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Rare, Leptonic, and Hadronic Decays of Charmed Mesons - A Review -

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Abstract

We review the physics of rare, leptonic, and hadronic decays of charmed mesons based on the results submitted to this conference (EPS 95, Brussels).

1 Rare and leptonic decays

1.1 $D_S^+ \to \mu^+\nu$

The decay $D_S^+ \to l^+\nu$ (l is e, μ, or τ) occurs through annihilation of constituent quarks and the rate is given by

$$\Gamma = |V_{cs}|^2 \frac{G_F^2 M_{D_S} f_{D_S}^2}{8\pi} m_l^2 \left(1 - \frac{m_l^2}{M_{D_S}^2}\right)^2;$$

thus, it is sensitive to the D_S decay constant f_{D_S} which in turn is related to the overlap of c and $\bar{s}$ quarks in the meson $\Psi(0)$ (in non-relativistic quark model) by[1]

$$f_{D_S} = \sqrt{\frac{12}{M_{D_S}}}|\Psi(0)|. \qquad (1)$$

This mode was first observed by WA75[2] using emulsion exposed to π^- beam from CERN SPS, followed by CLEO[3] and BES[4]. For this conference, CLEO has updated the measurement with higher statistics. CLEO observes this decay mode in the decay chain $D_S^{*+} \to D_S^+\gamma$, $D_S^+ \to \mu^+\nu$. The hermiticity of the detector was used to obtain the missing momentum in the hemisphere of the decay, which was then interpreted as the momentum of the neutrino. A clear peak in the mass difference $M_{D_S^*} - M_{D_S}$ is seen and the new result is shown in Table 1 together with previous results. The average of WA75, BES, and CLEO(95) gives (using both statistical and systematic errors)

$$f_{D_S}(\text{MeV}) = (273 \pm 30)\sqrt{\frac{B(D_S \to \phi\pi)}{3.5\%}}. \qquad (2)$$

The parameter f_{D_S} can also be obtained by comparing $B \to D_S^{(*)} D^*$ to semileptonic decay $B \to D^* l\nu$ assuming factorization. The new result from CLEO is (assuming $f_{D_S} = f_{D_S^*}$)[6]

$$f_{D_S^{(*)}}(\text{MeV}) = (281 \pm 39)\sqrt{\frac{3.5\%}{B(D_S \to \phi\pi)}}. \qquad (3)$$

The uncertainty in the model-dependent value $B(D_S \to \phi\pi) = 3.5 \pm 0.4\%$[8] has been a issue for some time, but the different dependence on $B(D_S \to \phi\pi)$ of the two f_{D_S} measurements (2) and (3) above allows us to determine both f_{D_S} and $B(D_S \to \phi\pi)$ just by the consistency[7] (still depends on the factorization assumption in $B \to D_S^{(*)} D^*$):

$$f_{D_S} = 277 \pm 25(\text{MeV}), \quad B(D_S \to \phi\pi) = 3.60 \pm 0.64\%.$$

1.2 *Isospin violating decay* $D_S^{*+} \to D_S^+\pi^0$

The decay $D_S^{*+} \to D_S^+\pi^0$ is prohibited by isospin. The amplitude of the dominant channel $D_S^{*+} \to D_S^+\gamma$ is proportional to the total effective magnetic moment which is naively given by

$$\vec{\mu} = \frac{q_c}{m_c}\vec{s}_c + \frac{q_s}{m_s}\vec{s}_s$$

where $q_c(= 2/3e)$ and $q_s(= -1/3e)$ are the charges of c and s quarks, and $\vec{s}$ are the corresponding spins which are aligned in the case of D_S^*. Using constituent masses $m_c = 1.5$ GeV and $m_s = 0.4$ GeV, one can see that the dominant mode is highly suppressed. Such near cancellation in the dominant mode makes it difficult to predict the branching fraction for $D_S^{*+} \to D_S^+\pi^0$. One

	f_{D_S} (MeV)	Method
WA75[2]	$232 \pm 45 \pm 20 \pm 48$	π^- on emulsion
CLEO(93)[3]	$344 \pm 37 \pm 52 \pm 42$	e^+e^- (10 GeV c.m.)
BES[4]	$430^{+150}_{-130} \pm 40$	e^+e^- (4 GeV c.m.)
CLEO(95)[5]	$284 \pm 30 \pm 30 \pm 16$	e^+e^- (10 GeV c.m.)

