Determination of Charm Hadronic Branching Ratios and New Modes

A. Ryd
Cornell University, Newman Laboratory, Ithaca NY 14853, USA

Recent results from CLEO-c, BABAR, and Belle on measurements of absolute branching fractions of $D$ and $D_s$ mesons are reviewed.

1. Introduction

Precise measurements of the absolute branching fractions for $D$ and $D_s$ meson decays are important as they serve to normalize most $B$ and $B_s$ decays as well as many charm decays. Recent measurements from CLEO-c, BABAR, and Belle for the measurements of the absolute hadronic branching fractions of $D$ and $D_s$ mesons are presented here.

Results from the CLEO-c experiment at the Cornell Electron Positron Storage Ring based on 281 pb$^{-1}$ recorded at the $\psi(3770)$ are presented here for studies of $D^0$ and $D^+$ decays. In addition, CLEO-c has analyzed 195 pb$^{-1}$ of $e^+e^-$ annihilation data near $E_{cm} = 4170$ MeV for studies of $D_s$ decays. These samples provide very clean environments for studying decays of $D$ and $D_s$ mesons. The $\psi(3770)$ produced in the $e^+e^-$ annihilation decays to pairs of $D$ mesons, either $D^+D^-$ or $D^0\bar{D}^0$. In particular, the produced $D$ mesons can not be accompanied by any additional pions. At $E_{cm} = 4170$ MeV $D_s$ mesons are primarily produced as $D^+_sD^-_s$ and $D^+D^-_s$ pairs.

The results from BABAR and Belle use their large samples of $e^+e^-$ data collected by these experiments. The different analyses presented here use integrated luminosities up to 0.55 ab$^{-1}$. For example, Belle has used 0.55 ab$^{-1}$ to study $D^+_s \rightarrow K^+K^-\pi^+$ in exclusive production of $e^+e^- \rightarrow D^+_sD^-_s$. BABAR has studied $D_s \rightarrow \phi \pi$ using a sample of $B \rightarrow D^{(*)}D^{(*)}_{s(j)}$ decays. These examples illustrate that charm produced both in the continuum and in $B$ meson decays are useful for studies of charm at the $B$-factories.

First I will discuss the determination of the absolute $D^0$ and $D^+$ branching fractions. New results from CLEO-c and BABAR are discussed here. Then results for $D_s$ branching fractions from CLEO-c, Belle, and BABAR are presented. Last a few inclusive and rare hadronic decay modes are discussed.

2. Absolute $D$ hadronic branching fractions at CLEO-c

This analysis makes use of a 'double tag' technique initially used by Mark III [4]. In this technique the yields of single tags, where one $D$ meson is reconstructed per event, and double tags, where both $D$ mesons are reconstructed, are determined. The number of single tags, separately for $D$ and $D$ decays, are given by $N_i = \epsilon_i B_i N_{D\bar{D}}$ and $N_j = \epsilon_j B_j N_{D\bar{D}}$ where $\epsilon_i$ and $B_i$ are the efficiency and branching fraction for mode $i$. Similarly, the number of double tags reconstructed are given by $N_{ij} = \epsilon_{ij} B_i B_j N_{D\bar{D}}$ where $i$ and $j$ label the $D$ and $\bar{D}$ mode used to reconstruct the event and $\epsilon_{ij}$ is the efficiency for reconstructing the final state. Combining the equations above and solving for $N_{D\bar{D}}$ gives the number of produced $D\bar{D}$ events as

$$N_{D\bar{D}} = \frac{N_i N_j \epsilon_{ij}}{\epsilon_{ij}}$$

and the branching fractions

$$B_i = \frac{N_{ij}}{N_j \epsilon_{ij}}.$$

In this analysis CLEO-c determine all the single tag and double tag yields in data, determine the efficiencies from Monte Carlo simulations of the detector response, and extract the branching fractions and $D\bar{D}$ yields from a combined fit to all measured data yields.

This analysis uses three $D^0$ decays ($D^0 \rightarrow K^-\pi^+$, $D^0 \rightarrow K^-\pi^+\pi^0$, and $D^0 \rightarrow K^-\pi^+\pi^-\pi^0$) and six $D^+$ modes ($D^+ \rightarrow K^-\pi^+\pi^0$, $D^+ \rightarrow K^-\pi^+\pi^-\pi^0$, $D^+ \rightarrow K_S^0\pi^+$, $D^+ \rightarrow K_S^0\pi^-\pi^0$, $D^+ \rightarrow K_S^0\pi^+\pi^-\pi^0$, and $D^+ \rightarrow K^-\pi^+\pi^0$). The single tag yields are shown in Fig. 1. The combined double tag yields are shown in Fig. 2 for charged and neutral $D$ modes separately. The scale of the statistical errors on the branching fractions are set by the number of double tags and precisions of $\approx 0.8\%$ and $\approx 1.0\%$ are obtained for the neutral and charged modes respectively. The branching fractions obtained are summarized in Table I.

