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Measurements of $B \to D_s^+ X$ Decays

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Abstract

This paper describes new measurements from CLEO-II of the inclusive $B \to D_s^+ X$ branching ratio as well as the $B^+ \to D_s^{(*)+} \bar{D}^{(*)o}$ and $B^o \to D_s^{(*)+} D^{(*)-}$ branching ratios. The inclusive branching ratio is found to be:

$$\mathcal{B}(B \to D_s^+ X) = \left[(11.81 \pm 0.43 \pm 0.94) \times \left(\frac{3.7 \pm 0.9\%}{\mathcal{B}(D_s^+ \to \varphi \pi^+)} \right) \right] \%$$

where the first error is statistical and the second is the systematic error. The sum of the $B \to D_s^{(*)+} \bar{D}^{(*)}$ measured from the the exclusive reconstruction of B meson final states is found to be consistent with the results from fits to the inclusive D_s^+ momentum spectrum where the ratios of the two-body widths are fixed to the values predicted using factorization. The results of the fits are also used in conjunction with the measured $B^o \to D^{(*)-} \pi^+/\rho^+$ branching ratios to arrive at a value for f_{D_s}, the D_s^+ decay constant.

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I. INTRODUCTION

The large samples of B mesons being collected by experimental groups at e^+e^- and hadron colliders have allowed for ever more precise measurements of B meson decay properties. Theoretical calculations are unable to describe the total inclusive B to charm rate (the so-called 'charm deficit') or the semi-leptonic branching ratio of the B meson [1,2]. The discrepancy in the total inclusive rate is particularly large in the case where the b quark decays to a charm quark plus a W boson and the W materializes as $\bar{c}s$ [3,4]. The external spectator B meson decay diagram for this process, shown in Figure 1, leads to a $D_s^{(*)+}$ in the final state whereas the internal W decay diagram results in the production of charmonium*. This paper reports on new measurements of $B \to D_s^+ X$ decays† from the CLEO-II experiment.

After a short description of the detector and the cuts used to select neutral and charged particle candidates, there are two sections dealing with directly measured quantities – the inclusive $B \to D_s^+ X$ branching ratio and the $B \to D_s^{(*)+}\bar{D}^{(*)}$ branching ratios. The rest of the paper describes the extraction of parameters which require input from theoretical models. Following a discussion of factorization, the predictions for the $B \to D_s^{(*)+}\bar{D}^{(*)}$ branching ratios are compared to the measurements. Fixing the ratios of these rates in the fit to the inclusive D_s^+ momentum spectrum allows for the the extraction of f_{D_s}, the D_s^+ decay constant.

II. EVENT AND TRACK SELECTION

The data used in this analysis were selected from hadronic events produced in e^+e^- annihilations at the Cornell Electron Storage Ring (CESR). The data consists of an integrated luminosity of 1.56 fb^{-1} collected at the $\Upsilon(4S)$ resonance and 0.70 fb^{-1} at a center-of-mass energy just below the threshold for producing $B\bar{B}$ mesons (refered to as the continuum). The on-resonance data corresponds to $(1.669 \pm .015) \times 10^6$ $B\bar{B}$ pairs.

The CLEO-II detector measures both neutral and charged particles with excellent resolution and efficiency, as described in [5]. Hadronic events are selected by requiring a minimum of three charged tracks, a total visible energy greater than 15% of the center-of-mass energy (this reduces contamination from two-photon interactions and beam-gas events), and a primary vertex within ± 5 cm in the z-direction and ± 2 cm in the r-ϕ plane of the nominal collision point. Since the B mesons are produced almost at rest, $B\bar{B}$ events tend to be spherical in shape whereas continuum $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) events are more jet-like in structure. The shape variable R_2, which is is the ratio of the second Fox-Wolfram moment to the zeroth moment [6], is found to be useful in discriminating between $B\bar{B}$ events and those in which lighter mass quarks were produced. An $R_2 < 0.35$ cut is applied to each event.

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*See GLS0248 for CLEO-II results on charmonium production in B decays.

†Reference to a specific state or decay will always imply that the charge-conjugate state or decay has also been included.

All charged tracks are required to be consistent with having originated from within ± 5 cm in the z-direction and ± 5 mm in the r-ϕ plane of the primary vertex. Tracks are also required to have dE/dx information which is consistent with the proposed particle hypothesis.

III. THE INCLUSIVE $B \to D_S^+ X$ BRANCHING RATIO

The D_s^+ mesons in the on-resonance data set originate from B meson decays as well as continuum charm production via $e^+e^- \to c\bar{c}$. Therefore, in order to measure $\mathcal{B}(B \to D_s^+ X)$, it is necessary to measure and subtract the continuum contribution to the total yield of D_s^+ mesons in the on-resonance data set.