Table 1: Mesurements of the decay constant f_{D_S} from the decay mode $D_S^+ \to \mu^+\nu$. The first error is statistical, second systematic, the third when given is uncertainty in D_S production rate (WA75) or $B(D_S \to \phi\pi)$ (CLEO).

estimate[9] based on η-π^0 mixing (together with HQET and chiral perturbation theory) gives a range of a few %. CLEO[10] has searched for this mode using the decay mode $D_S^+ \to \phi\pi^+$, and looks at the mass difference $M(D_S^{*+}) - M(D_S^+)$. A clean signal with $14^{+4.6}_{-4.0}$ events was observed. It is then normalized to the dominant radiative decay to give

$$\Gamma(D_S^{*+} \to D_S^+\pi^0)/\Gamma(D_S^{*+} \to D_S^+\gamma) = 0.062^{+0.020}_{-0.018} \pm 0.022.$$

The transition $D_S^* \to D_S\pi$ tells us that the parity of D_S^* is $(-)^J$ where J is the spin of D_S^*. Also, the decay $D_S^{*+} \to D_S^+\gamma$ indicates that $J \geq 1$. Thus, possible spin/parity of D_S^* is $1^-, 2^+, 3^- \ldots$, with 1^- being the most natural candidate. This is also consistent with the quark model prediction for the mass splitting[11]

$$M(^3S_1) - M(^1S_0) = \frac{32\pi\alpha_s}{9m_c m_s}|\Psi(0)|^2.$$

With $\alpha_s = 0.5$ and eq. (1), this gives 0.13 GeV which is quite consistent with the experimental value of 0.1416 ± 0.0018 GeV.

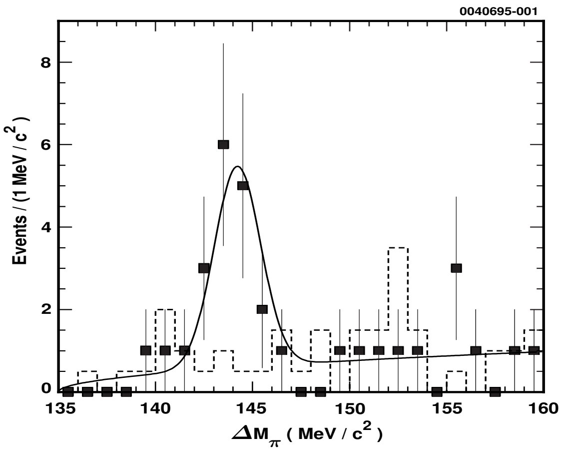

Figure 1: Mass difference $\Delta M_\pi \equiv M(D_S^{*+}) - M(D_S^+)$ for the isospin violating decay $D_S^{*+} \to D_S^+\pi^0$ (CLEO). The dotted line is the background estimated from the D_S^+ and π^0 sidebands.

2 Hadronic decays

In the factorization model of Bauer, Stech, and Wirbel (BSW)[12], the hadronic two-body decays of charmed mesons occur through the effective Hamiltonian given by

$$\mathcal{H}_{\rm had} = \frac{G_F}{\sqrt{2}} V_{ud}^* V_{cs} [a_1(\bar{d}u)_{\rm had}(\bar{c}b)_{\rm had} + a_2(\bar{d}b)_{\rm had}(\bar{c}u)_{\rm had}]$$

