Open charm $B$ decays

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New results on $B$ decays to charm-related modes from the Belle and CLEO experiments are presented.

1. Introduction

Studies of charm-related $B$ decays provide information about the dynamics of $B$ meson decays. Results of these fields can be used to check predictions of theoretical models. Recently new results appeared from the $B$ factories at KEK and SLAC and from CLEO. This report covers the recent results on this subject from Belle and CLEO.

The CLEO results are based on a 9.15 fb$^{-1}$ data sample collected at the center-of-mass (CM) energy of the $\Upsilon(4S)$ resonance, while the Belle results are obtained using various data samples from 29.2 fb$^{-1}$ to 78.7 fb$^{-1}$. Both group identify $B$ candidates by two kinematic variables: the energy difference, $\Delta E = (\sum_i E_i) - E_b$, and the beam constrained mass, $M_{bc} = \sqrt{E_b^2 - (\sum_i \vec{p}_i)^2}$, where $E_b = \sqrt{s}/2$ is the beam energy and $\vec{p}_i$ and $E_i$ are the momenta and energies of the decay products of the $B$ meson in the CM frame.

2. $B \to D\pi$ Isospin Analysis (CLEO Collaboration)

Precise measurements of the $B \to D\pi$ branching fractions can be used to extract of the strong phase difference $\delta_I$ between the $I = 1/2$ and $I = 3/2$ isospin amplitudes in the $D\pi$ system. Observation of the color-suppressed $B^0 \to D^0\pi^0$ decay completed the measurements of the $D\pi$ final states. Recently CLEO collaboration improved the accuracy in the $B^- \to D^0\pi^-$ and $B^0 \to D^+\pi^-$ branching fractions, these results are presented here.

$D^0$ mesons are reconstructed using three decay channels $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$ and $K^-\pi^+\pi^0$. Charged $D$ mesons are reconstructed via the mode $K^-\pi^+\pi^+$. In each case, $D$ candidates are required to have an invariant mass within $3\sigma$ of the nominal $D$ mass. The fitted $M_{bc}$ distributions for each of the $D$ decay modes are presented in Fig. 1. The following branching fractions have been obtained: $B(B^- \to D^0\pi^-) = (4.97 \pm 0.12 \pm 0.29 \pm 0.22) \times 10^{-3}$ and $B(B^0 \to D^+\pi^-) = (2.68 \pm 0.12 \pm 0.24 \pm 0.12) \times 10^{-3}$. Here the first error is statistical, the second is systematic and the third one is a separate systematic error due to the experimental uncertainty of the production fractions of charged and neutral $B$ mesons from $\Upsilon(4S)$ decays. Using the measurements of $B(B^0 \to D^0\pi^0)$, $\cos \delta_I = 0.863^{+0.024+0.036+0.038}_{-0.023-0.035-0.030}$ has been obtained. The difference of $\delta_I$ from zero is $2.3\sigma$ indicating the presence of final state interactions in $B \to D\pi$ decays.
Table 1
The signal yields and branching fractions for the $B^0 \rightarrow D_s^+ K^-$ and $B^0 \rightarrow D_s^+ \pi^-$ decay channels.

| Mode            | $M(D_s) - \Delta E$ yield | $M(D_s)$ yield | $\Delta E$ yield | $B \ (10^{-3})$ | Significance |
|-----------------|---------------------------|----------------|------------------|-----------------|--------------|
| $B^0 \rightarrow D_s^+ K^-$ | $16.4^{+3.9}_{-4.4}$     | $15.0^{+4.9}_{-3.8}$   | $17.5^{+4.2}_{-1.6}$   | $4.6^{+1.2}_{-1.0}$   | $6.4\sigma$ |
| $B^0 \rightarrow D_s^+ \pi^-$ | $10.1^{+3.7}_{-4.4}$     | $10.3^{+4.4}_{-3.4}$   | $9.5^{+4.5}_{-3.8}$   | $2.4^{+0.8}_{-0.7}$   | $3.6\sigma$  |

Figure 2. The $\Delta E$ spectra for the $B^0 \rightarrow D_s^+ K^-$ (top) and $B^0 \rightarrow D_s^+ \pi^-$ (bottom) candidates.

Figure 3. The $M(D_s)$ spectra for the $B^0 \rightarrow D_s^+ K^-$ (top) and $B^0 \rightarrow D_s^+ \pi^-$ (bottom) candidates.