The $D_s^+ \to \varphi\pi^+$, $\varphi \to K^+K^-$ decay channel was chosen for the inclusive $B \to D_s^+ X$ measurement because it offers the best combination of detection efficiency, branching ratio, and signal to background. As well as the K^+K^- mass requirement given in Table II, two angular cuts are used to suppress background. The two relevant angles are: 1) the helicity angle, θ_H, which is the angle between either of the kaons and the D_s^+ direction in the φ rest frame, and 2) the decay angle, θ_D, which is the angle between the φ (or the π) and D_s^+ lab direction evaluated in the D_s^+ rest frame. The signal follows a $\cos^2\theta_H$ distribution while the background is flat in $\cos\theta_H$ so a $|\cos\theta_H| > 0.35$ cut eliminates 35% of the background events while retaining 96% of the signal. A $\cos\theta_D < 0.75$ cut is employed because the $\cos\theta_D$ distribution for the signal is flat while combinatorial background from the many low momentum pions in these events tends to peak near $\cos\theta_D = 1$.

The efficiency of the cuts is calculated from Monte Carlo events which were generated using a full simulation of the CLEO-II detector and then passed through the same reconstruction software as used on the data. Figure 2 shows the D_s^+ detection efficiency as a function of the scaled D_s^+ momentum (x), where $x \equiv p_{D_s^+}/p_{max}$ and $p_{max} = \sqrt{E_{beam}^2 - m_{D_s^+}^2}$. For D_s^+ mesons produced in B decays, $x < 0.5$.

The on-resonance yield of D_s^+ mesons as a function of scaled momentum is extracted by fitting the $\varphi\pi^+$ invariant mass plot for each momentum bin. The bin size of $\Delta x = 0.03$ is much larger than the resolution in x. The fitting function consists of a straight line parameterization of the combinatorial background and a Gaussian for describing the signal. The width of the Gaussian is fixed to the value found from fitting the Monte Carlo sample. This resolution increases linearly with momentum from 6 MeV at low momentum to 8 MeV as x approaches 1. The mass was allowed to vary as a function of momentum in a first pass of fitting to the data and then fixed to the average value of 1.9686 GeV in the final pass. The resulting D_s^+ momentum spectrum before efficiency correction is shown in Figure 3.

The momentum spectrum for continuum produced D_s^+ mesons is constructed from the data by using the sum of the on- and off-resonance data for $x > 0.5$ and just the off-resonance data, scaled by the ratio of on/off luminosities, for $x < 0.5$. The number of D_s^+ mesons per momentum bin for this 'continuum' data sample is extracted in the same manner as described above. The resulting continuum D_s^+ momentum spectrum, shown in Figure 4, is fit with a function which was found to describe the Monte Carlo continuum D_s^+ momentum spectrum. It is the values of this function, properly rescaled, which are subtracted, bin by bin, from the D_s^+ momentum spectrum of Figure 3 to give the raw (i.e., not efficiency corrected) yield as a function of momentum of D_s^+ mesons produced in B decay. The raw yield of continuum subtracted D_s^+ mesons from B decays is 1978 ± 78 events. As can be seen in Figure 4, most of the continuum produced D_s^+ mesons have $x > 0.5$ so the error in $\mathcal{B}(B \to D_s^+ X)$ due to uncertainties in the exact shape of the continuum spectrum is not the dominant systematic error. The continuum subtracted, efficiency corrected D_s^+ momentum spectrum is shown in Figure 5.

From the total yield of D_s^+ mesons from B decay, the inclusive branching ratio is:

$$\mathcal{B}(B \to D_s^+ X) = \left[(11.81 \pm 0.43 \pm 0.94) \times \left(\frac{3.7 \pm 0.9\%}{\mathcal{B}(D_s^+ \to \varphi\pi^+)} \right) \right] \%$$

where the first error is statistical and the second is the systematic error‡. This value is larger than the previous CLEO and ARGUS measurements shown in Table I.

TABLE I: Measurements of $\mathcal{B}(B \to D_s^+ X)$. The first error is statistical and the second is the systematic error. The error due to the uncertainty in $\mathcal{B}(D_s^+ \to \varphi\pi^+)$ is not included in the systematic errors and is common to all the measurements.

Experiment	$\mathcal{B}(B \to D_s^+ X)$ $\times (3.7 \pm 0.9\% / \mathcal{B}(D_s^+ \to \varphi\pi^+))$
CLEO-II	$(11.81 \pm 0.43 \pm 0.94)$ %
ARGUS(92) [8]	$(7.89 \pm 1.05 \pm 0.84)$ %
CLEO-1.5 [9]	$(8.27 \pm 1.24 \pm 0.81)$ %
ARGUS(87) [10]	(11.4 ± 3.2) %
CLEO-I [11]	(10.3 ± 2.7) %

The largest error in the measurement is the $\sim$ 25% uncertainty in the $D_s^+ \to \varphi\pi^+$ branching ratio. This is specifically left out of the systematic error since it is common to all the measurements. The systematic error of 8% is dominated by the uncertainty in the tracking efficiency (2% per track for 6% total in $D_s^+ \to \varphi\pi^+, \varphi \to K^+K^-$). Other sources of systematic error which were studied include: continuum subtraction techniques, fitting functions both for the signal and the background, angular and track quality cuts, momentum bin width, the φ mass cut, and the efficiency of the particle identification criteria. The systematic error includes the uncertainty in the number of $B\bar{B}$ pairs and in the $\varphi \to K^+K^-$ branching fraction.

‡The $D_s^+ \to \varphi\pi^+$ branching fraction is taken from [7].