where $(..)_{\rm had}$ indicates the factorized current ready to form a final-state meson. The $\bar{d}$ can be changed to $\bar{s}$ and s may be changed to d with appropriate change in the CKM elements. It is convenient to classify the two-body decays to three categories: (Class-1) The amplitude is f_1a_1; e.g. $D^0 \to K^-\pi^+$. (Class-2) The amplitude is f_2a_2; e.g. $D^0 \to \bar{K}^0\pi^0$ ('color-suppressed'). (Class-3) The amplitude is $(f_1a_1 + f_2a_2)$; e.g. $D^+ \to \bar{K}^0\pi^+$. where the constants f_i depend on form factors and decay constants and typically well within factor of two of each other if related by flavor SU(3) (apart from isospin factors). Fitting the recent measurements of $D^0 \to K^-\pi^+, \bar{K}^0\pi^0$, and $D^+ \to \bar{K}^0\pi^+$, the values of a_1, a_2 are found to be

$$a_1 \sim 1.15, \quad a_2 \sim -0.51$$

which indicates that the Class 3 decays involve destructive interferences. The color suppression and interference suppression each amounts to very roughly a factor of 1/4 in decay rate. The parameters a_1 and a_2, however, in principle depend on final state and may not be the same for other decay modes such as $D \to KK, \pi\pi$. Another factor that can affect the rate is the phase space; in the comparisons that follow, however, the phase-space factors are mostly within 20% including P-wave decays.

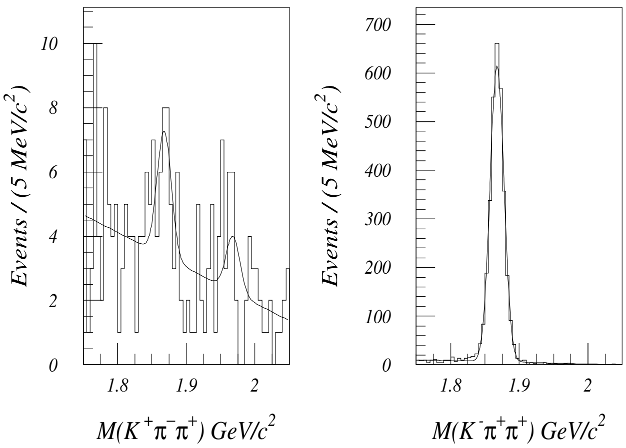

Figure 2: Mass distribution for the DCSD mode $D^+ \to K^+\pi^-\pi^+$ (left) and the corresponding Cabibbo-allowed decay (right) (E687). The enhancement at 1.97 GeV is $D_S^+ \to K^+\pi^-\pi^+$. Cuts are optimized for the D^+ decay.

2.1 *Singly and Doubly-Cabibbo-Suppressed Decays*

Possibly three DCSD (Doubly Cabibbo Suppressed Decay) modes have been observed thus far: $D^0 \to K^+\pi^-$, $D^+ \to K^+\pi^-\pi^+$, and $D^+ \to \phi K^+$. The results are given in Table 2. It should be noted that the decay $D^0 \to K^+\pi^-$ can also occur by $D^0 - \bar{D}^0$ mixing. Including the interference, the time-dependent and time-integrated decay rates are given by

$$\Gamma(D^0 \to K^+\pi^-)(t) = |a|^2 \left| \rho_D + \frac{1}{\sqrt{2}}\rho_M\, t \right|^2 e^{-t}, \qquad (4)$$

