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Unsolved Problems in Hadronic Charm Decay*

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Abstract

This paper describes several outstanding problems in the study of hadronic decays of charmed mesons where further experimental work and theoretical understanding is needed. Four topics are stressed: doubly Cabibbo suppressed decays (DCSD) of D^+ mesons, hadronic D_s decays, weak hadronic quasi-two-body decays to pairs of vector mesons, and penguin decays of D mesons.

Doubly Cabibbo Suppressed D^+ Decays

Doubly Cabibbo suppressed decays (DCSD) of the D^0 meson, and D^0 mixing, give rise to identical final states. The two processes can only be distinguished by their different time dependences, or at the ψ'', by taking advantage of effects due to quantum statistics. In contrast, the interpretation of DCSD in D^+ decays is not complicated by the effects of mixing. DCSD decays of D^+ mesons also test phenemenological models of charm decay.

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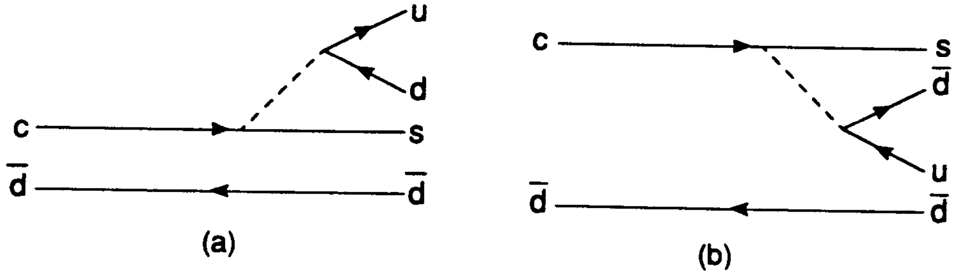

Figure 1(a). External W emission graph for D^+ decay. Figure 1(b). Internal W emission graph for D^+ decay.

Cabibbo favored and singly Cabibbo suppressed D^+ decays which do not involve the creation of $s\bar{s}$ quark pairs proceed by both the external and internal W-emission graphs shown in Figure 1(a),1(b). If the d_W quark and the $d_{spectator}$ quark occupy the same region of phase space, then by the Pauli exclusion principle (since the two quarks are identical fermions) the two graphs will interfere destructively. A more rigorous QCD based treatment also leads to the same conclusion.[1]

Pauli interference effects of this type are thought to be responsible for the suppression of the D^+ width relative to the D^0 or D_s widths (recall τ_{D^+}/τ_{D^0}, $\tau_{D^+}/\tau_{D_s} \sim 2.5$). There is also supporting evidence for this hypothesis in the observed pattern of D^+ decays. For instance, $B(D^+ \rightarrow \bar{K}^0 K^+)/B(D^+ \rightarrow \bar{K}^0 \pi^+)$ $= 0.317 \pm 0.08 \pm 0.048$. The decay mode in the numerator of the ratio is Cabibbo suppressed, and is not subject to interference whereas the decay mode in the denominator of the ratio is Cabibbo favored, and is subject to interference. In the absence of non-spectator effects, the above ratio should be $O(\tan^2\theta_c) \sim 0.05$. Similiarly, $B(D^+ \rightarrow \rho\pi^+)/B(D^+ \rightarrow \phi\pi^+) = 0.10 \pm .06$. The latter ratio of two singly suppressed modes should be roughly unity. However, the mode in the numerator of the ratio is subject to interference, while the mode in the denominator of the ratio is not subject to interference.

Figure 2 shows the Feynman graph for doubly suppressed D^+ decays. There are no identical quarks in the final state in this instance and thus there is no possibility of interference. Relative to Cabibbo favored D^+ decays, DCSD will therefore be enhanced.

A calculation of DCSD rates for several D^+ modes has been carried out by I.I. Bigi[2] using the phenemenological model of Bauer and Stech. The results are given below in terms of $\tan^4\theta_c$, the expected rate for doubly Cabibbo suppressed

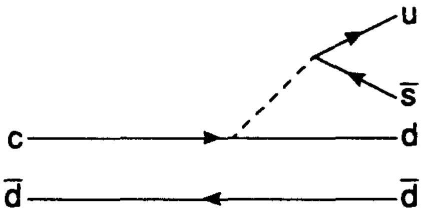

Figure 2. Feynman graph for doubly Cabibbo suppressed D^+ decay.

decays in the most naive spectator model.

$$
\begin{aligned}
Br(D^+ \rightarrow K^+\pi^0)/Br(D^+ \rightarrow \bar{K}^0\pi^+) &\sim 3\tan^4\theta_c \\
Br(D^+ \rightarrow K^{*0}\pi^+)/Br(D^+ \rightarrow \bar{K}^{*0}\pi^+) &\sim 5-11\tan^4\theta_c \\
Br(D^+ \rightarrow K^{*+}\pi^0)/Br(D^+ \rightarrow \bar{K}^{*0}\pi^+) &\sim 12-25\tan^4\theta_c \\
Br(D^+ \rightarrow K^+\rho^0)/Br(D^+ \rightarrow \bar{K}^0\rho^+) &\sim 0.35\tan^4\theta_c
\end{aligned}
$$

The above predictions are obtained from a model with several simplifying assumptions: the factorizatability of hadronic amplitudes, and the absence of final state interactions. If either of these assumptions is incorrect, there could be significant deviations from the pattern indicated by the above predictions.

