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Semileptonic Branching Fraction and Hadronic Width of the B Mesons in Light of the New CLEO Observation of $b \rightarrow \bar{D}X$

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Abstract

This talk reports the latest CLEO observation of \bar{D} production in b decays, which provides new insight of the QCD interactions in heavy quark systems. The observed B semileptonic branching fraction has been significantly lower than QCD expectations, as was confirmed by recent lepton-lepton correlation studies at various experiments that removed most of the model dependence in previous generation measurements. One possible explanation to accommodate this lepton shortage or a wider hadronic width of B mesons is that the process $b \rightarrow c\bar{c}s$ contributes at a higher rate than expected. That explanation, however, predicts more charm production than is observed. Using lepton tags in B events this analysis measures the fraction of $b \rightarrow \bar{D}X$ in addition to $b \rightarrow DX$. The first observation of $\bar{B} \rightarrow \bar{D}DX$ has profound implications to both experiment and theory.

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1 Introduction

The semileptonic branching fraction of the B meson has been a persistent problem in heavy quark physics as measurements have been significantly below theoretical predictions [1]. This branching ratio, simply $\Gamma_\ell/(\Gamma_\ell + \Gamma_{had})$ when the rare B decays are ignored, summarizes our understanding of the interactions in a heavy quark system.

While the semileptonic width Γ_ℓ is calculable since the electroweak current is separated from the strong interaction current as shown by the spectator diagram in Fig. 1, the calculation of the hadronic width Γ_{had} has not been possible until the recent development on Wilson operator product expansion [2]. This expansion technique in series of powers of $1/m_b$ provides a means to estimate the strong interaction in the non-perturbative region involving heavy quarks. Calculated to the second order for all the processes in Fig. 1, Bigi *et al.*, [1] concluded that the B semileptonic branching ratio B_ℓ is no less than 12%.

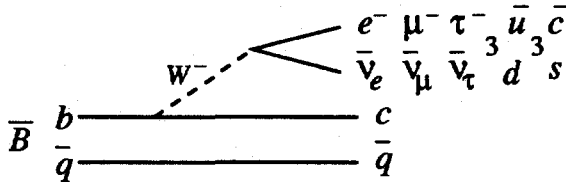


Figure 1: Dominant diagram in B meson decays.

Experimentally, a simple lepton counting would have given the semileptonic branching fraction were it not for the additional leptons from the secondary process $b \rightarrow c \rightarrow \ell$. As demonstrated in Fig. 2, the spectrum of primary leptons from B below 1.5 GeV/c must be separated from the background of secondary leptons. The results of the first generation of measurements are mostly between 10-11% as represented by CLEO at the $\Upsilon(4S)$ [3]. Though with small experimental errors, the uncertainties associated with theory were significantly larger as the separation of the pri-

mary and secondary spectra had to reply on shapes predicted by phenomenological models.

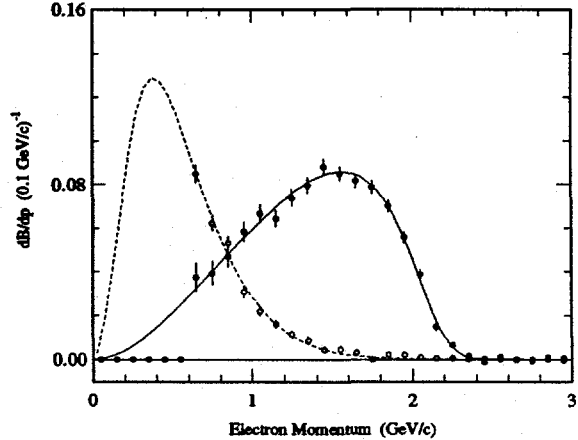


Figure 2: Lepton spectra from B decays. Dots and circles are from CLEO tagged data sample, and lines are fits to theory. The Dots are primary leptons and circles secondary.

With increased data samples, ARGUS [4] and CLEO [5], as well as the LEP experiments have been able to remove most of this model dependence in their measurements by using high momentum lepton tags. A lepton with momentum above 1.5 GeV/c is most likely from B decays. Its charge thus tags the charge of the b quark. The charge of the additional lepton in such events can be related to primary decay $b \rightarrow \ell$ or secondary charm decay $b \rightarrow c \rightarrow \ell$ by charge and kinematic correlations. With this lepton tagged technique, the primary lepton spectrum was separated from the secondary down to 0.6 GeV/c for the $\Upsilon(4S)$. This reduces the model dependence only to momenta below that which contributes a much smaller uncertainty. The discrepancy between experiments and theory therefore becomes significant. The CLEO result, for instance, as shown in Fig. 2, $B(B \rightarrow X\ell\nu) = (10.49 \pm 0.17 \pm 0.43)\%$ is now more than four standard deviations below the theoretical expectation, a serious problem.