3. $B \rightarrow D_s \pi/K$ (Belle Collaboration)

The decay $B^0 \rightarrow D_s^+ \pi^-$ is expected to be dominated by a $b \rightarrow u$ transition, with no penguin contribution. Therefore, it can provide a way to determine the CKM matrix element, $|V_{ub}|$. The decay $B^0 \rightarrow D_s^+ K^-$ can occur via $W$-exchange or final state rescattering and cannot be described by a spectator graph. The measurement of this decay mode can be used to estimate $W$-exchange or final state rescattering contributions in other $B$ decays. Only upper limits have been reported for these decays by CLEO [6]. Recently, the BaBar collaboration presented evidence for the $B^0 \rightarrow D_s^+ \pi^-$ decay [7].

Here Belle results [8,9] on a search for these decays are presented. The $D_s^+$ candidates are reconstructed in the $D_s^+ \rightarrow \phi \pi^+, K^{*0}K^+$ and $K_S^0 K^+$ decay channels. $D_s^+$ candidates are combined with a charged kaon or pion to form a $B$ meson. To extract the signal, a binned maximum likelihood fit to the two-dimensional distribution of data in $M(D_s)$ and $\Delta E$ is performed.

The $D_s^+$ signal is described by a two-dimensional Gaussian, while the background function includes three components: combinatorial (flat in $M(D_s)$ and $\Delta E$), $q\bar{q}$ events that peak in $M(D_s)$ and are flat in $\Delta E$, and $B$ decay events that peak in $\Delta E$ and are flat in $M(D_s)$. The levels of three background components are allowed to vary independently in the three reconstructed $D_s^+$ modes.

Figures 2 and 3 show the $\Delta E$ and $M(D_s)$ projections for events from the signal region, the fitted signal plus background combined shape by solid lines and background shape including the peaking background by dashed lines. In addition to the clear signals at the $D_s^+$ mass in Fig. 3, also seen are peaks at the $D^+$ mass, corresponding to the $B^0 \rightarrow D^+ \pi^-$ and $B^0 \rightarrow D^+ K^-$ decays. The fit results are given in Table 1. The results of one-dimensional fits to the $M(D_s)$ and $\Delta E$ distributions are also shown in Table 3 for comparison. A statistically significant signal ($6.4\sigma$) is observed for the $B^0 \rightarrow D_s^+ K^-$ decay channel, while only evidence is reported for the $B^0 \rightarrow D_s^+ \pi^-$ decay.
Table 2
The branching fractions and resonance parameters for the $D^{(*)+}\pi^-\pi^-$ final states.

| Mode | $B(B^{-}\rightarrow D_{X}\pi^-)B(D_{X}\rightarrow D^{(*)+}\pi^-)$ | $M(D_{X})$, MeV/$c^2$ | $\Gamma(D_{X})$, MeV/$c^2$ |
|------|-------------------------------------------------|----------------|----------------|
| $B^{-}\rightarrow D^{0}\pi^-\rightarrow D^{+}\pi^-\pi^-$ | $(3.5\pm0.3\pm0.5)x10^{-4}$ | $2460.7\pm2.1\pm3.1$ | $46.4\pm4.4\pm3.1$ |
| $B^{-}\rightarrow D_{1}^{0}\pi^-\rightarrow D^{+}\pi^-\pi^-$ | $(5.5\pm0.5\pm0.8)x10^{-4}$ | $2290\pm22\pm20$ | $300\pm30\pm30$ |
| $B^{-}\rightarrow D^{*0}\pi^-\rightarrow D^{+}\pi^-\pi^-$ | $(1.4\pm0.3\pm0.2)x10^{-4}$ | $2423.9\pm1.7\pm0.2$ | $26.7\pm3.1\pm2.2$ |
| $B^{-}\rightarrow D_{1}^{*0}\pi^-\rightarrow D^{*+}\pi^-\pi^-$ | $(6.2\pm0.5\pm1.1)x10^{-4}$ | $2290\pm22\pm20$ | $300\pm30\pm30$ |
| $B^{-}\rightarrow D^{*20}\pi^-\rightarrow D^{*+}\pi^-\pi^-$ | $(2.0\pm0.3\pm0.5)x10^{-4}$ | $2400\pm30\pm20$ | $380\pm100\pm100$ |

Figure 4. The $\Delta E$ distributions for the $B^{-}\rightarrow D^{+}\pi^-\pi^-$ (left) and $B^{-}\rightarrow D^{*+}\pi^-\pi^-$ (right) candidates.