Using the lower side of Bigi's predictions, conservative detection efficiencies, and the design luminosity of the tau charm facility, the event rates listed in Table 1 are obtained. The number listed in the last column is the number of observed DCSD decays opposite a fully reconstructed ("tagged ") D^- meson that are expected in a one year run at design luminosity.

Table 1. Expected Event Rates for Doubly Cabibbo Suppressed D^+ Decays at the Tau Charm Facility.

Decay Mode	Efficiency	Branching Fraction	Detected Events
$D^+ \rightarrow K^+\pi^0$	0.43	0.02	142
$D^+ \rightarrow K^+\rho^0$	0.42	0.07	498
$D^+ \rightarrow K^{*0}\pi^+$	0.28	0.06	232
$D^+ \rightarrow K^{*+0}\pi^0$	0.13	0.05	106
$D^+ \rightarrow K^+\pi^-\pi^+$	0.42	0.07	512

A detailed study of possible background contaminations to DCSD of D^+ mesons has been carried out by R.H. Schindler. This study assumed a detector with the same acceptance and particle identification capabilities as the MarkIII. The typical pion/kaon misidentification probability was about 10%. Estimates of possible feedthroughs are listed in Table 2. Backgrounds marked with asterisks can be eliminated with simple cuts e.g. cut on $\pi^-\pi^+$ mass and vertex position to eliminate $D^0 \to \bar{K}^0\pi^+$ decays where one of the pions is misidentified.

We estimate 415 background events and 512 events in the DCSD mode $D^+ \to K^+\pi^-\pi^+$ or a signal to background ratio of about 1:1 in the signal region of the D mass. If a TOF system with 120 psec resolution is used, (recall the resolution for the MarkIII system was about 180 psec) then the pion/kaon misidentification probabilty can be reduced to below 1%. In this case, the signal to background for DCSD will increase to 10:1 since the largest backgrounds are due misidentified D^+ modes.

Table 2. Sources of Background to the DCSD decay $D^+ \to K^+\pi^+\pi^-$ at the Tau Charm Facility

Decay Mode	Number of Background Events
$D^+ \to K^-\pi^+\pi^+$	245
$D^+ \to \bar{K}^{*0}\pi^+$	153
$D^+ \to \bar{K}^0K^+$	142 *
$D^+ \to \bar{K}^0\pi^+$	160*
$D^+ \to \bar{K}^0\rho^+$	161*
$D^+ \to \bar{K}^0\pi^+\pi^0$	20*
$D^+ \to \pi^-\pi^+\pi^+$	17
$D^+ \to \pi^-\pi^+\pi^+\pi^0$	50*

Due to the long D^+ lifetime, samples of D^+ decays to all charged final states with low backgrounds have been obtained at fixed target experiments. Both fixed target and B factory experiments will, however, have to contend with large feedthroughs from misidentified $D_s^+ \to K^-K^+\pi^+$ decays which peak in the signal region for the DCSD decay $D^+ \to K^+\pi^-\pi^+$. Modes such as $D^+ \to K^+\pi^0$ will be impossible to observe at fixed target experiments or at a B factory. At the former, a charged vertex is required while at the latter the backgrounds without tagging will be insurmontable.

Hadronic D_s Decays

All D_s decay measurements are normalized to $B(D_s \to \phi\pi)$. In addition, to extract $B(B \to D_s X)$ from a measurement of $B \to D_s X_i \to \phi\pi X_i$ for a final state X_i requires knowledge of the absolute branching fraction $B(D_s \to \phi\pi^+)$. There exist several measurements of the D_s branching fraction which depend either on theoretical models of charm hadronization or on assumptions about charm baryon production. These results suggest that $B(D_s \to \phi\pi)$ lies in the range 1.5 – 3.5%.[3] To date, the only model independent result is the MarkIII limit $B(D_s \to \phi\pi^+) <$ 4.1%.[4]

At the tau charm factory, precise measurements of absolute branching fractions for D_s decays will be possible using the double tagging technique that was sucessfully used to extract absolute branching fractions for D^0 and D^+ mesons.[5] The optimal center of mass energy for this measurement will be 4.03 GeV where monochromatic $D_s^+ D_s^-$ pairs are produced nearly at rest. Note that, unlike the MarkIII data sample recorded at 4.14 GeV (where $D_s^+ D_s^{*-}$ pairs are produced), the full power of kinematic fits will be available for D_s decays at this energy.

The detection efficiency for $D_s \to K^- K^+ \pi^+$ will be about 18% at the tau charm factory detector. The detection efficiency for $D_s \to \pi^- \pi^+ \pi^+$ will be about 55%. If only well established modes which decay to all charged final states are used ($D_s \to \phi\pi, D_s \to \bar{K}^{*0} K^+, D_s \to \bar{K}^0 K^+$, and $D_s \to f_0(975)\pi^+$) we will therefore be able to observe roughly $163300 * B(D_s \to \phi\pi)$ or 3270 fully reconstructed doubly tagged events if $B(D_s \to \phi\pi) \sim 2\%$.