R (def.)	Exp.	$R(\%)$	R in unit of λ^4 or λ^2
$\Gamma(D^0 \to K^+\pi^-)/\Gamma(D^0 \to K^-\pi^+)$	CLEO[13]	$0.77 \pm 0.25 \pm 0.25$	$(2.92 \pm 0.95 \pm 0.95)\lambda^4$
$\Gamma(D^+ \to K^+\pi^-\pi^+)/\Gamma(D^+ \to K^-\pi^+\pi^+)$	E687[14]	$0.72 \pm 0.23 \pm 0.17$	$(2.73 \pm 0.87 \pm 0.64)\lambda^4$
	E791[15]	$1.03 \pm 0.24 \pm 0.13$	$(3.9 \pm 0.9 \pm 0.5)\lambda^4$
$\Gamma(D^+ \to K^{*0}\pi^+)/\Gamma(D^+ \to K^-\pi^+\pi^+)$	E687[14]	< 0.021	
$\Gamma(D^+ \to K^+\rho^0)/\Gamma(D^+ \to K^-\pi^+\pi^+)$	E687[14]	< 0.067	
$\Gamma(D^+ \to K^+K^-K^+)/\Gamma(D^+ \to \phi\pi^+)$	E687[16]	< 2.5	
$\Gamma(D^+ \to \phi K^+)/\Gamma(D^+ \to \phi\pi^+)$	E687[16]	< 2.1	$< 0.41\lambda^2$
$\Gamma(D^+ \to \phi K^+)/\Gamma(D^+ \to \phi\pi^+)$	E691[17]	$5.8^{+3.2}_{-2.6} \pm 0.7$	$(1.1^{+0.6}_{-0.5} \pm 0.1)\lambda^2$
$\Gamma(D_S^+ \to K^+\pi^-\pi^+)/\Gamma(D_S^+ \to \phi\pi^+)$	E687[14]	$28 \pm 6 \pm 5$	
$\Gamma(D_S^+ \to \bar{K}^{*0}\pi^+)/\Gamma(D_S^+ \to \phi\pi^+)$	E687[14]	$18 \pm 5 \pm 4$	$(3.5 \pm 1.0 \pm 0.8)\lambda^2$
$\Gamma(D_S^+ \to K^+\rho^0)/\Gamma(D_S^+ \to \phi\pi^+)$	E687[14]	< 8	
$\Gamma(D_S^+ \to K^+K^-K^+)/\Gamma(D_S^+ \to \phi\pi^+)$	E687[16]	< 1.6	
$\Gamma(D_S^+ \to \phi K^+)/\Gamma(D_S^+ \to \phi\pi^+)$	E687[16]	< 1.3	$< 0.25\lambda^2$

Table 2: Mesurements of DCSD modes of D^+ and singly-Cabibbo-suppressed modes of D_S^+. The Cabibbo suppression factor used is $\lambda \equiv \tan\theta_C = 0.226$. Also listed are two Cabibbo-suppressed modes of D_S^+. E687, E691 (photo-production) and E791 (hadro-production) are fixed-target experiments at Fermilab.

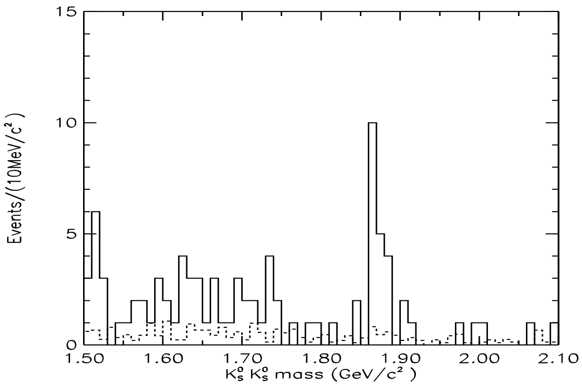

Figure 3: The decay $D^0 \to K_S K_S$ tagged by $D^{*+} \to D^0\pi^+$ and $D^{*0} \to D^0\pi^0$ (CLEO). The dotted line shows the D^* side band.

$$R \equiv \frac{B(D^0 \to K^+\pi^-)}{B(D^0 \to K^-\pi^+)} = r_D + \sqrt{2 r_D r_M}\cos(\phi_D - \phi_M) + r_M,$$

where

$$\rho_D \equiv \frac{a_D}{a} \equiv \sqrt{r_D}e^{i\phi_D},\ \rho_M \equiv \frac{\delta\gamma/2 + i\delta m}{\sqrt{2}\gamma} \equiv \sqrt{r_M}e^{i\phi_M},$$

with $a \equiv Amp(D^0 \to K^-\pi^+)$, $a_D \equiv Amp(D^0 \to K^+\pi^-)$, γ is the average D^0 decay rate, t is in unit of $1/\gamma$, and assumed $r_{M,D} \ll 1$. The expressions above are identical for $\bar{D}^0 \to K^+\pi^-$ with the redefinitions $a \equiv Amp(\bar{D}^0 \to K^+\pi^-)$ $a_D \equiv Amp(\bar{D}^0 \to K^-\pi^+)$. Assuming CP symmetry, values of $\rho_{D,M}$ are the same for the charge conjugate cases. Note that the parameter r_M is the standard mixing parameter $r_M = (D^0 \text{ decays as } \bar{D}^0)/(D^0 \text{ decays as } D^0)$. E691[19] gives $r_M < 0.39\%$ neglecting the interference term. The limit, however, increases about factor of three when no constraint is imposed on the interference phase.