CLEO-c has presented updated results for these branching fractions since these results were presented. The new results, including $B(D^0 \rightarrow K^-\pi^+) = (3.891 \pm 0.035 \pm 0.059 \pm 0.035)\%$, are consistent with the preliminary results presented here. The last error is the uncertainty due to final state radiation.

3. Measurement of $B(D^0 \rightarrow K^-\pi^+)$ at BABAR

BABAR has used a sample of 210 fb$^{-1}$ of $e^+e^-$ data collected at the $\Upsilon(4S)$ resonance to study the
decay $D^0 \to K^- \pi^+$ decay [3]. They use semileptonic $B$ decays, $\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}$ followed by $D^{*+} \to D^0 \pi^+$, where they use the lepton in the $B$ decay and the slow pion from the $D^*$ to tag the signal. As the energy release in the $D^*$ decay is very small the reconstructed slow pion momentum can be used to estimate the four-momentum of the $D^*$ — the slow pion and the $D^*$ have approximately the same velocity. BABAR extracts the number of $\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}$ decays using the missing mass squared, $M^2_\ell$, against the $D^*$ and the lepton. The $M^2_\ell$ distribution is shown in Fig. 3. A clear signal is observed for $M^2_\ell > -2.0$ GeV$^2$. However, there are substantial backgrounds that need to be subtracted due to combinatorial backgrounds in $B\bar{B}$ events and continuum production. Table I summarizes the event yields for the inclusive $\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}$ reconstruction in the column labeled 'Inclusive'. BABAR finds 2,170,640 ± 3,040 events.

$\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}$ decays followed by $D^{*+} \to D^0 \pi^+$. The next step in this analysis is to use this sample of events and reconstruct the $D^0 \to K^- \pi^+$ decay. To extract a clean signal BABAR studies the mass difference $\Delta M \equiv m_{K\pi\pi} - m_{K\pi}$ where $\pi_s$ indicate the slow pion from the $D^*$ decay. The mass difference is shown in Fig. 4. The yields for this 'Exclusive' analysis are given in Table II. Using simulated events BABAR determine an efficiency of $39.96 \pm 0.09\%$ for reconstructing the $D^0 \to K^- \pi^+$ final state. Combining this with the data yields given above BABAR determines $B(D^0 \to K^- \pi^+) = (4.007 \pm 0.037 \pm 0.070)\%$.

This is slightly larger than the branching fraction CLEO-c obtained, but within errors they are consistent.
Table II Event yields for the inclusive $\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}$ reconstruction and the exclusive analysis where the $D^0 \rightarrow K^- \pi^+$ final state is reconstructed in the BABAR analysis to determine the branching fraction for $D^0 \rightarrow K^- \pi^+$ decay.

| Source             | Inclusive | Exclusive |
|--------------------|-----------|-----------|
| Data               | 4, 412, 390 ± 2100 | 47, 270 ± 220 |
| Continuum          | 460, 030 ± 2990 | 3, 090 ± 170 |
| Combinatorial $BB$ | 1, 781, 720 ± 680 | 8, 190 ± 50 |
| Peaking            | 1, 630 ± 80    |           |
| Cabibbo suppressed | 550 ± 10      |           |
| Signal             | 2, 170, 640 ± 3, 040 | 33, 810 ± 290 |

Figure 4: The $\Delta M$ distribution for the reconstructed $D^0 \rightarrow K^- \pi^+$ candidates in events with a $\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}$ tag. (From Ref. [3].)

Figure 5: Single tag yields for $D_s$ modes used in the CLEO-c analysis.

4. Absolute branching fractions for hadronic $D_s$ decays at CLEO-c

This analysis uses a sample of 195 pb$^{-1}$ of data recorded at a center-of-mass energy of 4170 MeV. At this energy $D_s$ mesons are produced, predominantly, as $D_s^- D_s^{*-}$ or $D_s^- D_s^{*-}$ pairs. CLEO-c uses the same tagging technique as for the hadronic $D$ branching fractions; they reconstruct samples of single tags and double tags and use this to extract the branching fractions.