IV. EXCLUSIVE $B \to D_S^{(*)+}\bar{D}^{(*)}$ DECAYS

The near hermeticity of the CLEO-II detector coupled with its excellent photon detection and charged particle reconstruction capabilities allow for the reconstruction of all eight $B^o \to D_s^{(*)+}D^{(*)-}$ and $B^+ \to D_s^{(*)+}\bar{D}^{(*)o}$ modes.

The data, and event selection and track quality cuts are the same as were used in the inclusive analysis. Photons are required to have deposited more than 30 MeV of energy in the calorimeter and to be isolated from charged tracks. They are also required to have been detected within the 'barrel' region of the detector, defined by $|\cos\theta| < 0.707$ where θ is the angle between the photon momentum vector and the z axis, unless they are candidate π^o or η daughters in which case one of the photons can be from outside of barrel[§]. The mass cuts and branching ratios for the various non-charmed resonances used in this analysis are given in Table II. The π^o/η candidates within these mass windows are kinematically fitted to the known π^0/η mass before use in reconstructing charmed mesons.

TABLE II: Mass cuts and branching ratios for the non-charmed mesons used in this analysis.

Decay Mode	Mass Cut (GeV)	Branching Ratio (%)
$\pi^o \to \gamma\gamma$	$0.1200 < m_{\gamma\gamma} < 0.1500$	98.8 ± 0.03
$\eta \to \gamma\gamma$ [a]	$0.5174 < m_{\gamma\gamma} < 0.5774$	38.9 ± 0.50
$K^0 \to K_s \to \pi^+\pi^-$	$0.4877 < m_{\pi^+\pi^-} < 0.5077$	34.3 ± 0.14
$\varphi \to K^+K^-$	$1.0095 < m_{K^+K^-} < 1.0295$	49.1 ± 0.80
$K^{*o} \to K^+\pi^-$	$0.8461 < m_{K^+\pi^-} < 0.9461$	66.6 ± 0.01
$\rho^+ \to \pi^+\pi^o$ [a]	$0.6161 < m_{\pi^+\pi^o} < 0.9201$	100

[a] decay angle cut of $\cos\theta_D < 0.9$

The $D_s^{(*)+}$ and $D^{(*)}$ decay channels used, the mass cuts applied, and the assumed branching ratios, are given in Tables III and IV, respectively. The D_s^+ and D^o branching ratios are given relative to those for the two normalizing modes; $D_s^+ \to \varphi\pi^+$ [7] and $D^o \to K^-\pi^+$

[§]For photons detected outside the barrel, the minimum photon energy cut is raised to 50 MeV.

[14]**. The $D_s^{(*)+}$ and $D^{(*)}$ candidates within these mass windows are kinematically fit to their known masses.

TABLE III: The $D_s^{(*)+}$ mass cuts and branching ratios used in this analysis.

Decay Mode	Mass or ΔM Cut (GeV)	Branching Ratio (%)
$D_s^{*+} \to D_s^+ \gamma$ [a]	$0.132 < m_{D_s^{*+}-D_s^+} < 0.152$	100
$D_s^+ \to \varphi\pi^+$ [b,c]	$1.9542 < m_{\varphi\pi^+} < 1.9822$	3.7 ± 0.9
Decay Mode	Mass Cut (GeV)	$\frac{\mathcal{B}}{\mathcal{B}(D_s^+ \to \varphi\pi^+)}$
$D_s^+ \to K^o K^+$	$1.9532 < m_{K_s K^+} < 1.9832$	1.00 ± 0.25
$D_s^+ \to K^{*o} K^+$ [c]	$1.9530 < m_{K^{*o}K^+} < 1.9835$	0.93 ± 0.25
$D_s^+ \to \varphi\rho^+$	$1.9442 < m_{\varphi\rho^+} < 1.9922$	1.86 ± 0.54
$D_s^+ \to \eta\pi^+$	$1.9374 < m_{\eta\pi^+} < 1.9990$	0.54 ± 0.14
$D_s^+ \to \eta\rho^+$ [c]	$1.9338 < m_{\eta\rho^+} < 2.0036$	2.82 ± 0.75

[a] $E_\gamma > 90$ MeV
[b] decay angle cut of $\cos\theta_D < 0.75$
[c] helicity angle cut of $|\cos\theta_H| > 0.35$

Since the $\Upsilon(4S)$ decays only to $B\bar{B}$, the B meson energy is equal to the beam energy. This fact can be exploited to select B meson candidates and to get a better measure of their mass, as explained below. In the case of multiple candidates in a specific B meson decay chain (e.g., $B^+ \to D_s^+ \bar{D}^o$), only the candidate with the smallest absolute value of the energy difference, ΔE, is selected, where $\Delta E = E_{beam} - E_{meas}$ and E_{meas} is the measured sum of charged and neutral energies of the daughters of the B candidate and E_{beam} is the beam energy. The ΔE resolution is ~ 10 MeV, independent of decay mode, according to an analysis of Monte Carlo $B \to D_s^{(*)+}\bar{D}^{(*)}$ events. All B candidates must satisfy a $|\Delta E| \leq 25$

**The values for the relative branching ratios are taken from the PDG [12] except for $\mathcal{B}(D^+ \to K^-\pi^+\pi^+)/\mathcal{B}(D^o \to K^-\pi^+)$ which is from CLEO-II [13].