Only a handful of D_s modes have been observed. Table 3 summarizes the observations of modes which lead to final states with charged and neutral kaons. Table 4 summarizes the conflicting observations of modes which contain pions. If $B(D_s \to \phi\pi) \sim 2\%$ then only about 19% of the hadronic D_s decay modes have been experimentally accounted for. The expected hadronic branching fraction should be about 85%. One possibility is large quasi two body decays to an axial vector and a vector (AV), to an axial vector and a pseudoscalar (AP), to a scalar and a vector (SV), to a scalar and a a pseudoscalar (SP),[6] or to a pair of scalars (SS). Typical decays are $D_s \to \eta a_1^+$, $D_s \to \bar{K}_1(1270)\rho^+$, $D_s \to \bar{K}_1(1270)K^+$, $D_s \to \bar{K}_1(1400)K^+$ and $D_s \to \bar{K}_0^*(1430)K^+$. It has also been suggested that the remaining modes will appear in nonresonant non quasi-two-body final states.[7] If this is the case, hadronic D_s decays differ significantly from D^0 and D^+ decays which are nearly saturated by quasi-two-body PP, PV, and VV decays. Equivalently, there may be large branching ratios for modes such as $D_s \to \eta\pi^-\pi^+\pi^+$, $D_s \to K^- K^+ \pi^+ \pi^0 \pi^0$, or $D_s \to \bar{K}^0 K^+ a_1^0 \to \bar{K}^0 K^+ \pi^- \pi^+ \pi^0$. Independent of these speculations, the remaining unobserved D_s decays will typically have high charged multiplicities and multiple neutrals. In addition, it is likely that there will be few submass constraints to reduce backgrounds.

The observation of high multiplicity modes with neutrals is experimentally feasible at the tau-charm factory. Figure 3 shows the beam constrained mass distribution for the decay chain $D_s \to \eta\pi^+\pi^-\pi^+$, $\eta \to \pi^-\pi^+\pi^0$ using a conservative electromagnetic calorimeter with $\Delta E/E = 8\%/\sqrt{E} + 1\%$ and a photon efficiency which rises from 20% at 20 MeV to 100% at 100 MeV. The Monte Carlo study includes backgrounds from other D_s decays and from other D decays expected at 4.03 GeV. If $Br(D_s \to \eta\pi^-\pi^+\pi^+) \sim 1\%$, then 2×10^4 singly tagged events can be reconstructed at design luminosity. Figure 4 shows the beam constrained mass distribution for $D^0 \to K^-\pi^-\pi^0\pi^0$, using the same nominal calorimeter resolution. A clear signal with an efficiency of 17% is visible without the use of double tagging. It therefore should be possible to measure $D_s \to \phi\pi^+\pi^0\pi^0$ and $D_s \to \eta\pi^+\pi^0\pi^0$.

Measurements of such high multiplicity decay modes will probably not be possible at a B factory due to the large combinatorial backgrounds and the absence of the beam energy constraint. High multiplicity decays with a single π^0 have been observed at fixed target experiments with high precision vertex detectors. Typically, these decay modes have been observed by reconstructing the full final state or by observing the satellite peak when the π^0 is not detected.[8] These experiments have not yet demonstrated the possibility of observing decays with two π^0s using either technique.

There are several other open questions in D_s physics which could be easily resolved by a high statistics run at 4.03 GeV.

The pattern of Cabibbo suppressed D_s decays should be determined. The easiest to observe will be $D_s \to K^+\pi^-\pi^+$ and $D_s \to \bar{K}^0\pi^+$. It is important to compare the observed pattern of Cabibbo suppressed decays with the corresponding D^0 and D^+ meson decays.

The strength of annihilation in the D_s is not yet fully understood. It would be useful to measure $D_s \to \pi^0\pi^0\pi^+$, $D_s \to \pi^-\pi^+\pi^+\pi^0\pi^0$ and $D_s \to \pi^-\pi^+\pi^+\pi^-\pi^+$ and understand the pattern of annihilation decays. A more complete analysis of the established mode $D_s \to \pi^-\pi^+\pi^+$ can be carrried out with higher statistics. Using a sample of about 68 events, Fermilab Experiment E691 has already performed a Dalitz plot analysis of this mode and has found that it is mostly nonresonant;[9] there is no $\rho^0\pi^+$ component as wll as a contribution from $D_s \to f_0(975)\pi^+$. It is important to determine whether $D_s \to f_2(1270)\pi^+$ or other quasi-two-body channels saturate the "non resonant " component as well as measure the $f_0(975)$ lineshape and compare it with the lineshape determined from the reaction $J/\psi \to \phi f_0(975)$. Such an interdisciplinary analysis (on the border between charm physics and hadron physics) could help determine whether the $f_0(975)$ is a single resonance and whether it is a q qbar state, a four quark state, or a glueball.

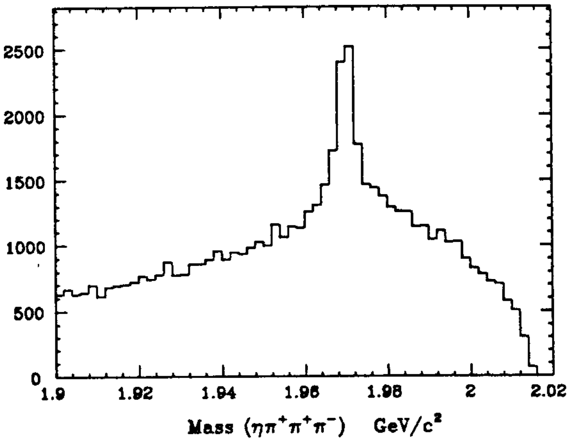

Figure 3. $D_s \to \eta\pi^+\pi^-\pi^+$ beam constrained mass distribution. Photon candidates were selected using a 1-C fit to a π^0. The fitted photon energy was required to be greater than 30 MeV and the cosine of the angle between each photon and the nearest charged track was required to be less than 0.95.

