Determination of Charm Hadronic Branching Ratios and New Modes

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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 discussed here. Then results of single tags, where one $D$ meson is reconstructed, are determined. The number of single tags, separately for $D$ and $D$, decays, are given by $N_i = \epsilon_i B_i N_{DD}$ and $N_j = \epsilon_j B_j N_{DD}$ 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 $N_{ij} = \epsilon_{ij} B_i B_j N_{DD}$ where $i$ and $j$ label the $D$ and $D$ mode used to reconstruct the event and $\epsilon_{ij}$ is the efficiency for reconstructing the final state. Combining the equations above and solving for $N_{DD}$ gives the number of produced $DD$ events as

$$N_{DD} = \frac{N_i N_j}{\epsilon_{ij} \epsilon_{ij}}$$

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 $DD$ 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 $D^0 \rightarrow K^-\pi^+\pi^0\pi^0$) and six $D$ modes ($D^+ \rightarrow K^-\pi^+\pi^+\pi^0$, $D^+ \rightarrow K^-\pi^+\pi^0\pi^0$, $D^+ \rightarrow K^0_S\pi^+$, $D^+ \rightarrow K^0_S\pi^+\pi^0$, $D^+ \rightarrow K^0_S\pi^+\pi^0\pi^0$, and $D^+ \rightarrow K^-\pi^+\pi^0\pi^0$). 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 1.

CLEO-c has presented updated results for these branching fractions[3] 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.

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

This analysis makes use of a ’double tag‘ technique initially used by Mark III[5]. 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 $N_i = \epsilon_i B_i N_{DD}$ and $N_j = \epsilon_j B_j N_{DD}$ 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 $N_{ij} = \epsilon_{ij} B_i B_j N_{DD}$ where $i$ and $j$ label the $D$ and $D$ mode used to reconstruct the event and $\epsilon_{ij}$ is the efficiency for reconstructing the final state. Combining the equations above and solving for $N_{DD}$ gives the number of produced $DD$ events as

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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 \cite{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 $B^0 \to D^{*+} \ell^- \bar{\nu}$ decays using the missing mass squared, $M^2_{bc}$, against $D^*$ and the lepton. The $M^2_{bc}$ distribution is shown in Fig. 3. A clear signal is observed for $M^2_{bc} > -2.0$ 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 $B^0 \to D^{*+} \ell^- \bar{\nu}$ reconstruction in the column labeled 'Inclusive'. BABAR finds 2,170,640 $\pm$ 3,040 $B^0 \to D^{*+} \ell^- \bar{\nu}$ 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 $\Delta M \equiv m_{K^- \pi^+} - m_{K^0 \pi^0}$ 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 $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ reconstruction and the exclusive analysis where the $D^0 \to K^-\pi^+$ final state is reconstructed in the BABAR analysis to determine the branching fraction for $D^0 \to K^-\pi^+$ decay.

<table>
<thead>
<tr>
<th>Source</th>
<th>Inclusive</th>
<th>Exclusive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>4, 412, 390 ± 2100</td>
<td>47, 270 ± 220</td>
</tr>
<tr>
<td>Continuum</td>
<td>460, 030 ± 2990</td>
<td>3, 090 ± 170</td>
</tr>
<tr>
<td>Combinatorial $B\bar{B}$</td>
<td>1, 781, 720 ± 680</td>
<td>8, 190 ± 50</td>
</tr>
<tr>
<td>Peaking</td>
<td>1, 630 ± 80</td>
<td></td>
</tr>
<tr>
<td>Cabibbo suppressed</td>
<td>550 ± 10</td>
<td></td>
</tr>
<tr>
<td>Signal</td>
<td>2, 170, 640 ± 3, 040 33, 810 ± 290</td>
<td></td>
</tr>
</tbody>
</table>
Figure 6: Double tag yields for $D_s$ modes used in the CLEO-c analysis.

