Exclusive and Inclusive Decays of B Mesons into D_s Mesons

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We have studied the production of D_s mesons in the decays of B mesons at the $\Upsilon(4S)$ resonance. We report on the first observation of exclusive B-meson decays $B \to D_s^- D^{*+}$, $B \to D_s^- D^+$, and $B \to D_s^- D^0$. We also present a new measurement of the branching ratio and the momentum spectrum for the inclusive decay $B \to D_s X$.

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Exclusive decay modes of B mesons provide a testing ground for the predictions of the theoretical models of heavy-flavor decays. A special class of B-meson decay modes is the exclusive double-charm decays which can arise from the decay chain $b \to cW^- \to c(\bar{c}s)$. Previous studies of the inclusive D_s production in B decays have provided indirect evidence for the presence of such decays through the observation of a peak in the momentum spectrum of D_s mesons.[1] In this Letter, we report on a direct observation of exclusive decays $B \to D_s D$, where D represents either D^0, D^+, or D^{*+}. We also report on an improved measurement of the branching ratio and the momentum spectrum for the inclusive decay $B \to D_s X$. The decay $\bar{B}^0 \to D_s^- \pi^+$ could result from the $b \to u$ coupling and the decay $\bar{B}^0 \to D_s^+ K^-$ from the W-exchange process. We will present upper limits for the branching ratios of these two modes. Throughout this paper charge-conjugate modes are implied.

The data used for this study were collected with the upgraded CLEO detector in the 10-GeV energy region at the Cornell Electron Storage Ring (CESR). The CLEO detector and our event-selection criteria have been described in detail elsewhere.[2] The main modification to the detector has been the installation of a new drift-chamber system with 64 layers of tracking. This improvement results in a momentum resolution given by $(\delta p/p)^2 = (0.23\% p)^2 + (0.7\%)^2$, with p expressed in GeV/c. An rms resolution of 6.5% in the measurement of the specific ionization is obtained.[3] The data consist of 212 pb^{-1} at the $\Upsilon(4S)$, and 101 pb^{-1} at an energy below the $B\bar{B}$ threshold. The $\Upsilon(4S)$ data contain 242000 $B\bar{B}$ events.

The decay mode $D_s^- \to \phi\pi^-$ was used to measure the inclusive D_s^- yield from B-meson decays. The reconstruction procedure for this and other D_s decay modes in the CLEO detector are described in detail elsewhere.[4]

Briefly, ϕ-meson candidates are identified in the mode $\phi \to K^- K^+$ and are combined with the remaining charged tracks in the event to form $\phi\pi$ combinations. We require the measurements of the specific ionization (dE/dx) of charged tracks in the drift chamber to be within 3 standard deviations of the expected value for their mass assignment in the track combination. We also exploit the characteristic angular distribution of the decay $D_s^- \to \phi\pi$ to suppress combinatorial backgrounds.[1,4] The $\phi\pi$ invariant-mass distribution is shown in Fig. 1 for data taken at the $\Upsilon(4S)$. Also shown are data for the nonresonant e^-e^+ annihilation scaled to account for the luminosity and the energy dependence of the cross section. A clear peak at the D_s^- mass is evident in the $\Upsilon(4S)$ data. The mass and the width of the signal are consistent with those expected from the Monte Carlo simulation of the detector.

Subtracting the continuum component and fitting the resulting mass spectrum to a Gaussian representing the signal and a polynomial background shape we find a total of 257 ± 41 D_s mesons from $B\bar{B}$ events in our data sample. By fitting the mass spectra corresponding to momentum bins we determine the momentum distribution of the D_s mesons. The D_s detection efficiency is determined by using a Monte Carlo procedure which includes the effects of geometrical acceptance, tracking, the kinematic requirements, and particle-identification efficiencies. The particle-identification efficiencies are determined using samples of π's, K's, and p's from kinematically identified K_S, ϕ, and Λ decays. The efficiency corrected momentum distribution of D_s^- mesons from B decay is shown in Fig. 2. Integrating this distribution and dividing by the number of B mesons in the data sample, we determine $B(B \to D_s X) B(D_s \to \phi\pi) = (3.06 \pm 0.47) \times 10^{-3}$. This result is consistent with previous measurements.[1]

In order to determine the inclusive branching ratio $B(B \to D_s X)$ we need the absolute branching ratio for the decay $D_s^- \to \phi\pi^-$. Since this has not yet been measured, throughout this paper we use the estimated $B(D_s^- \to \phi\pi^-) = 2\%$, which was obtained using arguments based on the measured charm-hadron cross sections in nonresonant e^+e^- annihilation in the 10-GeV energy region.[4] This gives $B(B \to D_s X) = (15.3 \pm 2.3)\%$.