CLEO-c studies six $D_s$ final states ($D_s^+ \rightarrow K^0_s K^+$, $D_s^+ \rightarrow K^+ K^- \pi^+$, $D_s^0 \rightarrow K^+ K^- \pi^+$, $D_s^+ \rightarrow \pi^+ \pi^- \pi^+$, $D_s^+ \rightarrow \eta \pi^+$, and $D_s^+ \rightarrow \eta' \pi^+$). The single tag event yields are shown in Fig. 5. The double tag yields are extracted by a cut-and-count procedure in the plot of the invariant mass of the $D_s^+$ vs. $D_s^-$. This plot is shown in Fig. 6. Backgrounds are subtracted from the sidebands indicated in the plot and a total of 471 double tag events are found.

From these yields CLEO-c determines the branching fractions listed in Table III. CLEO-c is not quoting branching fractions for $D_s^+ \rightarrow \phi \pi^+$ as the $\phi$ signal is not well defined. In particular, the $\phi$ resonance interferes with the $f_0$ resonance. CLEO-c reports preliminary results for partial branching fractions for $D_s^+ \rightarrow K^+ K^- \pi^+$ in restricted invariant mass ranges of $m_{K K}$ near the $\phi$ resonance. In particular, for a 10 MeV cut around the $\phi$ mass the partial branching fraction of $(1.98 \pm 0.12 \pm 0.09)$% is found while for a 20 MeV cut the corresponding branching fraction is $(2.25 \pm 0.13 \pm 0.12)$%.

Since these results were presented CLEO-c has
updated this analysis to include 298 pb$^{-1}$ of data recorded at the $E_{\text{cm}} = 4170$ MeV. In addition to the six mode used in the analysis described above CLEO-c also uses $D^{*+} \rightarrow K^+\pi^+\pi^-$ and $D^{*+} \rightarrow K_S^0 K^-\pi^+\pi^-$. Among the updated results is the branching fraction $B(D^{*+} \rightarrow K^+K^-\pi^+) = (5.67 \pm 0.24 \pm 0.18)^\%$, in good agreement with the preliminary result presented above.

5. Belle study of $D_s^+ \rightarrow K^+K^-\pi^+$

Using 0.55 ab$^{-1}$ of $e^+e^-$ data recorded with the Belle detector at KEKB the Belle collaboration has studied the process $e^+e^- \rightarrow D^{*+}D^{*+}_s$ followed by $D^{*+}_s \rightarrow D^{*0}K^-$ and $D^+_s \rightarrow D^+_s\gamma$. The final state is reconstructed in two ways; either by partially reconstructing the $D^{*+}_s$ or the $D^+_s$.

Belle obtains the branching fraction $B(D^+_s \rightarrow K^+K^-\pi^+) = (4.0 \pm 0.4 \pm 0.4)^\%$. This is somewhat lower than the CLEO-c result presented in the previous section.

6. BABAR studies of $D_s \rightarrow \phi\pi$

An earlier BABAR study has used $B \rightarrow D^*D^*_s$ decays and a technique of partially reconstructing either the $D^*$ or the $D^*_s$ to measure the $D_s \rightarrow \phi\pi$ branching fraction. They quote $B(D^*_s \rightarrow \phi\pi^+) = (4.81 \pm 0.52 \pm 0.38)^\%$ based on a sample of $123 \times 10^6 BB$ decays. More recently BABAR has presented preliminary results based on 210 fb$^{-1}$ of data where they use a tag technique in which one $B$ is fully reconstructed. In events with one fully reconstructed $B$ candidate BABAR reconstructs one additional $D^{(*)}$ or $D^{(*)}_{s(J)}$ meson. Then they look at the recoil mass against this reconstructed candidate. The recoil masses are shown in Figs. 7 and 8.

From these modes BABAR extracts $B(D_{sJ}(2460)^- \rightarrow D^{*0}\pi^0) = (56 \pm 13 \pm 9)^\%$ and $B(D_{sJ}(2460)^- \rightarrow D^{*+}\gamma) = (16 \pm 4 \pm 3)^\%$ in addition to $B(D_s^- \rightarrow \phi\pi^+) = (4.62 \pm 0.36 \pm 0.50)^\%$.

7. Inclusive measurements of $\eta, \eta'$, and $\phi$ production in $D$ and $D_s$ decays

Using samples of tagged $D$ and $D_s$ decays CLEO-c has measured the inclusive production of $\eta, \eta'$, and $\phi$ mesons by looking at the recoil against the tag. The results are summarized in Table XV. The knowledge of inclusive measurements before this CLEO-c
CLEO-c and BABAR finds branching fractions in good agreement with each other, \( \mathcal{B}(D^+ \to K^+\pi^0) = (2.24 \pm 0.36 \pm 0.15 \pm 0.08) \times 10^{-4} \) and \( \mathcal{B}(D^+ \to K^+\pi^0) = (2.52\pm0.46\pm0.24\pm0.08) \times 10^{-4} \) respectively.