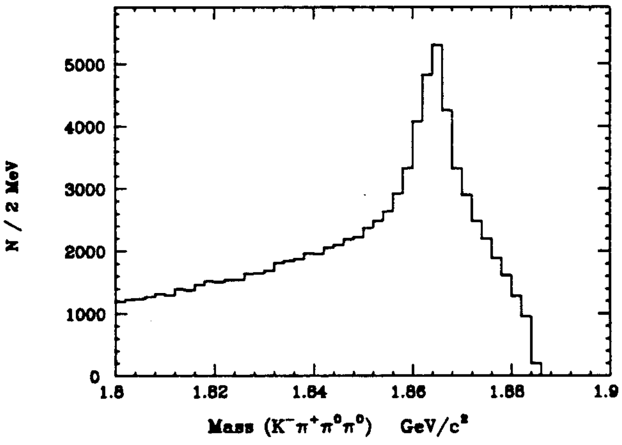

Figure 4. $D^0 \to K^-\pi^+\pi^0\pi^0$ beam constrained mass distribution.

If the D_s has a large gluonium component in its wavefunction, then the W annihilation diagram with two gluon emission off the initial sbar quark leg could be large and decays such as $D_s \to$ glue π^+ could be significant. Possible final states in which dedicated searches should be attempted are:

Table 4. Branching Ratios of D_s modes with kaons relative to $\phi\pi$

Decay Mode	Experiment	Result or Limit
$D_s \to \bar{K}^0 K^+$	MarkIII	$0.92 \pm 0.32 \pm 0.20$
	CLEO	$0.99 \pm 0.17 \pm 0.06$
$D_s \to \bar{K}^{*+} K^0$	CLEO	$1.2 \pm 0.21 \pm 0.13$
$D_s \to \bar{K}^0 \pi^+$	MarkIII	< 0.21 at 90% CL
$D_s \to \bar{K}^{*0} K^+$	E691	$0.87 \pm 0.13 \pm 0.05$
	ARGUS	1.44 ± 0.37
	MarkIII	$0.84 \pm 0.30 \pm 0.22$
	CLEO	$1.05 \pm 0.17 \pm 0.06$
$D_s \to \bar{K}^{*0} K^{*+}$	NA32	2.3 ± 1.2
$D_s \to \phi \pi^+ \pi^0$	E691	$2.4 \pm 1.0 \pm 0.5$
	NA14	< 2.6 at 90% CL
$D_s \to (K^- K^+ \pi^+)_{NR}$	E691	$0.25 \pm .07 \pm .05$
	NA32	0.96 ± 0.32
$D_s \to \phi \pi^- \pi^+ \pi^+$	E691	$0.42 \pm 0.13 \pm .07$
	NA32	0.39 ± 0.17
	Argus(a)	$1.11 \pm 0.37 \pm 0.28$
	Argus(b)	$0.41 \pm 0.13 \pm 0.11$
$D_s \to (K^- K^+ \pi^+ \pi^0)_{NR}$	E691	< 2.4 at 90% CL
$D_s \to (K^- K^+ \pi^- \pi^+ \pi^+)_{NR}$	E691	$< .32$ at 90% CL
	NA32	0.11 ± 0.07

$$D_s \to \eta(1430)\pi^+ \to K^- K^+ \pi^0 \pi^+$$
$$D_s \to \eta(1430)\pi^+ \to \bar{K}^0 K^- \pi^+ \pi^+$$
$$D_s \to \eta(1430)\pi^+ \to \eta \pi^- \pi^+ \pi^+$$
$$D_s \to f_2(1720)\pi^+ \to K^- K^+ \pi^+$$
$$D_s \to f_2(1720)\pi^+ \to \eta\eta\pi^+$$

Table 5. Branching Ratios of D_s modes without kaons relative to $\phi\pi$

Decay Mode	Experiment	Result or Limit
$D_s \rightarrow \rho\pi^+$	E691	< 0.08 at 90% C.L.
	Argus	< 0.22 at 90% C.L.
$D_s \rightarrow f_0(975)\pi^+$	E691	$0.28 \pm 0.1 \pm .03$
	MarkIII	$0.58 \pm 0.21 \pm 0.28$
$D_s \rightarrow \eta\pi^+$	E691	< 1.5 at 90 % CL
	MarkII	3.0 ± 1.1
	MarkIII	< 2.5 at 90% CL
$D_s \rightarrow \eta'\pi^+$	MarkII	4.8 ± 2.1
	NA14	$6.9 \pm 2.4 \pm 1.4$
	MarkIII	< 1.9 at 90% CL
	E691	< 1.7 at 90% CL
$D_s \rightarrow \omega\pi^+$	E691	< 0.5 at 90% CL
	E564	seen
$D_s \rightarrow (\pi^-\pi^+\pi^+)_{NR}$	E691	$0.29 \pm .09 \pm .03$
$D_s \rightarrow (\pi^-\pi^+\pi^+\pi^-\pi^+)_{NR}$	E691	$< .29$ at 90% CL

D_s decays can be used to constrain the structure of the charm changing weak lagrangian. For instance the decay $D_s \rightarrow \pi^+\pi^0$ should be forbidden unless there is a $\Delta I = 2$ component in the lagrangian. This possibility has not yet been experimentally tested.