Figure 5. The Dalitz plot distributions for $B^{-}\rightarrow D^{+}\pi^-\pi^-$ (left) and $B^{-}\rightarrow D^{*+}\pi^-\pi^-$ (right) candidates.

4. $B^{-}\rightarrow D^{(*)+}\pi^-\pi^-$ (Belle Collaboration)

A study of charmed meson production in $B$ decays provides an opportunity to test predictions of Heavy Quark Effective Theory (HQET) and QCD sum rules. $B$ decays to $D^{(*)+}\pi$ final states are the dominant hadronic $B$ decay modes and are measured quite well [10]. The large data sample accumulated in the Belle experiment allows to study production of $D$ meson exited states. 

$D^{**}$s are P-wave excitations of quark-antiquark systems that contain one charmed and one light ($u,d$) quark. The $B\rightarrow D^{**}\pi$ decays have been studied by Belle [14] using the $D^{+}\pi^-\pi^-$ and the $D^{*+}\pi^-\pi^-$ final states.

Figure 4 shows the $\Delta E$ distributions for the $B^{-}\rightarrow D^{+}\pi^-\pi^-$ and $B^{-}\rightarrow D^{*+}\pi^-\pi^-$ candidates. The following branching fractions are measured: $\mathcal{B}(B^{-}\rightarrow D^{+}\pi^-\pi^-) = (1.07\pm0.05\pm0.16)\times10^{-3}$ and $\mathcal{B}(B^{-}\rightarrow D^{*+}\pi^-\pi^-) = (1.24\pm0.07\pm0.22)\times10^{-3}$, without any assumption about the intermediate final states.

To study the dynamics of $B\rightarrow D^{(*)+}\pi\pi$ decays, an analysis of the Dalitz plots shown in Fig. 5 is performed. The fit to the $D^{+}\pi^-\pi^-$ Dalitz plot includes three final states: $D_{2}^{*0}\pi^-$, $D_{0}^{*0}\pi^-$ and the contribution of the process with virtual $D^{*0}\pi$ production($D^{*0}\pi^-$). The results are presented in Table 3.

Two additional degrees of freedom should be taken into account in the $D^{*+}\pi^-\pi^-$ final state: the angle ($\alpha$) between the pion from the $D^{*+}$ decay and the pion from the $D^{*}$ decay in the $D^{*}$ rest frame and the azimuthal angle ($\gamma$) of this particle relative to the plane of the $B^{-}\rightarrow D^{*+}\pi^-\pi^-$ decay. The fit to the $D^{*+}\pi^-\pi^-$ distribution includes three final states: $D_{1}\pi^-$, $D_{2}^{*0}\pi^-$ and $D_{3}^{*0}\pi^-$.

Using these measurements the ratio of $D_{2}^{*0}$ branching fractions $h = B(D_{2}^{*0}\rightarrow D^{*+}\pi^-)/B(D_{2}^{*0}\rightarrow D^{+}\pi^-) = 1.77\pm0.49$, consistent with the world average $h = 2.3\pm0.6$ [10], is obtained. The measured ratio $R = B(B^{-}\rightarrow D_{2}^{*0}\pi^-)/B(B^{-}\rightarrow D_{1}^{0}\pi^-) = 0.89\pm0.14$ is lower than the CLEO measurement $1.8\pm0.8$ [14] (al-
Figure 6. The $\Delta E$ distributions for (a) $B^0 \to D^0 \pi^+\pi^-$ and (b) $B^{*0} \to D^0 \pi^+\pi^-$ candidates.

though the results are consistent within errors) but is still a factor of 3 larger than the factorization prediction [14]. Belle measurements show that the narrow resonances compose $(33 \pm 4\%)$ of the $D\pi\pi$ decays and $(66 \pm 7\%)$ of the $D^*\pi\pi$ decays. This result is inconsistent with the QCD sum rule prediction and may indicate a large contribution from a color suppressed amplitude.

5. $B^0 \to D^{(*)0}\pi^+\pi^-$ (Belle Collaboration)

Exclusive hadronic decay rates provide important tests of models for $B$ meson decays. The $B^0 \to D^{(*)0}\pi^+\pi^-$ decays provide a precision testing ground for factorization [15] and the possibility to search for resonant substructure in the final state. At present, only an upper limit $\mathcal{B}(B^0 \to D^0\pi^+\pi^-) < 1.6 \times 10^{-3}$ [16] exists.