MeV cut. Furthermore, since the B mesons are produced with the beam energy, the B mass resolution can be improved by using the beam-constrained mass (M_B), defined by:

$$M_B^2 = E_{beam}^2 - \left(\sum_i \vec{p_i}\right)^2 , \quad (1)$$

where $\vec{p_i}$ is the momentum of the i-th daughter of the B candidate. The M_B resolution of about 2.6 MeV is determined by the beam energy spread and is a factor of ten better than the resolution in invariant mass obtained from simply summing the 4-momenta of the B daughters.

TABLE IV: The $D^{(*)}$ mass cuts and branching ratios that are used in this analysis.

Decay Mode	Mass or ΔM Cut (GeV)	Branching Ratio (%)
$D^{*+} \to D^o \pi^+$	$0.1430 < m_{D^{*+}-D^o} < 0.1480$	67.9 ± 2.3
$D^{*o} \to D^o \pi^o$	$0.1406 < m_{D^{*o}-D^o} < 0.1446$	63.5 ± 4.2
$D^o \to K^- \pi^+$	$1.8457 < m_{K^-\pi^+} < 1.8833$	3.95 ± 0.08
Decay Mode	Mass Cut (GeV)	$\frac{\mathcal{B}}{\mathcal{B}(D^o \to K^- \pi^+)}$
$D^o \to K^- \pi^+ \pi^o$	$1.8355 < m_{K^-\pi^+\pi^o} < 1.8935$	3.10 ± 0.30
$D^o \to K^- \pi^+ \pi^- \pi^+$	$1.849 < m_{K^-\pi^+\pi^-\pi^+} < 1.8800$	2.05 ± 0.14
$D^+ \to K^- \pi^+ \pi^+$	$1.8530 < m_{K^-\pi^+\pi^+} < 1.8856$	2.35 ± 0.16

The beam-constrained mass plot for the sum of the eight B^o and B^+ decay channels is shown in Figure 6. The function which is fitted to the data to extract the yield of B mesons contains two parts: 1) a background function which is linear for $M_B < 5.282$ GeV and parabolic, with a kinematic cutoff, for larger values of M_B [16] and 2) a Gaussian to describe the signal. The mass and width from the fit to the sum of all modes are consistent with those obtained from the Monte Carlo. The total in the peak is 134.3 ± 14.6 events.

The beam-constrained mass plots for the individual B^o and B^+ decay channels are shown in Figures 7 and 8. The mass and width for these fits are fixed to the value obtained from the fit to the sum of all the modes. The resulting exclusive branching ratios are listed in Table V. Two other variables which are useful to cut on are the B production angle, θ_B, which is the angle between the B meson and beam direction, and the sphericity angle, θ_S, which is the angle between the B meson and the sphericity axis of the rest of the event. For B mesons the production angle is distributed like $\sin^2\theta_B$ whereas the continuum background is flat. Conversely, the continuum background would populate large values of $\cos\theta_S$ whereas the signal is flat in this variable.

TABLE V: The efficiency times sub-mode branching ratios ($\varepsilon \cdot \mathcal{B}$), the number of reconstructed events, and the measured branching ratios for each of the eight B decay channels. The error on $\varepsilon \cdot \mathcal{B}$ is just that due to Monte Carlo statistics. The error on the number of events is purely statistical. The third error in the branching ratios after the statistical and systematic error is the $\sim 25\%$ uncertainty in $\mathcal{B}(D_s^+ \to \varphi\pi^+)$ which is common to all measurements.

Decay Channel	$\varepsilon \cdot \mathcal{B}$ (10^{-3})	# Events	Branching Ratio (%)
$B^+ \to D_s^+ \bar{D}^o$ [a,b,c]	1.90 ± 0.09	49.4 ± 9.0	$1.55 \pm 0.28 \pm 0.30 \pm 0.38$
$B^+ \to D_s^{*+} \bar{D}^o$ [a,b,c,d]	1.12 ± 0.05	15.5 ± 5.1	$0.83 \pm 0.27 \pm 0.20 \pm 0.20$
$B^+ \to D_s^+ \bar{D}^{*o}$ [c,e,f]	0.44 ± 0.02	7.3 ± 3.4	$1.00 \pm 0.47 \pm 0.22 \pm 0.24$
$B^+ \to D_s^{*+} D^{*o}$ [c,f]	0.29 ± 0.01	10.2 ± 3.6	$2.12 \pm 0.75 \pm 0.52 \pm 0.52$
$B^o \to D_s^+ D^-$ [b,c]	1.22 ± 0.10	15.3 ± 5.0	$0.75 \pm 0.25 \pm 0.20 \pm 0.18$
$B^o \to D_s^{*+} D^-$ [c,d,f]	0.63 ± 0.05	9.4 ± 3.6	$0.90 \pm 0.34 \pm 0.20 \pm 0.22$
$B^o \to D_s^+ D^{*-}$ [e,f]	0.85 ± 0.04	13.9 ± 3.9	$0.99 \pm 0.28 \pm 0.20 \pm 0.24$
$B^o \to D_s^{*+} D^{*-}$ [f]	0.45 ± 0.02	12.8 ± 3.8	$1.69 \pm 0.50 \pm 0.36 \pm 0.41$