Hadronic Vector Vector Decays

A number of $D \rightarrow PP$ and $D \rightarrow PV$ decays have now been measured and can be satisfactorily explained in two phenemenological models. So far these models have not been tested for the case of $D \rightarrow VV$ decays.[10,11]

Recent observations appear to indicate that many of the VV decay rates are smaller than expected. For instance, the measured rate for $D^0 \rightarrow \bar{K}^{*0}\rho$ ($2.3 \pm 0.3 \pm 0.7\%$) is a factor of three smaller than the theoretical expectation (6.1%). The branching ratio for the decay $D_s \rightarrow \phi\pi^+\pi^0$, which is expected to include a large $\phi\rho^+$ contribution, is $2.4 \times (D_s \rightarrow \phi\pi^+)$, at least a factor of three smaller than the prediction [$6.3\times(D_s \rightarrow \phi\pi)$]. Similiarly, even if the decay $D^+ \rightarrow K^-\pi^+\pi^+\pi^0$ is saturated by $D^+ \rightarrow \bar{K}^{*0}\rho^+$, the observed rate [$3.7\pm0.8\pm0.8\%$] is still significantly lower than the BSW prediction[$\sim$ 13%]. This intriguing discrepancy could be the symptom of the breakdown of the factorization Ansatz in decays with little energy release.[12] If the same models are used to extract information about the weak interaction in B decays, it is necessary to understand why phenomenological models fail in the case of $D \rightarrow V\ V$.

A complete resonant substructure analysis has been carried out for $D^0 \rightarrow K^-\pi^-\pi^+\pi^+$ by the MarkIII group using a sample of 1281 ± 45 events.[13] Analyses of comparable sophistication will become possible in the $D^0 \rightarrow K^-\pi^+\pi^0\pi^0$, $D^+ \rightarrow K^-\pi^+\pi^+\pi^0$, and $D^0 \rightarrow \bar{K}^0\pi^-\pi^+\pi^0$ channels if charm samples with an order of magnitude more events and good neutral efficiency are collected.[14]

If the rates and phases for $D^0 \rightarrow \bar{K}^{*0}\rho^0$, $D^0 \rightarrow K^{*-}\rho^+$, and $D^+ \rightarrow \bar{K}^{*0}\rho^+$ are measured, then the isospin sum rule[15]

$$\sqrt{2}A(D^0 \rightarrow \bar{K}^{*0}\rho^0) = A(D^+ \rightarrow \bar{K}^{*0}\rho^+) - A(D^0 \rightarrow K^{*-}\rho^+)$$

can be used to determine whether final state interactions play a significant role in these decays. If the above sum rule cannot be satisfied with relatively real amplitudes, then final state interactions are required.

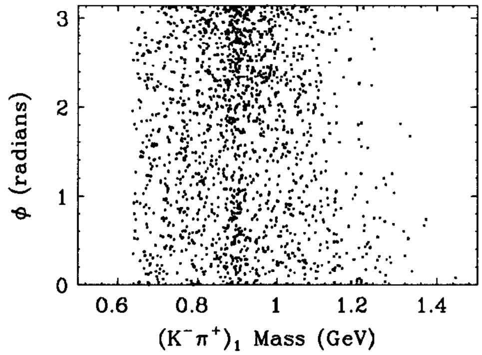

Figure 5. Scatter plot of K^{*0} mass vs ϕ, where ϕ is the angle between the K^{*0} and ρ^0 decay planes as seen from the D^0 rest frame. In the K^{*0} band, an enhancement near ϕ=0 and a larger enhancement near $\phi = \pi$ are visible. The transverse $\bar{K}^{*0}\rho^0$ amplitude is proportional to $\cos\phi$ and accounts for this distribution. Since the sign of this amplitude reverses from $\phi = 0$ to $\phi = \pi$, there is more constructive interference near $\phi = \pi$.

In addition to measurements of the absolute rates of $D \rightarrow V\ V$ decays, it is also possible to measure angular correlations between the two vectors in $D \rightarrow V\ V$

decays. This is useful for testing the factorization hypothesis.[16] If the two vectors are both polarized perpendicular to the D^0 direction, one expects that the angular dependence of the amplitude will have the form $A_T \propto \cos(\phi) \sin\theta_1 \sin\theta_2$ where ϕ is the angle between the decay planes of the two vector mesons, and θ_1, θ_2 are the helicity angles of the ρ and K^* mesons, respectively. If the polarization is longitudinal, $A_L \propto \cos\theta_1 \cos\theta_2$. If factorization is a valid assumption, longitudinal polarization is expected to be dominant; a recent analysis by the MarkIII group, however, indicates that the transverse polarization is large in $D^0 \to \bar{K}^{*0}\rho^0$. The observed angular correlation for $D^0 \to \bar{K}^{*0}\rho^0$ events is indicated in Figure 5.

