state, $K^+K^-\pi^+\pi^-$, was studied by FOCUS [22], who determine that the decay amplitude is dominated by axial-vector-pseudoscalar and vector-vector transitions. The contributions with the largest fit fractions are $K_1(1270)^+K^-$ (33%), $K_1(1400)^+K^-$ (22%), and $\rho^0\phi$ (29%).

An asymmetry between $\mathcal{B}(D^+ \to K^0_S\pi^+)$ and $\mathcal{B}(D^+ \to K^0_L\pi^+)$ can arise from interference among competing amplitudes [23]. CLEO detects the neutral kaon inclusively by fully reconstructing the D^- as well as the π^+ daughter of the D^+ and computing the missing mass of the event, which peaks at the neutral kaon mass for both $K_S^0\pi^+$ and $K_L^0\pi^+$ signal decays. The dominant background comes from $D^+ \to \eta\pi^+$, which partially overlaps with $K^0\pi^+$ in missing mass. Using $\mathcal{B}(K_S^0\pi^+)$ from Table 1, the preliminary asymmetry measured by CLEO is $[\mathcal{B}(K_L^0\pi^+) - \mathcal{B}(K_S^0\pi^+)]/[\mathcal{B}(K_L^0\pi^+) + \mathcal{B}(K_S^0\pi^+)] = -0.01 \pm 0.04 \pm 0.07$, which is consistent with the prediction of $\mathcal{O}(10\%)$ [23].

6. D_s^+ LIFETIME

Charm hadronic lifetimes are useful for converting branching fractions into partial widths, with which one can extract CKM matrix elements and test isospin invariance. FOCUS measures [24] the D_s^+ lifetime to be $(507.4 \pm 5.5 \pm 5.1)$ fs, which has higher precision than the previous world average. In addition, they find the ratio of lifetimes $\tau(D_s^+)/\tau(D^0)$, which probes the weak annihilation contribution to the decay amplitudes, to be 1.239 ± 0.017.

7. SUMMARY AND OUTLOOK

Much recent activity in the study of hadronic charm decays has led to new high-precision branching fraction measurements and the observation of complex resonant substructure and interesting interference effects in multi-body final states. In the future, charm physics will continue to be a rich area of exploration, as more data is collected at the B factories, at hadron colliders, and at the charm factories. In addition, the next few years should see the emergence of BES III, LHCb, and PANDA, which will enhance the available charm sample even further. Thus, improvements on all fronts can be expected.

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