[a] $D_s^+ \to \eta\rho^+$ not combined with $\bar{D}^o \to K^+\pi^-\pi^o$
[b] production angle cut of $|\cos\theta_B| \leq 0.80$
[c] sphericity angle cut of $|\cos\theta_S| \leq 0.95$
[d] helicity angle cut of $|\cos\theta_H| < 0.80$
[e] helicity angle cut of $|\cos\theta_H| > 0.30$
[f] production angle cut of $|\cos\theta_B| \leq 0.90$

When calculating the systematic error, a tracking efficiency error of 2% per track is used except for the slow pion from the decay of the D^{*+} which is assigned a 5% error. The tracking errors add linearly. For example, for the $D^{*+} \to D^o\pi^+$, $D^o \to K^-\pi^+\pi^+\pi^-$ decay chain, the systematic error associated with tracking is 13%. The systematic associated with neutrals is 3% per photon and 5% per neutral meson (i.e., π^o or η). These also add linearly while the charged and neutral systematics are added in quadrature. The total systematic error in a particular branching ratio due to uncertainties in efficiencies is then the weighted average of the systematic errors of the submodes where the weight is the $\varepsilon \cdot \mathcal{B}$ for that submode. The systematic error due to the uncertainties in the relative branching ratios are calculated in the same manner. These are the two dominant sources of systematic error. The quoted systematic error is the sum of these two contributions added in quadrature. The other possible sources of systematic error which were investigated include: cross-talk between the eight channels, uncertainty in the efficiency due to the method of choosing the candidate with the smallest $|\Delta E|$, parameterization of the background in the beam-constrained mass plots, and particle identification cuts. There is a non-negligible contribution to the systematic error due to the background parameterization for the modes where there is a significant background (such as $B \to D_s^+ \bar{D}$).

V. FACTORIZATION AND PREDICTIONS FOR TWO-BODY RATES

As shown in Figure 1, the only way to get a two-body decay of the type $B \to D_s^{(*)+} D^{(*)}$ (or $B \to D_s^{(*)+} D^{**}$) is if the $D_s^{(*)+}$ is produced from the fragmentation of the W^+. There is no way to get a D_s^+ from internal W decay and the annihilation/W-exchange diagrams are expected to be heavily suppressed. There are two mechanisms giving three-body final states. Events of the type $B \to D_s^{(*)+} \bar{D}^{(*)} X$ are produced via the same external W^+ diagram of Figure 1 with the popping of an extra $q\bar{q}$ pair. Conversely, a D_s^- (i.e., of the opposite sign from the previous example) results when an $s\bar{s}$ is produced from one of the lower quark lines and the s quark then combines with the anti-charm quark from the decay of the $\bar{b}$ quark. These two three-body mechanisms are sometimes referred to as 'upper-' and 'lower-vertex' three-body decays, respectively. The correlation between the charge of the $D_s^\pm$ with that of the B cannot be exploited in the analysis of the inclusive D_s^+ momentum spectrum because the flavor of the B which produced the $D_s^\pm$ is not measured.

The only method for calculating exclusive branching fractions involves using the factorization ansatz pioneered by Bauer, Stech, and Wirbel (BSW) [15]. Any calculation of widths using factorization arrives at the following equation:

$$\Gamma(B \to D_s^{(*)-} D^{(*)}) = K G_F^2 a_1^2 \left|V_{cb} V_{cs}^*\right|^2 f_{D_s^{(*)}}^2 F_{(*)}^2 \tag{2}$$

where K is a kinematic factor and $F_{(*)}$ is the relevant form factor term (summed over polarizations for decays involving D^* mesons, etc.). The factorization parameter a_1 is the relevant one for external spectator decays and can, in principle, be derived from $B \to D^{(*)}\pi$ decays [16] although there are at least some reasons for doing so with caution, as is discussed in section VII. The CKM matrix element $|V_{cb}|$ can be measured from an analysis of $B \to D^* l\nu$ decays[††] leaving $f_{D_s^{(*)}}$, the $D_s^{(*)-}$ decay constant, as the remaining "unknown."

[††]See GLS0251 and GLS0385 for the CLEO-II results.

The difference between the various 'model' predictions comes from the form factor term – BSW use the simple pole form while other calculations [17–21] use form factors motivated by Heavy Quark Effective Theory, HQET (i.e., a parameterization of the Isgur-Wise function, $\xi(v \cdot v')$, where v and v' are the four-velocities of the parent and daughter heavy quarks). Unfortunately, HQET alone does not lead to any useful relations between the $B \to D_s^{(*)+}\bar{D}^{(*)}$ amplitudes [22]. The exclusive $B \to D_s^{(*)+}\bar{D}^{(*)}$ branching ratio predictions for several models are given in Table VI. A value of $|V_{cs}| = .974$ was used to convert the values in the paper by Deandrea *et al.* into those given in the Table. Mannel *et al.* [21] found differences on the order of 15% in the prediction of a particular branching ratio that were directly attributable to the choice of parameterization of $\xi(v \cdot v')$.