Penguins in Charmed Meson Decays

The diagram for the gluonic D meson penguin is shown in Figure 6. The most experimentally accessible final states from these processes are:

$$
\begin{aligned}
&D^0 \to K^-K^+\\
&D^0 \to \pi^-\pi^+\\
&D^0 \to \bar{K}^0K^0\\
&D^0 \to \bar{K}^{*0}K^{*0}
\end{aligned}
$$

$$
\begin{aligned}
&D^+ \to \bar{K}^0K^+\\
&D^+ \to \bar{K}^{*0}K^+
\end{aligned}
$$

(these will be referred to as class I penguins). Using tagged events and/or very tight cuts, the modes listed below can probably be observed. (These will be referred to as class II modes).

$$
\begin{aligned}
&D^0 \to \pi^0\pi^0\\
&D^0 \to \eta\eta\\
&D^0 \to \eta'\eta'\\
&D^0 \to \pi^0\eta\\
&D^0 \to \pi^0\eta'
\end{aligned}
$$

$$
\begin{aligned}
&D^+ \to \pi^+\pi^0\\
&D^+ \to \eta\pi^+\\
&D^+ \to \eta'\pi^+
\end{aligned}
$$

Precise measurements of class I penguins will be possible. For $D^0 \to K^-K^+$, the detection efficiency will be 48%. We expect to observe 2.9×10^4 tagged events and therefore will measure the branching ratio to a statistical accuracy of 1%. For $D^0 \to \pi^-\pi^+$, the detection efficiency will be 76%. Therefore, 1.8×10^4 tagged $D^0 \to \pi^-\pi^+$ events can be reconstructed, allowing for a 1% measurement as well. The backgrounds from singly misidentified decays such as $D^0 \to K^-\pi^+$ are easily controlled since they are shifted in invariant mass plots.

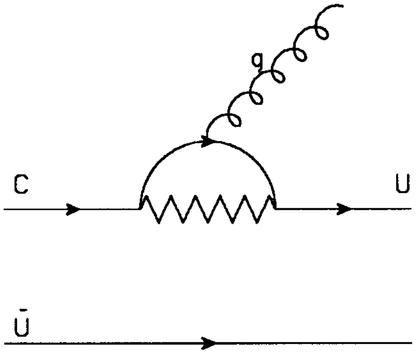

Figure 6. Gluonic Penguin

An easy class II penguin mode, $D^0 \to \pi^0\pi^0$, can be reconstructed with an efficiency of about 5%. If the branching ratio for this mode is 0.2%, 10^3 tagged events can be reconstructed, allowing for a 3% statistical error on the final measurement. A more challenging class II penguin $D^0 \to \eta\eta$ can be detected with an efficiency of 5% in the $\gamma\gamma$ mode. If the branching ratio for this channel is 0.1%, 100 tagged events can be reconstructed and a 10% measurement of the branching ratio will be possible.

Class I penguins are accessible at both fixed target and B factory experiments. Class II D^0 penguins may be observed at B factories using the $D^* \to D^0\pi^+$ decay chain. With the exception of the D^+ modes, class II penguins probably cannot be observed at fixed target experiments.

Although all the decay modes listed above are experimentally accessible, the theoretical unfolding of the strength of the gluonic Penguin is highly nontrivial. In each case, there is a Cabibbo suppressed spectator graph which gives rise to the same final state and is expected to be somewhat larger. It is hoped that by precisely measuring the complete pattern of these decays and with a better theoretical understanding of nonleptonic charm decay, such an unfolding will become possible. Precise measurements of the D^0 decays listed above will also be useful in theoretical determinations of the magnitude of the long distance contribution to $D^0 - \bar{D}^0$ mixing.[17]

It is worth remembering that the problem of the ratio $Br(D^0 \to K^-K^+)$ $/Br(D^0 \to \pi^-\pi^+)$ is still unresolved. This ratio should be of order unity (0.86) in the limit of $SU(3)$ flavor symmetry. Experimentally, it is found to lie in the range $2.2 - 3.7$.[18] Finjord et. al.[19] as well as Yem[20] have proposed that this ratio could deviate from unity if the interference term between the penguin amplitude and the spectator graph is large. In the case of $D^0 \to K^- K^+$ the interference term will be multiplied by a factor of $\cos\theta_c \sin\theta_c$ while for $D^0 \to \pi^- \pi^+$ the interference term will be multiplied by a factor of $-\cos\theta_c \sin\theta_c$. Therefore this interference could enhance $D^0 \to K^- K^+$ and suppress $D^0 \to \pi^- \pi^+$. This hypothesis can be tested by measuring the ratios: $Br(D^0 \to K^0 \bar{K}^0)/Br(D^0 \to \pi^0 \pi^0)$, $Br(D^+ \to \bar{K}^0 K^+)/Br(D^+ \to \pi^0 \pi^+)$ and $Br(D_s \to \phi K^-)/Br(D_s \to \bar{K}^0 \pi^+)$ which would then all be expected to be greater than unity after correcting for phase space.

Radiative penguins decays where the gluon is replaced by a photon are also possible in the charm system. The simplest and experimentally most accessible modes will be $D^0 \to \rho\gamma$ and $D^0 \to \omega\gamma$. (Both angular momentum conservation and $U(1)$ gauge invariance forbid the decays $D^+ \to \pi^+\gamma$ and $D^0 \to \pi^0\gamma$).