In the B-meson rest frame, a two-body decay such as $B \to D_s D$ yields a monochromatic momentum spectrum for the D_s meson. At the $\Upsilon(4S)$, however, B mesons are produced with a momentum of about 0.3 GeV/c, which results in a small Doppler broadening of the momentum spectra. The observed hard spectrum (Fig. 2) clearly indicates the presence of two-body modes. We fitted the spectrum to a linear combination of functions representing the two-body double-charm decay modes $B^- \to D_s D$, $B^- \to D_s D^*$, $B^- \to D_s^* D$, and $B^- \to D_s^* D^*$ and a possible three-body process such as $B \to D_s D\pi$. The relative contribution of two-body modes $(B \to D_s D)/(B \to D_s X)$ is determined to be $(56 \pm 10)\%$.[5]

While this inclusive analysis provides the combined rate for the two-body double-charm decays, the determination of the branching ratios for the various modes requires the reconstruction of each decay process. Here we have searched for the modes $B^- \to D_s^- D^0$, $\bar{B}^0 \to D_s^- D^{*+}$, and $\bar{B}^0 \to D_s^- D^+$. Because of the poor resolution and low efficiency of photon identification in the CLEO-I detector, the reconstruction of modes involving D_s^{*-} mesons is not feasible. In order to enhance our reconstruction efficiency, we use most of the known decay modes of the charmed mesons which result in final states containing only charged particles. These are $D_s \to \phi\pi^-$, $K^{*0}K^-$, K^0K^-, $K^{*-}K^0$, and $K^{*-}K^{*0}$;

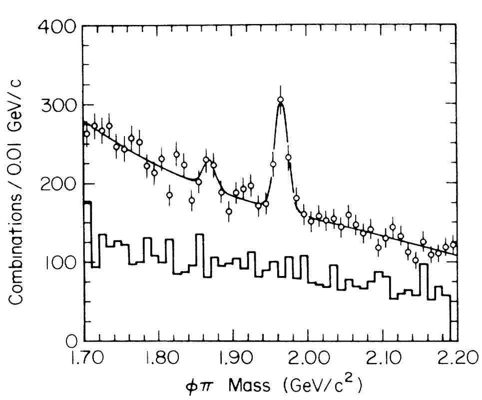

FIG. 1. The $\phi\pi$ mass spectrum for $0.0 < P_{\phi\pi} < 2.5$ GeV/c from $\Upsilon(4S)$ (circles) data and nonresonant e^+e^- annihilation collisions (solid histogram). The smooth curve shows a polynomial background and fits to a D_s peak as well as a peak from the rare decay $D^+ \to \phi\pi^+$.

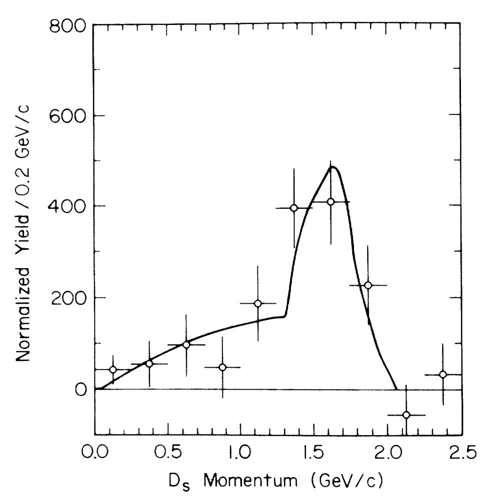

FIG. 2. The momentum distribution of D_s mesons from B decays. The curve is the fit by a linear combination of functions representing the two-body decays $B \to D_s D$ and the three-body process $B \to D_s D\pi$.

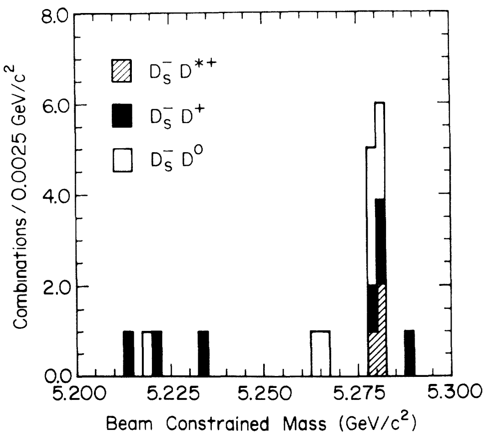

FIG. 3. The distribution of the beam-constrained mass for $B \to D_s D$ candidates.