TABLE VI: Predictions of the $B \to D_s^{(*)+}\bar{D}^{(*)}$ branching ratios (in %) assuming $f_{D_s^{(*)}} =$ 280 MeV, $V_{cb} = .036$, and $\tau_B = 1.49\ ps$. From $B^o \to D^{(*)+}\pi^-/\rho^-$ decays, $|a_1| = 1.07 \pm 0.04 \pm 0.06$ [16]. The CLEO-II values are the weighted averages of the B^+ and B^o results. Only the statistical error is quoted on the same row as the experimental result. The two errors listed in the bottom row are the systematic error, and the error due to the uncertainty in $\mathcal{B}(D_s^+ \to \varphi\pi^+)$.

Model	$D_s^+\bar{D}$	$D_s^{*+}\bar{D}$	$D_s^+\bar{D}^*$	$D_s^{*+}\bar{D}^*$
BSW [15]	$1.28a_1^2$	$0.77a_1^2$	$0.58a_1^2$	$2.11a_1^2$
Neubert *et al.* [18]	$0.98a_1^2$	$0.70a_1^2$	$0.67a_1^2$	$1.78a_1^2$
Du & Liu [19]	$1.29a_1^2$	$0.87a_1^2$	$0.96a_1^2$	$2.37a_1^2$
Deandrea *et al.* [20]	$0.86a_1^2$	$0.59a_1^2$	$0.60a_1^2$	$2.25a_1^2$
CLEO-II	1.24 ± 0.19	0.81 ± 0.21	1.07 ± 0.23	1.98 ± 0.42
	$\pm 0.29 \pm 0.30$	$\pm 0.19 \pm 0.20$	$\pm 0.23 \pm 0.26$	$\pm 0.45 \pm 0.48$

While there are 50% differences between model predictions for any particular branching ratio, the variations in the predictions for the ratios of widths due to the different parameterizations of the form factors are much smaller. These predictions are given in Table VII. There is only one row for Mannel *et al.* in Table VII because all three parameterizations of the Isgur-Wise function examined in their paper give the same ratios of widths. The decay constant dependence is given explicitly in Table VII although, in the heavy quark limit, the vector and pseudoscalar decay constants are equal. More precisely, $f_P^2 = f_V^2 = 12|\Psi(0)|^2/M$ where $|\Psi(0)|$ is the wave function of the light antiquark and heavy quark at zero relative separation, and M is the heavy-meson mass [17]. BSW assumed values for the $c\bar{s}$ decay constants such that $(f_{D_s^*}/f_{D_s})^2 = 1.86$ leading to their prediction that $\Gamma(B \to D_s^{*+}\bar{D})$ is some 2.5 times larger than $\Gamma(B \to D_s^+ \bar{D}^*)$. As can be seen in Table VII, with $f_{D_s^*} = f_{D_s}$, these widths are predicted to be roughly equal in all the other models.

Although the BSW predictions for the ratios of widths are not excluded by the experimental results, the predictions of the other models do a better job of describing the data. The data also favor the prediction that $f_{D_s} = f_{D_s^*}$. This is one of the few comparisons with data that is unaffected by the large uncertainty in $\mathcal{B}(D_s^+ \to \varphi\pi^+)$. Also, most of the experimental systematic errors cancel other than the contribution due to an extra slow π or γ (e.g., $B \to D_s^{*+} D / B \to D_s^+ D$) and the addition of the uncertainty in the D^+ branching ratio scale in $\mathcal{B}(B \to D_s^{(*)+} D)$.

TABLE VII: Predictions for ratios of widths in $B \to D_s^{(*)+} D^{(*)}$ decays.

Model	$\frac{\Gamma(B \to D_s^{*+} D)}{\Gamma(B \to D_s^+ D^*)}$	$\frac{\Gamma(B \to D_s^+ D)}{\Gamma(B \to D_s^+ D^*)}$	$\frac{\Gamma(B \to D_s^{*+} D^*)}{\Gamma(B \to D_s^{*+} D)}$
BSW [15]	$1.31 \left(f_{D_s^*}/f_{D_s}\right)^2$	2.24	2.77
Rosner [17]	$1.00 \left(f_{D_s^*}/f_{D_s}\right)^2$	1.43	2.59
Neubert *et al.* [18]	$1.04 \left(f_{D_s^*}/f_{D_s}\right)^2$	1.47	2.56
Du & Liu [19]	$0.91 \left(f_{D_s^*}/f_{D_s}\right)^2$	1.35	2.72
Deandrea *et al.* [20]	$0.97 \left(f_{D_s^*}/f_{D_s}\right)^2$	1.42	3.84
Mannel *et al.* [21]	$1.00 \left(f_{D_s^*}/f_{D_s}\right)^2$	1.56	3.01
CLEO-II	0.75 ± 0.26	1.16 ± 0.32	2.46 ± 0.84

VI. FIT TO THE INCLUSIVE D_S^+ MOMENTUM SPECTRUM

As mentioned in section V, both upper- and lower-vertex decays contribute to the inclusive D_s^+ momentum spectrum. Since the B mesons are produced nearly at rest, the two-body decays result in $D_s^{(*)+}$ momentum spectra which are flat distributions, about 300 MeV wide, around the decay momentum. The D_s^{*+} decays predominantly to $D_s^+\gamma$ while the P-wave $c\bar{s}$ mesons, the $D_{s1}^+(2536)$ and the recently discovered $D_{s2}^{*+}(2570)$ [23], decay to $D^{(*)}K$. Therefore, $B \to D_s^{*+} X$ decays contribute D_s^+ mesons to the inclusive spectrum with distributions which are slightly broadened and shifted down in momentum from the corresponding $B \to D_s^+ X$ decay while the other $c\bar{s}$ resonances do not contribute to the inclusive D_s^+ momentum spectrum.