Naively, one expects that a DCSD mode to be suppressed by a factor λ^4 ($\lambda \equiv \tan\theta_c$) relative to the corresponding Cabibbo-favored mode. Assuming no $D^0 - \bar{D}^0$ mixing, the DCSD decay $D^0 \to K^+\pi^-$ is about 3 times larger than the naive expectation even though statistically not very significant. A straight application of the BSW model[12] predicts 1.5 λ^4 where the enhancement is almost entirely accounted for by the difference in the decay constants: $(f_K/f_\pi)^2$. The measured DCSD enhancement for $D^+ \to K^+\pi^-\pi^+$ is slightly more significant. This is expected since the only resonance submode in the Cabibbo-favored mode is $D^+ \to$ "$\bar{K}^{*0}$"π^+ ("$\bar{K}^{*0}$" stands for any excited state of $\bar{K}^0$) which is Class-3 and suppressed by the destructive interference. In fact, the $D^+ \to K^-\pi^+\pi^+$ is the only mode among $D \to K\pi\pi$ 3-body decays that is not dominated by resonance submodes[20].

The decay of D^+ to 3 charged kaons is a DCSD by charge conservation. At quark diagram level, the spectator DCSD has a pair of $d\bar{d}$ quarks while the $3K^\pm$ final state has no valence $d\bar{d}$ quarks. Thus, the strong final state interaction (FSI) should annihilate the $d\bar{d}$ pair and create $s\bar{s}$ pair. Another possibility is the annihilation mode $c\bar{d} \to u\bar{s}$ followed by creation of a $s\bar{s}$ pairs, but this mode itself is doubly-Cabibbo-suppressed and expected to be small. This leads to suppression of the $3K^\pm$ DCSD mode relative to the naive expectation. As can be seen in the table, the experimental upper limit for $B(D^+ \to \phi K^+)/B(D^+ \to \phi\pi^+)$ ($\phi \to K^+K^-$) is less than half (E687) or about equal to (E691) the naive value. Note that the normalization mode $\phi\pi^+$ itself is color-suppressed (Class-2). The abnormally large value $B(D^+ \to K^+K^-K^+)/B(D^+ \to K^-\pi^+\pi^+) = (5.7 \pm 2.0 \pm 0.7)\%$ by WA82[18] (which is about 20 times larger than the naive expectation) is not consistent with these re-

Exp.	$D^0 \to K^+K^-(\%)$	$D^0 \to K^0K^0(\%)$
CLEO[24]	$0.455 \pm 0.029 \pm 0.024$	$0.048 \pm 0.012 \pm 0.006$
E687[25]	$0.437 \pm 0.028 \pm 0.060$	$0.207 \pm 0.069 \pm 0.073$
average	0.451 ± 0.033	0.051 ± 0.021

Table 3: Cabibbo-suppressed decays $D^0 \to K^+K^-, K^0\bar{K}^0$.

R(def.)	Exp.	ratio
$\frac{\Gamma(D^+ \to \bar{\pi}^0\pi^+)}{\Gamma(D^+ \to \bar{K}^-\pi^+\pi^+)}$	CLEO[26]	$0.028 \pm 0.006 \pm 0.006$
$\frac{\Gamma(D^+ \to \bar{K}^0K^+)}{\Gamma(D^+ \to \bar{K}^0\pi^+)}$	E687[27]	$0.25 \pm 0.04 \pm 0.02$
$\frac{\Gamma(D_S^+ \to K^0\pi^+)}{\Gamma(D_S^+ \to \bar{K}^0K^+)}$	E687[27]	0.18 ± 0.21
$\frac{\Gamma(D_S^+ \to K^0\pi^+)}{\Gamma(D_S^+ \to \phi\pi^+)}$	MKIII[28]	< 0.21

Table 4: Cabibbo-suppressed decays of D^+ and D_S^+ to two pseudoscalars.