$D^0 \to K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$, and $K^0\pi^+\pi^+$; $D^+ \to K^-\pi^+\pi^+$, $K^0\pi^+$, and $K^0\pi^+\pi^-\pi^+$; and $D^{*+} \to D^0\pi^+$. Invariant masses of the D candidates were required to be within 2 standard deviations (2×20 MeV) of the known masses of the mesons. B candidates were found by forming D_sD combinations having flavor and sign consistent with the decay chain $b \to c(\bar{c}s)$. Since B mesons are produced as pairs in the process $e^+e^- \to \Upsilon(4S) \to \bar{B}B$, we require that the reconstructed energy of the B candidates be within 3 standard deviations of the beam energy. From Monte Carlo studies, we determine the rms resolution of the difference between the reconstructed energy of B candidates and the beam energy to be about 25 MeV. This requirement also suppresses the "feed-down" background from the decay modes with a missing π^0 or γ, such as $\bar{B}^0 \to D_s^{*-}D^{*+}$, where $D_s^{*-} \to D_s^-\gamma$ or $D^{*+} \to D^+\pi^0$.

We compute the beam-constrained invariant mass M_B of the B candidates from $M_B^2 = E_{\rm beam}^2 - \mathbf{p}_B^2$, where $E_{\rm beam}$ is the beam energy and $\mathbf{p}_B$ is the vector sum of the momenta of tracks forming the B candidate. The resolution of the beam-constrained mass, which is dominated by the spread of the beam energy, is estimated from Monte Carlo studies to be about 2.6 MeV. The mass distribution of the B candidates is shown in Fig. 3. A cluster of 11 events is evident around the B-meson mass at 5.28 GeV. Assuming a flat background, we estimate 0.2 background event in the observed signal, by using the mass region $5.200 < M_B < 5.265$ GeV. The reconstruction efficiency for each mode of B decay can be expressed as $\epsilon_B = \sum_{ij} B_i B_j \epsilon_{ij}$, where the sum is over all charmed-meson decay modes used in the search, and B_i, B_j, and ϵ_{ij} are the corresponding branching ratios and the reconstruction efficiencies, respectively.

In Table I, we summarize the exclusive measurements and the theoretical predictions[6] of the branching ratios for the two-body double-charm decays. In calculating the branching ratios, we have assumed an equal production ratio for $B^0\bar{B}^0$ and B^-B^+ pairs at the $\Upsilon(4S)$ resonance. The exclusive branching ratios make up about 40% of the inclusive branching ratio, consistent with the results of the fit to the D_s momentum spectrum. The sum of exclusive modes appears to be larger than the summed theoretical predictions. However, it should be noted that this apparent discrepancy vanishes if one uses $B(D_s^- \to \phi\pi^-) = 4\%$, which is consistent with the current experimental bound on the D_s branching ratios.[4]

Using a similar technique we have also searched for the decays $\bar{B}^0 \to D_s^-\pi^+$ and $\bar{B}^0 \to D_s^+K^-$. Since much of the background to these processes is from continuum jetlike events, we require $|\cos\theta_s| < 0.8$, where θ_s is the angle between the direction of the D_s^- meson and the sphericity axis of all tracks in the event excluding those in the B candidate. We find no evidence for these decays and set upper limits on the branching ratios $\bar{B}^0 \to D_s^-\pi^+ < 0.13\%$ and $\bar{B}^0 \to D_s^+K^- < 0.13\%$ at 90% confidence level.

The detection efficiency for double-charm decays is handicapped by the small branching ratios of the D_s and D mesons into easily detectable modes. For the processes $\bar{B}^0 \to D_s^-D^{*+}$ and $\bar{B}^0 \to D_s^{*-}D^{*+}$, where $D^{*+} \to D^0\pi^+$, a method which exploits the kinematics characteristics of the decays can be used to avoid explicit reconstruction of the D^0 meson. This technique has been described in detail in an earlier publication[7] of the measurement of the branching ratio for the decay $B \to D^{*+}\pi^-$. Briefly, it involves identification of events where a $\phi\pi^-$ combination and a soft pion from the decay $D^{*+} \to D^0\pi^+$ are present. Using the measured momen-

TABLE I. Branching ratios for two-body $B \to D_s$ decays. Here we have used $B(D_s^- \to \phi\pi^-) = 2\%$.