The function used in the fit to the inclusive D_s^+ momentum spectrum includes contributions from the two-body decays (including $D_s^{(*)+}\bar{D}^{**}$) as well as three-body upper- and lower-vertex decays. The relative amounts of each particle type in the three-body decays like $B \to D_s^{(*)+}\bar{D}^{(*)}\pi^{(*)}$ (where π^* denotes ρ or ω) are unknown and so this contribution to the fitting function consists of the sum of the individual spectra where each was added with equal weight. The relative areas of the four $B \to D_s^{(*)+}\bar{D}^{(*)}$ spectra were fixed to the ratios given in Table VII, leaving just an overall normalization for the sum of these modes. The D_s^+ momentum spectra due to the other upper-vertex decays, i.e., $B \to D_s^{(*)+}\bar{D}^{**}$ and $B \to D_s^{(*)+}\bar{D}^{(*)}\pi^{(*)}$, die away by $x \sim 0.34$. The lower-vertex decays result in a D_s^+ momentum spectrum which extends beyond $x = 0.41$, which is the kinematic limit for the upper-vertex decays. However, the D_s^+ yield in this region is consistent with having all come from the continuum[‡‡]. Also, the lower-vertex decays are expected to be suppressed. Hence, the region of x from 0.3 to 0.4 is dominated by the $B \to D_s^{(*)+}\bar{D}^{(*)}$ decays and the systematic error due to knowledge of the shapes and relative populations of the other contributions to the spectrum is small.

The result of the fit to the spectrum of Figure 5 is that the ratio of the sum of the four $B \to D_s^{(*)+}\bar{D}^{(*)}$ rates to the total inclusive rate is $(45.5 \pm 3.2 \pm 3.2 \pm 3.0)\%$. The last error is the model uncertainty calculated from the spread in the sum coming from fixing the ratios of two-body widths to the various theoretical predictions of Table VII. ARGUS and CLEO-1.5 measured this ratio to be $(58 \pm 7 \pm 9)\%$ and $(56 \pm 10)\%$, respectively [8,9].

The result of the fit using the ratios of widths from Neubert *et al.* is shown in Figure 9. In this fit, as in most of the fits, the fraction of $B \to D_s^{(*)+}\bar{D}^{**}$ to the total is found to be around 20% although the errors on this fraction are very large due to the uncertainty in the three-body shape. There are no published predictions for the $B \to D_s^{(*)+}\bar{D}^{**}$ widths.

VII. EXTRACTION OF F_{D_S}

The D_s^+ decay constant can, in principle, be extracted using the measured $B \to D_s^{(*)+}\bar{D}^{(*)}$ branching ratios, the predictions given in Table VI, and experimental information on a_1, V_{cb}, and τ_B. Unfortunately, there are at least some theoretical reasons for expecting a_1 to have different values depending on whether the W^+ fragments to $u\bar{d}$ or $c\bar{s}$ [18,24,25].

Most of the dependence on the various constants drops out by dividing the $B \to D_s^{(*)+}\bar{D}^{(*)}$ width by the corresponding width for the case where the W^+ fragments to $u\bar{d}$. For example, in calculations which use HQET motivated form factors:

$$\frac{\Gamma(B \to \bar{D}D_s^+)}{\Gamma(B^o \to D^-\pi^+)} = K R_{a_1}^2 \frac{f_{D_s}^2}{f_\pi^2} \frac{|V_{cs}|^2}{|V_{ud}|^2} \frac{|\xi(q^2 = m_{D_s}^2)|^2}{|\xi(q^2 = m_\pi^2)|^2} \tag{3}$$

where K is a calculable kinematic factor and $R_{a_1} \equiv a_1^{c\bar{s}}/a_1^{u\bar{d}}$, where the superscript of a_1 refers to the W^+ fragmentation mode[§§]. The CKM matrix elements are known to good precision as is the pion decay constant.

[‡‡]An excess of D_s^+ mesons above continuum in the $0.4 < x < 0.5$ region could be due to either $b \to u$ transitions or annihilation/W-exchange decays as well as lower-vertex decays.

[§§]In all of the calculations discussed in this note, $R_{a_1} = 1$.