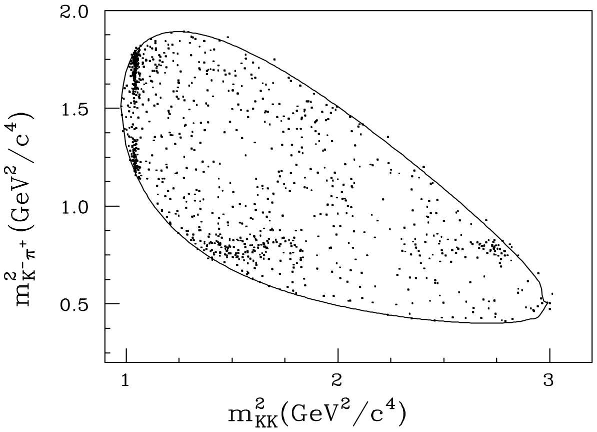

Figure 4: Dalitz plot of the Cabibbo-suppressed decay $D^+ \to K^-K^+\pi^+$ by E687. The $\phi\pi^+$ band and the $\bar{K}^{*0}\pi^+$ band are clearly seen.

sults. Also listed is the singly-Cabibbo-suppressed modes of D_S^+ which have the same final states as the DCSD modes of D^+ and thus can be measured in the same analyses. The decay $D_S^+ \to \phi K^+$ is Class-3 and expected to be suppressed by destructive interference (there are two $\bar{s}$ quarks in the final state) which is consistent with the upper limit. The decay $D_S^+ \to \bar{K}^{*0}\pi^+$ is Class-1 and one would expect that the naive suppression factor should work; the measurement, however, is on the high side.

In the flavor SU(3) limit, the Cabibbo-suppressed modes $D \to KK$ and $D \to \pi\pi$ are expected to be the same. In comparing with the data, however, one needs to take into account the FSI which rotates the phases of isospin amplitudes. For $D^0 \to KK$, we have

$$\begin{aligned} Amp(K^+K^-) &= \sqrt{\tfrac{1}{2}}(A_1 + A_0) \\ Amp(K^0\bar{K}^0) &= \sqrt{\tfrac{1}{2}}(A_1 - A_0), \end{aligned}$$

where $A_I (I = 0, 1)$ is the isospin=I amplitude. Note that phase rotations of A_I change the decay rate of each mode, but keep the sum unchanged:

$$\Gamma(K^+K^-) + \Gamma(K^0\bar{K}^0) = \frac{1}{2}(|A_0|^2 + |A_1|^2).$$

The mode $D^+ \to \bar{K}^0K^+$ is purely $I = 1$, and thus the rate does not change under the FSI. Here we are assuming that the FSI is elastic (i.e. KK channels stay within KK channels), and if the FSI is inelastic the above relations are no longer correct. The inelastic FSI, however, is expected to be small. The situation is similar for $D^0 \to \pi\pi$.

The $K^0\bar{K}^0$ mode is detected by K_SK_S. Since the two neutral kaons are produced coherently in a symmetric L=0 state, one has to take into account the quantum correlation when converting the K_SK_S rate to the $K^0\bar{K}^0$ rate. The state can be written as

$$D^0 \to K^0\bar{K}^0 + \bar{K}^0K^0 = K_SK_S + K_LK_L$$

which means that half the time it shows up as K_SK_S and half the as K_LK_L. This is correct even with CP violation. Thus we have

$$B(D^0 \to K^0\bar{K}^0) = 2B(D^0 \to K_SK_S).$$

The decay $D^0 \to K^0\bar{K}^0$ cannot occur by a spectator diagram without FSI. It could occur by exchange diagrams: $c\bar{u} \to s\bar{s}$ with a $d\bar{d}$ pair creation from vacuum, or $c\bar{u} \to d\bar{d}$ with a $s\bar{s}$ pair creation from vacuum. The two exchange amplitudes, however, cancel exactly in the limit of the flavor SU(3) in 2 generations (an example of GIM cancellation)[29]. Thus, it is likely that the $K^0\bar{K}^0$ mode is dominated by the feed though from the K^+K^- mode due to FSI. Latest results for $D^0 \to KK$ are given in Table 3. Together with $D \to \pi\pi$ data from the particle data group[8], we get