Decay mode	Efficiency (%)	Events	Branching ratio (%)	Theoretical prediction (%)
$\bar{B}^0 \to D^{*+}D_s^-$	0.05	3	2.4 ± 1.4	0.40–0.67
$\bar{B}^0 \to D^+D_s^-$	0.10	3	1.2 ± 0.7	0.90
$B^- \to D^0D_s^-$	0.07	5	2.9 ± 1.3	0.8–1.0
$\bar{B}^0 \to \pi^+D_s^-$	0.90	< 3	< 0.13 at 90% C.L.	$0.35\,\lvert V_{ub}/V_{cb}\rvert^2$
$\bar{B}^0 \to K^-D_s^+$	0.90	< 3	< 0.13 at 90% C.L.	⋯

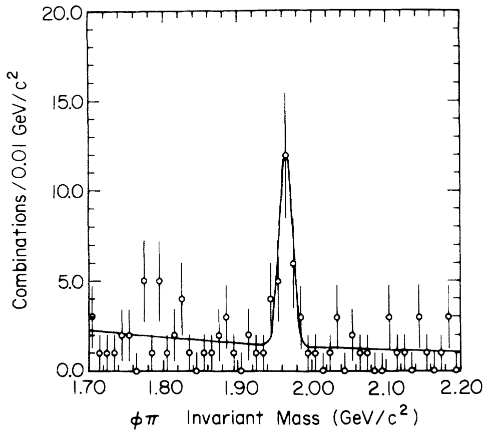

FIG. 4. The $\phi\pi$ invariant-mass distribution for the mass cut $5.275\text{ GeV} < M_B' < E_{\text{beam}}$.

ta of the $\phi\pi^-$ combination and of the soft π^+ we calculate an approximate beam-constrained mass M_B' for the $\bar{B}^0$ candidates from

$$(M_B')^2 = E_{\text{beam}}^2 - (\mathbf{p}_{\phi\pi} + \mathbf{p}_{D^0} + \mathbf{p}_\pi)^2 .$$

Here, the magnitude of the D^0 momentum is obtained from the energy-conservation relation $E_{\text{beam}} = E_{D^0} + E_\pi + E_{\phi\pi}$. The D^0 direction is estimated using the constraint $m_{D^{*+}}^2 = (E_{\text{beam}} - E_{\phi\pi})^2 - (\mathbf{p}_{D^0} + \mathbf{p}_\pi)^2$ and by maximizing the value of M_B'. Monte Carlo studies have shown that the distribution of M_B' for the two-body decays $\bar{B}^0 \to D_s^- D^{*+}$ and $\bar{B}^0 \to D_s^{*-} D^{*+}$ peaks near the beam energy 5.29 GeV, while the distributions for the decays such as $B \to D^{**} D_s$ and $B \to D^* D_s \pi$ are flat in the range $5.21 < M_B' < 5.29$ GeV. Requiring $M_B' > 5.275$ GeV results in a detection efficiency of 6% for two-body modes and an efficiency of less than 0.3% for multibody modes.[8] In Fig. 4, we display the distribution of the invariant mass of the $\phi\pi$ combinations for the B candidates satisfying the above mass criterion. A clear peak at the D_s mass is evident. Fitting this spectrum we find 22 ± 5 events at the D_s^- mass. In order to estimate the background to this signal we have examined the distributions for (a) wrong-sign combinations $D_s^- \pi^-$, (b) right-sign combinations from continuum data, (c) the mass region $5.19 < M_B' < 5.21$ GeV, and (d) right-sign combinations for which the direction of the soft pion has been inverted. None of these distributions show any enhancement at the D_s^- mass.

Attributing the observed D_s^- signal in Fig. 4 to the sum of the decays $\bar{B}^0 \to D_s^- D^{*+}$ and $\bar{B}^0 \to D_s^{*-} D^{*+}$, and correcting for the reconstruction efficiency and the branching ratio $B(D_s^- \to \phi\pi^-) = 2\%$, we calculate the branching ratio

$$B(\bar{B}^0 \to D_s^- D^{*+} + \bar{B}^0 \to D_s^{*-} D^{*+}) = (7.5 \pm 2)\% .$$

This result is consistent with the results of the inclusive measurements and the exclusive reconstruction technique.

In conclusion, we have measured the branching ratio and the momentum spectrum for the inclusive decay $B \to D_s X$. We have searched for exclusive decays $B \to D_s D$ and find eleven such decays in our data sample. The measured branching ratios of the exclusive modes are consistent with those inferred from the D_s momentum spectrum. We have also set upper limits on the branching ratios of the decays $\bar{B}^0 \to D_s^+ K^-$ and $\bar{B}^0 \to D_s^- \pi^+$.

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[5]If we estimate the two-body component by allowing a contribution from the process $B \to D_s^+ K W^-$, where W^- is the virtual W decaying into pairs of leptons and quarks and the D_s^+ meson is produced from the fragmentation of the valence primary charm quark from $b \to c$ coupling, the two-body component is reduced to 45%.

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[8]Here we have assumed $\bar{B}^0 \to D_s^- D^{*+} : \bar{B}^0 \to D_s^{*+} = 1{:}3$. Assuming an equal production rate for these processes leads to a detection efficiency of 7%.