The method for obtaining f_{D_s} is then, for each model, to use the prediction for the left hand side of equation (3), the measured $\mathcal{B}(B \to D_s^{(*)+}\bar{D}^{(*)})$ branching ratios taken from the fit to the inclusive D_s^+ momentum spectrum (where the ratios of widths are taken from the same model), and the CLEO-II measurements of $\mathcal{B}(B \to \bar{D}^*\pi/\rho)$ [16]. In this manner it is possible to quantify the systematic error due to model dependence by examining the spread in f_{D_s} between the results using the different models. Using the branching ratios extracted from the fit to the inclusive D_s^+ momentum spectrum, rather the results from the full reconstruction, has the advantage of smaller statistical and systematic errors and is also a good measure of the model dependence since both the ratios of $B \to D_s^{(*)+}\bar{D}^{(*)}$ widths used in the inclusive fit and the analagous ratios to equation (3) are used to get a range of f_{D_s} values. There is also the systematic error associated with using the factorization assumption which is much more difficult to assess. The arguments justifying the factorization approach suggest that it is more applicable for the denominator of equation (3), i.e., $B^o \to D^-\pi^+$ decays, than for the numerator. However, the width predictions are not as sensitive to the parameterization of the Isgur-Wise function as $v \cdot v'$ approaches 1 (the so-called Voloshin-Shifman point) and $v \cdot v'$ is closer to 1 for the numerator, i.e., $B \to \bar{D}D_s^+$ decays, than for the denominator.

The D_s^+ decay constant is found to be:

$$R_{a_1} f_{D_s} = (285 \pm 11 \pm 29 \pm 25) \times \sqrt{(3.7 \pm 0.9\%)/\mathcal{B}(D_s^- \to \varphi\pi^-)}\ \ \text{MeV}$$

where the first error is statistical, the second error is the systematic error, and the final error reflects the model dependence. It should be emphasized that there is a further uncertainty derived from using the factorization assumption which is difficult to quantify. This result is consistent (assuming R_{a_1} is close to 1) with the value of $f_{D_s} = 344 \pm 37 \pm 52 \pm 42$ MeV obtained by CLEO-II using $D_s^+ \to \mu^+\nu$ decays [7]. A value for f_{D_s} was previously derived in a similar manner by taking the ratio of the $B \to D_s^+\bar{D}^*$ to $B \to \bar{D}^* l^+\nu$ rates [29].

VIII. CONCLUSIONS

The CLEO-II result for the inclusive $B \to D_s^+ X$ branching fraction is:

$$\mathcal{B}(B \to D_s^+ X) = \left[(11.81 \pm 0.43 \pm 0.94) \times \left(\frac{3.7 \pm 0.9\%}{\mathcal{B}(D_s^+ \to \varphi\pi^+)}\right)\right]\%$$

where the first error is statistical and the second is the systematic error. The measurements of the $B \to D_s^{(*)+}\bar{D}^{(*)}$ branching ratios are given in Table V. The weighted averages of the B^o and B^- results are:

$$\begin{aligned}
\mathcal{B}(B \to D_s^+\bar{D}) &= (1.24 \pm 0.19 \pm 0.26 \pm 0.30)\% \\
\mathcal{B}(B \to D_s^{*+}\bar{D}) &= (0.81 \pm 0.21 \pm 0.19 \pm 0.30)\% \\
\mathcal{B}(B \to D_s^+\bar{D}^*) &= (1.07 \pm 0.23 \pm 0.26 \pm 0.26)\% \\
\mathcal{B}(B \to D_s^{*+}\bar{D}^*) &= (1.98 \pm 0.42 \pm 0.50 \pm 0.48)\%
\end{aligned}$$

where the first error is statistical, the second error is the systematic error due to detector effects and the uncertainties in the sub-mode branching ratios (other than the normalizing modes) and efficiencies, and the last error is the due to the uncertainty in the two normalizing branching ratios, $\mathcal{B}(D_s^+ \to \varphi\pi^+)$ and $\mathcal{B}(D^o \to K^-\pi^+)$. The final error is completely dominated by the $\sim 25\%$ uncertainty in the D_s^+ branching ratio scale.

The total two-body branching fraction is $(5.10 \pm 0.56 \pm 1.25 \pm 1.24)\%$. This is consistent with the results from a fit to the inclusive D_s^+ momentum spectrum where the sum of the $B \to D_s^{(*)+}\bar{D}^{(*)}$ rates is found to comprise $(45.5 \pm 3.2 \pm 3.2 \pm 3.0)\%$ (where the last error reflects model dependence) of the total inclusive rate. The models using HQET motivated form factors predict ratios of rates which compare well with the data and favor $f_{D_s^*} = f_{D_s}$.

Assuming factorization and using the $B \to D_s^{(*)+}\bar{D}^{(*)}$ branching ratios derived from the fit to the inclusive D_s^+ momentum spectrum along with the $B \to D^{(*)}\pi$ and $B \to D^{(*)}\rho$ measurements from CLEO-II, the D_s^+ decay constant is:

$$R_{a_1} f_{D_s} = (285 \pm 11 \pm 29 \pm 25) \times \sqrt{(3.7 \pm 0.9\%)/\mathcal{B}(D_s^- \to \varphi\pi^-)}\ \text{MeV}$$

where the first error is statistical, the second error is the systematic error, and the final error reflects the model dependence. The variable R_{a_1} is defined as $a_1^{c\bar{s}}/a_1^{u\bar{d}}$, where the superscript of a_1 refers to the W^+ fragmentation mode, to allow for the possible mass scale dependence of a_1. It should be emphasized that there is a further uncertainty associated with using the factorization assumption.

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