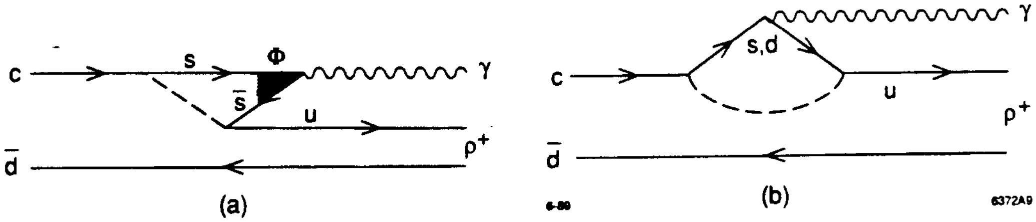

Figure 7. (a) Long distance radiative penguin (b) Short distance radiative penguin

The lowest order contribution to the radiative penguin in D decay will include terms from a W loop with an internal s or d quark. As in $D^0 - \bar{D}^0$ mixing and other second order weak interaction effects in the charm sector, the sum of these two terms will be proportional to $(m_s^2 - m_d^2)/M_W^2$ multiplied by $\sin^2\theta_c \cos^2\theta_c$. In the limit of exact SU(3) flavor symmetry, it will be exactly zero. Therefore one finds that the branching ratio from the zeroth order short distance contribution will be $O(10^{-8}) - O(10^{-9})$. As in the case of radiative B penguins, QCD radiative corrections might be an order of magnitude larger than the lowest order term.[21] So far, no theoretical calculation has been attempted since the momenta which dominate the integrals are the same order of magnitude as the strange quark mass.

In addition, in this case, rescattering or long distance effects are expected to be several orders of magnitude larger than the short distance contribution. A typical example of such a rescattering process is indicated below:

$$D^0 \rightarrow \phi\rho \rightarrow \gamma\rho.$$

Therefore $Br(D^0 \rightarrow \gamma\rho^0) \sim Br(D^0 \rightarrow \phi\rho^0)\times\alpha_{EM}/\pi$.[22] Using the CLEO measurement $Br(D^0 \rightarrow \phi\rho) = 0.34 \pm 0.1$, we estimate that the long distance contribution could be $O(0.8 \times 10^{-5})$. Decays such as $D^0 \rightarrow \bar{K}^{*0}\gamma$ which do not have a corresponding short distance contribution can also occur via rescattering processes such as

$$D^0 \rightarrow \bar{K}^{*0}\omega \rightarrow \bar{K}^{*0}\gamma$$

with branching ratios $O(10^{-4})$.

It is important to understand the size of such rescattering effects if we hope to extract information about the weak interaction (e.g. constraints on the top quark mass and on the masses of supersymmetric particles) from radiative B penguin decays such as $B \rightarrow K^*\gamma$ which should be observable in the next generation of experiments. In the case of B penguins, the contributions from the rescattering process

$$B^0 \rightarrow \psi K^* \rightarrow \gamma K^*$$

may be the same order of magnitude as the contribution from the short distance W loop diagram with an internal top quark.[23,24]

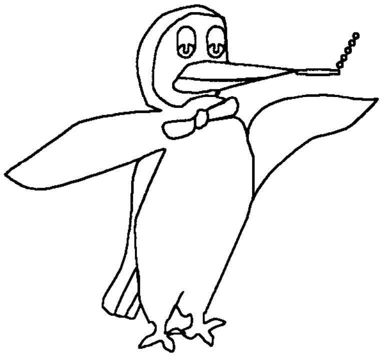

Figure 8. Smoking Penguin

For the decay $D^0 \rightarrow \rho^0\gamma$ where the D^0 is produced at rest, the energy of the photon will be given by:

$$E_\gamma \sim (m_D^2 - m_\rho^2)/2m_D \sim 773\text{MeV}.$$

Due to the small boost and the width of the ρ meson, this will not be a perfectly monochromatic distribution. From similiar considerations, $E_\gamma \sim 769$ MeV for the photon from the decay $D^0 \rightarrow \omega\gamma$.

The most severe experimental background to the mode $D^0 \rightarrow \rho\gamma$ originates from the decay mode $D^0 \rightarrow \pi^+\pi^-\pi^0$ (branching ratio $\sim 10^{-2}$) where one of the photons is undetected or both photons merge. The photon energy spectrum for this decay is rapidly falling as a function of energy; it does, however, extend into the energy range of the photon from the penguin decay. A clear separation is also evident in the beam constrained mass distribution. Further rejection should also be possible using a kinematic fit, although this study has not yet been carried out. If double tags are used, this background can easily be eliminated. There are other experimental handles which will allow this decay to be separated from background even with single tags. Since the photon is transversely polarized, the angle between the π^+ in the ρ rest frame and the D^+ flight direction will have a $\sin^2\theta$ distribution. An efficient photon veto will further suppress the background from $D^0 \rightarrow \pi^-\pi^+\pi^0$. From a Monte Carlo study using single tags, the detection efficiency for $D^0 \rightarrow \rho\gamma$ is about 19%. Therefore, a branching ratio of 10^{-6} will be accessible. If double tags are required for background suppression, 18 double tags will be observed if $Br(D^0 \rightarrow \rho^0\gamma) \sim 1 \times 10^{-5}$ and the detection efficiency is 25%.