Table III Preliminary branching fractions for $D_s$ decays determined in the CLEO-c analysis.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Branching Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(D_s^+ \rightarrow K_\ell^0 K^+)$</td>
<td>$1.50 \pm 0.09 \pm 0.05$</td>
</tr>
<tr>
<td>$B(D_s^+ \rightarrow K^+ K^- \pi^+)$</td>
<td>$5.57 \pm 0.30 \pm 0.19$</td>
</tr>
<tr>
<td>$B(D_s^+ \rightarrow K^+ K^- \pi^+ \pi^0)$</td>
<td>$5.62 \pm 0.33 \pm 0.51$</td>
</tr>
<tr>
<td>$B(D_s^+ \rightarrow \pi^+ \pi^- \pi^0)$</td>
<td>$1.12 \pm 0.08 \pm 0.05$</td>
</tr>
<tr>
<td>$B(D_s^+ \rightarrow \eta \pi^0)$</td>
<td>$1.47 \pm 0.12 \pm 0.14$</td>
</tr>
<tr>
<td>$B(D_s^+ \rightarrow \eta' \pi^0)$</td>
<td>$4.02 \pm 0.27 \pm 0.30$</td>
</tr>
</tbody>
</table>

updated this analysis to include 298 pb$^{-1}$ of data recorded at the $E_{cm} = 4170$ MeV [4]. In addition to the six mode used in the analysis described above CLEO-c also uses $D_s^+ \rightarrow K^+ \pi^+ \pi^-$ and $D_s^+ \rightarrow K_\ell^0 K^- \pi^+ \pi^-$. Among the updated results is the branching fraction $B(D_s^+ \rightarrow K^+ \pi^- \pi^+) = (5.67 \pm 0.24 \pm 0.18)\%$, 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 $e^+e^- \rightarrow D_s^+ D_{s1}^-$ followed by $D_{s1}^+ \rightarrow D^{*0} K^-$ and $D_s^+ \rightarrow D_s^+ \pi^-$. The final state is reconstructed in two ways; either by partially reconstructing the $D_{s1}$ 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 $D_s^{(*)}$ 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 $B(D_{sJ}(2460)^- \rightarrow D_s^+ \pi^0) = (56 \pm 13 \pm 9)\%$ and $B(D_{sJ}(2460)^- \rightarrow D_s^- \gamma) = (16 \pm 4 \pm 3)\%$ 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 IV. The knowledge of inclusive measurements before this CLEO-c
measurement was poor, besides limits only $B(D^0 \to \phi X) = 1.7 \pm 0.8$ was measured. As expected the $\eta, \eta'$, and $\phi$ rates are much higher in $D_s$ decays.

8. The doubly Cabibbo suppressed decay $D^+ \to K^+\pi^0$

Both CLEO-c and BABAR have studied the doubly Cabibbo suppressed decay $D^+ \to K^+\pi^0$. CLEO-c has reconstructed candidates in a 281 pb$^{-1}$ sample of $e^+e^-$ data recorded at the $\psi(3770)$. BABAR has used a sample of 124 fb$^{-1}$ recorded at the $\Upsilon(4S)$.

9. Modes with $K^0_L$ or $K^0_S$ in the final states

It has commonly been assumed that $\Gamma(D \to K^0_S X) = \Gamma(D \to K^0_L X)$. However, as pointed out by Bigi and Yamamoto, this is not generally true as for many $D$ decays there are contributions from Cabibbo favored and Cabibbo suppressed decays that interfere and contribute differently to final states with $K^0_S$ and $K^0_L$. As an example consider $D^0 \to K^0_S\pi^0$. 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 $K^0_S$ but rather the $K^0_S$ and the $K^0_L$. As these two amplitudes interfere constructively to form the $K^0_S$ final state we will see a rate asymmetry. Based on factorization Bigi and Yamamoto predicted

$$R(D^0) = \frac{\Gamma(D^0 \to K^0_S\pi^0) - \Gamma(D^0 \to K^0_L\pi^0)}{\Gamma(D^0 \to K^0_S\pi^0) + \Gamma(D^0 \to K^0_L\pi^0)} \approx 2\tan^2\theta_C \approx 0.11.$$  

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

$$R(D^+) = \frac{\Gamma(D^+ \to K^0_S\pi^+) - \Gamma(D^+ \to K^0_L\pi^+)}{\Gamma(D^+ \to K^0_S\pi^+) + \Gamma(D^+ \to K^0_L\pi^+)} = 0.030 \pm 0.023 \pm 0.025.$$

Prediction of the asymmetry in charged $D$ decays is more involved. D.-N. Gao predicts 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 fractions.

Acknowledgments

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References