$$\frac{B(K^+K^-) + B(K^0\bar{K}^0)}{B(\pi^+\pi^-) + B(\pi^0\pi^0)} = 2.03 \pm 0.27$$

which is larger than the naive value of unity. The BSW model prediction is 1.3 which is still smaller than the experimental value above.

Cabibbo-suppressed 2-body decays of D^+ and D_S^+ are shown in Table 4. As mentioned earlier, the decays $D^+ \to \pi^0\pi^+$ and $\bar{K}^0K^+$ do not suffer from (elastic) FSI. The $D^+ \to \pi^0\pi^+$ mode is Class-3, and thus expected to be suppressed due to the destructive interference, while the $D^+ \to \bar{K}^0K^+$ mode is not. Using $B(D^+ \to \bar{K}^0\pi^+)$ $= 2.74 \pm 0.29\%$ and $B(D^+ \to K^-\pi^+\pi^+) = 9.1 \pm 0.6\%$[8], the ratio of the two Cabibbo-suppressed decays is

$$\frac{\Gamma(D^+ \to \bar{K}^0K^+)}{2\Gamma(D^+ \to \pi^0\pi^+)} = 1.4 \pm 0.5,$$

where the factor of 2 in the denominator is the isospin factor, or equivalently due to the fact that π^0 is half

$u\bar{u}$ and half $d\bar{d}$. This factor is expected to be enhanced due to the suppression of $\pi^0\pi^+$. The ratio $\Gamma(D^+ \to \bar{K}^0K^+)/\Gamma(D^+ \to \bar{K}^0\pi^+) = 0.25 \pm 0.04 \pm 0.02$ itself is larger than the naive Cabibbo suppression of $\lambda^2 \sim 0.05$. This is probably because the normalization mode $D^+ \to \bar{K}^0\pi^+$ is suppressed by the destructive interference (Class-3).

For D_S^+, the normalization mode $D_S^+ \to \bar{K}^0K^+$ is color-suppressed (i.e. Class-2), while $D_S^+ \to K^0\pi^+$ is not (Class-1). Thus, we expect the ratio to be enhanced with respect to the naive factor of $\lambda^2 \sim 0.05$. The experimental data is not yet conclusive at this point. It should be noted that $\bar{K}^0$ or K^0 in any decay mode is usually measured as K_S and thus DCSD mode could interfere with the corresponding Cabibbo-favored mode.[32] As a result, the oft-used relation $B(\bar{K}^0X) = 2B(K_SX)$ does not hold. The correction is typically of order 5 to 10%, but for some channels it could be as large as 25%. One such example is the normalization mode $D_S^+ \to K_SK^+$, where the Cabibbo-favored mode $D_S^+ \to \bar{K}^0K^+$ is color-suppressed (i.e. Class-2) but the DCSD mode $D_S^+ \to K^0K^+$ is not. The exact amount of correction depends on unknown FSI phase, and it is difficult to reliably estimate.

For $D^+, D_S^+ \to K^-K^+\pi^+$ modes, we now have Dalitz plot analysis from E687.[30] Figure 4 shows the Cabibbo-suppressed mode $D^+ \to K^-K^+\pi^+$. The position of the $K^*(892)$ band was found to be shifted in a way consistent with existence of $K^*(1430)$. After the fit including the interferences, the ratios of partial widths are found to be

$$\begin{aligned}\frac{\Gamma(D^+\to\bar{K}^{*0}(892)K^+)}{\Gamma(D^+\to K^-\pi^+\pi^+)} &= 0.044 \pm 0.003 \pm 0.004 \\ \frac{\Gamma(D^+\to\phi\pi^+)}{\Gamma(D^+\to K^-\pi^+\pi^+)} &= 0.058 \pm 0.006 \pm 0.006.\end{aligned}$$

The $D^+ \to \phi\pi^+$ mode is color-suppressed, but the decay constant of ϕ (which is 'emitted' from the hadronic current $D \to \pi$ in the factorization picture) is quite large ($f_\phi \sim 233$ MeV), could bring it up to the same level as $D^+ \to K^{*0}K^+$ which is a Class-1 decay.