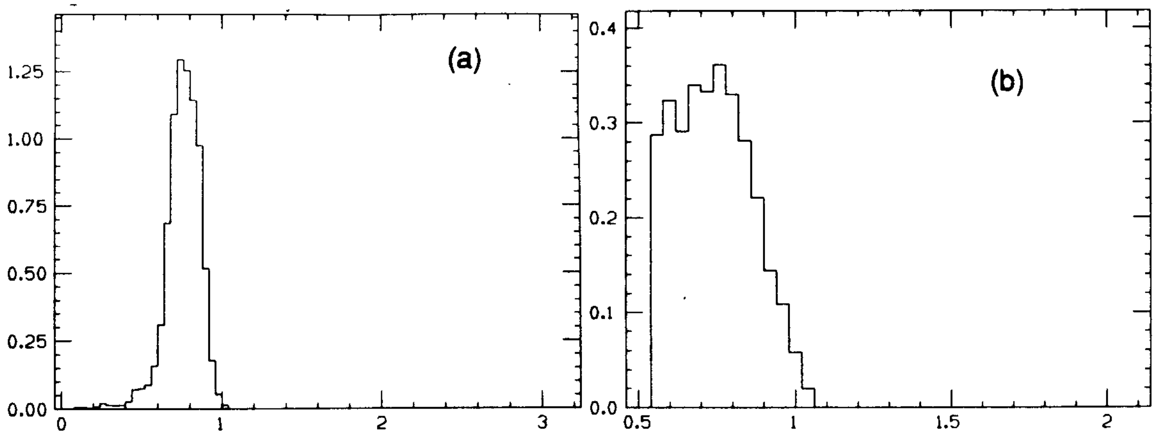

Figure 9. (a) E_γ for $D^0 \rightarrow \rho\gamma$ (b) E_γ for $D^0 \rightarrow \pi^-\pi^+\pi^0$

Backgrounds from $D^0 \rightarrow \pi^-\pi^+$ where one of the pions emits a bremstrahlung photon are expected to be unimportant. These decays are suppressed by at least a factor of $1/\alpha_{EM}$ relative to the Cabibbo suppressed decay and have very soft photon energy spectra typical of bremstrahlung emission [$\propto 1/E_\gamma$]. Similiar considerations apply to $D^0 \rightarrow K^-\pi^+$ decays with bremstrahlung emission (in order for this mode to contribute as a background, the kaon must be misidentified).

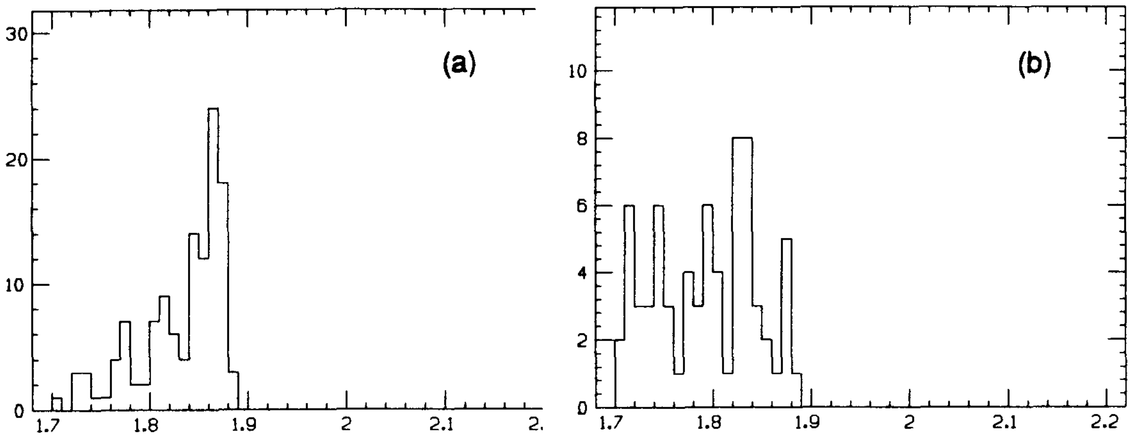

Figure 10. (a) Beam constrained mass for $D^0 \to \rho\gamma$ (b) Beam constrained mass for $D^0 \to \pi^-\pi^+\pi^0$

The sensitivity to $D^0 \to \omega\gamma$ should be comparable. If $\epsilon(D^0 \to \omega\gamma) \approx 8\%$, 5 double tags are expected if the branching ratio is $O(10^{-5})$. This decay may also be accesible using single tags down to branching ratios at the 10^{-6} level. In addition, to the experimental constraints listed above, there is the submass constraint from the $\omega \to \pi^-\pi^+\pi^0$ decay and less smearing of the photon line since the ω meson is narrow.

Summary

At the tau charm factory significant progress in four areas of hadronic charm decay can be made:

1). Detailed measurements of DCSD of D^+ mesons will be possible. Therefore the D^0 and D^+ mesons will be the only heavy quark systems in which the Cabibbo favored, singly Cabibbo suppressed and doubly Cabibbo suppressed decays can be measured.

2). It will be possible to determine D_s absolute branching fractions and observe all the remaining D_s decays.

3). The quasi two body $D \to V\ V$ components of numerous D decay channels can be extracted. The validity of the factorization Ansatz can be tested and the importance of final state interactions can be determined.

4). Hadronic final states in which gluonic penguins diagrams contribute can be precisely measured. Radiative penguins decays (e.g. $D^0 \to \rho^0\gamma$) will also be accessible. Measurements of the latter will be important for understanding the short distance contribution to radiative penguin decays of B mesons.

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