9. Modes with \( K_L^0 \) or \( K_S^0 \) in the final states

It has commonly been assumed that \( \Gamma(D \to K_S^0 X) = \Gamma(D \to K_L^0 X) \). However, as pointed out by Bigi and Yamamoto\(^\text{[11]}\) this is not generally true as for many \( D \) decays there are contributions from Cabibbo favored and Cabibbo suppressed decays that interfere and contributes differently to final states with \( K_S^0 \) and \( K_L^0 \). As an example consider \( D^0 \to K_S^0 \phi^0 \). Contributions to these final states involve the Cabibbo favored decay \( D^0 \to K^0\pi^0 \) as well as the Cabibbo suppressed decay \( D^0 \to K^0\pi^0 \). However, we don’t observe the \( K^0 \) and the \( \phi^0 \) but rather the \( K_S^0 \) and the \( K_L^0 \). As these two amplitudes interfere constructively to form the \( K_S^0 \) final state we will see a rate asymmetry. Based on factorization Bigi and Yamamoto predicted

\[
R(D^0) \equiv \frac{\Gamma(D^0 \to K_S^0\pi^0) - \Gamma(D^0 \to K_L^0\pi^0)}{\Gamma(D^0 \to K_S^0\pi^0) + \Gamma(D^0 \to K_L^0\pi^0)} \approx 2\tan^2\theta_C \approx 0.11.
\]

Using tagged \( D \) mesons CLEO-c has measured this asymmetry and obtained

\[
R(D^0) = 0.122 \pm 0.024 \pm 0.030
\]

which is in good agreement with the prediction.

Similarly, CLEO-c has also measured the corresponding asymmetry in charged \( D \) mesons and obtained

\[
R(D^+) = \frac{\Gamma(D^+ \to K_S^0\pi^+)}{\Gamma(D^+ \to K_S^0\pi^+) + \Gamma(D^+ \to K_L^0\pi^+)} = 0.030 \pm 0.023 \pm 0.025.
\]

Prediction of the asymmetry in charged \( D \) decays is more involved. D.-N. Gao predicts\(^\text{[12]}\) this asymmetry to be in the range 0.035 to 0.044, which is consistent with the observed asymmetry.

10. Summary

Recently there has been a lot of progress on the determination of absolute hadronic branching fractions of \( D \) and \( D_s \) mesons. Here recent results from CLEO-c and the B-factory experiments, BABAR and Belle, were reported. CLEO-c uses the extremely clean environment at threshold for these measurements while...
the B-factory experiments use their very large data
samples to explore partial reconstruction techniques
to determine the absolute hadronic branching frac-
tions.

Acknowledgments

This work was supported by the National Science
Foundation grant PHY-0202078 and by the Alfred
P. Sloan foundation.

References

[1] R. M. Baltrusaitis et al. (Mark III Collab.),
Phys. Rev. Lett. 56, 2140 (1986); J. Adler et al.
(Mark III Collab.), Phys. Rev. Lett. 60, 89 (1988).
[2] Q. He et al. (CLEO Collab.), Phys. Rev. Lett. 95,
121801 (2005).
[3] K. Abe et al. (Belle Collab.),
arXiv:hep-ex/0701053 (2007).
[4] A. Ryd (on behalf of the CLEO Collab.), “CLEO-
c $D$ and $D_s$ Hadronic Decays”, presented at
Charm2007, Ithaca NY, August 5-8, 2007.
[5] B. Aubert et al. (BABAR Collab.),
arXiv:0704.2080 [hep-ex] (2007).
[6] B. Aubert et al. (BABAR Collab.),
Phys. Rev. D71, 091104(R) (2005).
[7] B. Aubert et al. (BABAR Collab.),
Phys. Rev. D74, 031103(R) (2006).
[8] G. S. Huang et al. (CLEO Collab.),
Phys. Rev. D74, 112005 (2006).
[9] S. A. Dytman et al. (CLEO Collab.),
Phys. Rev. D74, 071102(R) (2006).
[10] B. Aubert et al. (BABAR Collab.),
Phys. Rev. D74, 011107(R) (2006).
[11] I. I. Bigi and H. Yamamoto Phys. Lett. B349,
363 (1995).
[12] D.-N. Gao, Phys. Lett. B645, 59 (2007).