2.2 *CP Violation*

CP asymmetries in D decays can occur through 1) direct CP violation[21,22], 2) mixing[31], or 3) interference of Cabibbo-favored mode and DCSD in modes involving K_S[32]. The asymmetries are expected to be quite small in the standard model (10^{-3} level or less); any asymmetry much larger is thus a signal of physics beyond the standard model.

Direct CP violation should involve at least two quark-level diagrams with different CKM phases and different FSI phases. The two diagrams may be two spectators[21], spectator plus penguin[22], or spectator plus annihilation[23]. At least in the standard model, the asymmetries are larger for Cabibbo-suppressed modes; since the main goal now is to search effects beyond the standard model, however, Cabibbo-favored modes also need to be checked. Table 5 shows recent measurements of CP asymmetries of $D^{+,0}$ decays. Since there is an asymmetry in photo-production of D and $\bar{D}$ in E687 numbers are normalized to corresponding Cabibbo-favored decays $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+$. All numbers are consistent with zero.

	Mode	Exp.	Asymmetry
$D^+ \to$	$K^+K^-\pi^+$	E687[33]	-0.031 ± 0.068
	$\bar{K}^{*0}K^+$		-0.12 ± 0.13
	$\phi\pi^+$		0.066 ± 0.086
$D^0 \to$	K^+K^-	E687[33]	0.024 ± 0.084
		CLEO[34]	0.069 ± 0.059
	$K_S\phi$	CLEO[34]	-0.007 ± 0.090
	$K_S\pi^0$	CLEO[34]	-0.013 ± 0.030
	$K^-\pi^+$	CLEO[34]	0.009 ± 0.011

Table 5: CP asymmetries of $D^{0,+}$ decays. The asymmetries by E687 are normalized to $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+$. CLEO tags the flavor of D by the decay $D^{*+} \to D^0\pi^+$.

For $D^0 \to K\pi$, CP violation in mixing introduces additional factor between ρ_D and ρ_M in (4) which differ for $D^0 \to K^+\pi^-$ and $\bar{D}^0 \to K^-\pi^+$ (assuming that there is no direct CP violation):

$$\rho_M \to \frac{q}{p}\rho_M \quad (D^0), \qquad \rho_M \to \frac{p}{q}\rho_M \quad (\bar{D}^0)$$

where p and q are the coefficients of D^0 and $\bar{D}^0$ for the mass eigenstates $D_{H,L}$:

$$D_H = pD^0 + q\bar{D}^0, \quad D_L = pD^0 - q\bar{D}^0.$$

If $p \neq q$, then the additional factor is in general different for D^0 and $\bar{D}^0$ resulting in CP asymmetry in the time-dependent $\Gamma(D^0 \to K^+\pi^-)(t)$ vs. its CP conjugate channel as well as in the time-integrated rates. In the limit of $\Im(a_D/a) = 0$ and $\delta\gamma = 0$, there is no term linear in t in the expression (4). Even then, CP violation in mixing would give rise to a term linear in t which is also *CP* odd. Such asymmetry that increases linearly with time would indicate both CP violation and mixing simultaneously[35]. The table also lists asymmetries for CP self-conjugate final states; the results are all consistent with zero.

3 Summary

The charm physics has matured. We now see rare decays such as pure leptonic decay and isospin violating decay. A few Doubly-Cabibbo-Suppressed decays have been observed, and detailed studies of singly-Cabibbo-suppressed modes have been done and ongoing. Most of the modes are qualitatively understandable in terms of the color-suppression and the destructive interference together with known SU(3) breaking effects such as the differences in decay constants. The experimental sensitivities for CP asymmetries are still a few orders of magnitude away from the level expected by the standard model.

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