Here the Belle results [17] on a study of these decays are presented. $D^0$ candidates are reconstructed in the $K^-\pi^+, K^-\pi^+\pi^-\pi^+$ and $K^-\pi^+\pi^0$ final states. Figure 7 shows the $\Delta E$ distributions for the $B^0 \to D^{(*)0}\pi^+\pi^-$ candidates. The following branching fractions are measured:

$\mathcal{B}(B^0 \to D^0\pi^+\pi^-) = (7.5 \pm 0.7 \pm 1.5) \times 10^{-4}$ and

$\mathcal{B}(B^0 \to D^{*0}\pi^+\pi^-) = (6.2 \pm 1.2 \pm 1.7) \times 10^{-4}$.

Figure 7 shows the $\pi^+\pi^-$ invariant mass spectra for the selected events. These distributions are fitted by a sum of the $\rho^{0,\sigma}$ and $f_0(1370)$ resonances. The amplitudes and phases are free parameters in the fit. The branching fraction of $\mathcal{B}(B^0 \to D^3\rho^0) = (3.0 \pm 1.2 \pm 0.4) \times 10^{-4}$ and the 90% CL upper limit $\mathcal{B}(B^0 \to D^{*0}\rho^0) < 5.1 \times 10^{-4}$ are obtained.

Figure 7. The $\pi^+\pi^-$ invariant mass spectra for the (a) $B^0 \to D^0\pi^+\pi^-$ and (b) $B^{*0} \to D^0\pi^+\pi^-$ candidates.

6. $B^- \to D^0K^{*-}$ (Belle Collaboration)

The decay $B^- \to D^0K^{*-}$ can be used for $\phi_3$ determination [18]. This mode has been previously observed by the CLEO Collaboration [19].

$D^0$ mesons are reconstructed in the decay channels $D^0 \to K^-\pi^+, K^-\pi^+\pi^-\pi^+$ and $K^-\pi^+\pi^0$ using a $2\sigma$ mass window from the nominal $D^0$ mass. The $K^{*-}$ candidates are combined from the $K^0_S\pi^-$ pairs.

The $\Delta E$ and $M_{bc}$ distributions are presented in Fig. 8(a) and (b) respectively. A signal of $114.4 \pm 13.5$ events with $10.9\sigma$ statistical significance is observed. The fit results are presented in Table 3. The measured branching fraction $\mathcal{B}(B^- \to D^0K^{*-}) = (5.4 \pm 0.6 \pm 0.8) \times 10^{-4}$ agrees well with the world average [14]. Figure 8 shows the $K^{*-}$ helicity and invariant mass distributions obtained by fitting the $M_{bc}$ spectra in each bin.

Figure 8. The (a) $\Delta E$, (b) $M_{bc}$ distributions for the $B^0 \to D^0K^{*-}$ candidates.
Table 3
The signal yields and branching fractions for the $B^- \to D^0K^*$ decay channel.

| Decay mode | $\Delta E$ yield | $M_{bc}$ yield | $B \times 10^{-3}$ |
|------------|-----------------|---------------|------------------|
| $D^0 \to K^-\pi^+$ | 52.5 $\pm$ 8.1 | 51.6 $\pm$ 8.5 | 6.1 $\pm$ 0.9 $\pm$ 0.8 |
| $D^0 \to K^-\pi^+\pi^0$ | 36.1 $\pm$ 6.8 | 32.9 $\pm$ 6.4 | 5.1 $\pm$ 0.9 $\pm$ 0.7 |
| $D^0 \to K^-\pi^+\pi^-\pi^0$ | 31.0 $\pm$ 7.0 | 29.4 $\pm$ 6.8 | 4.6 $\pm$ 1.1 $\pm$ 0.8 |
| Weighted mean | | | 5.4 $\pm$ 0.9 $\pm$ 0.8 |

![Image](image.png)

Figure 9. The (a) $K^*$ helicity and (b) $K^*-$ invariant mass distributions for the $B^- \to D^0K^*$ signal region.

7. Conclusion

A nonzero strong phase $\delta_I$ is obtained using the CLEO and Belle measurements of the branching fractions $B(B \to D\pi)$. The 2.3$\sigma$ difference from zero indicates the presence of final state interactions in $B \to D\pi$ decays. The observation of the $B^0 \to D^*_sK^-$ decay by Belle emphasizes the importance of $W$ exchange or final state rescattering. In $B^- \to D^{(*)}\pi^-\pi^+$ decays all four $P$-wave $D^*$ have been observed and their parameters have been measured by Belle. For the broad $D^+_s$ and $D^+_s$ states this is the first measurement.

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