2 Contribution from $b \rightarrow c\bar{c}s$

This shortage in lepton production in theoretical prescriptions is mainly an under estimate of Γ_{had} , the hadronic width of the B meson, as the leptonic width calculation bares a much smaller uncertainty due to the fact that the electroweak current of W decaying to lepton and neutrino is well understood.

Examining the decay modes in Fig. 1, we put together Table 1 to summarize the fraction of B decays we understand so far either by measurements or by theoretical calculations. The semileptonic decays into electron and muons are measured with precision at the $\Upsilon(4S)$ (the Z^0 measurements will be discussed later). The decay to τ is measured at LEP [6], in good agreement with the standard model expectations. They summed up to $23.6 \pm 0.5\%$.

Table 1: Fraction of B decays. First errors are experimental and second errors theoretical.

Decay	B(%)	Source
$b \rightarrow x e \nu$	10.5 ± 0.5	CLEO
$b \rightarrow x \mu \nu$	10.5 ± 0.5	CLEO
$b \rightarrow x \tau \nu$	2.6 ± 0.1	LEP
$b \rightarrow x l \nu$ sum	23.6 ± 0.5	Γ_{lTB}
$b \rightarrow x \bar{u}d$	$42.0 \pm 2.0 \pm 4.2$	theory
$b \rightarrow c\bar{c}s$		
$\rightarrow D_s X$	10.0 ± 2.7	CLEO
$\rightarrow c\bar{c}$	3.0 ± 0.5	CLEO
\rightarrow baryons	1.1 ± 0.8	CLEO
$b \rightarrow c\bar{c}s$ sum	14.1 ± 2.9	CLEO
$b \rightarrow$ hadrons sum	$56.1 \pm 3.5 \pm 4.2$	Γ_{hadTB}
Total	$79.7 \pm 4.2 \pm 4.2$	Γ_{BTB}

For B decays to hadronic final states, the $W^- \rightarrow \bar{u}d$ can be estimated with fair accuracy in heavy quark expansion. A recent QCD calculation to second order [7] gives $\mathcal{B}(b \rightarrow x \bar{u}d) = (42.0 \pm 2.0 \pm 4.2)\%$, where the first error is associated with

the B_l measurement which was used to normalize the calculation and the second error was the estimated theoretical uncertainty. In the case of $b \rightarrow c\bar{c}s$, the measured branching fractions include $B \rightarrow D_s X$, $B \rightarrow J/\psi(\eta_c)$ and the case where two charmed baryons were produced from B decays. They amount to $(14.1 \pm 2.9)\%$ so far.

The sum of all decays in Table 1 is approximately 80%. This clearly indicates that 20% of hadronic decays are still missing in our picture which contributed to the 20% higher theoretical expectation on the measured semileptonic branching fraction B_l . Rare B decays such as $b \rightarrow s\gamma$, $b \rightarrow sg$ can not close the gap as they are measured or expected with branching ratios of $10^{-4} - 10^{-3}$. E. Bagan *et al.*, [7] suggest that the process $b \rightarrow c\bar{c}s$ could contribute substantially more than the 14.4% we observed so far. They have further demonstrated that in this scenario they would be able to accommodate B_l at the 11% level. This was, however, at a price that drives up the fraction of charm quarks produced in B decays to 130%, which the measured result $(111 \pm 5)\%$ is already short of the current theoretical expectations of 120%, as is shown in Table 2.

The fact this ran into difficulty does not mean that the scenario of more $b \rightarrow c\bar{c}s$ is not true. The cause of the difficulty may lie elsewhere. A recent paper by I. Dunietz *et al.*, [8] suggests that the observed 14% D_s and Ξ_c may be only half of all $b \rightarrow c\bar{c}s$ decays. Based on experimental data and a few simple theoretical arguments they predict that the decay $B \rightarrow D\bar{D}KX$ would contribute to $b \rightarrow c\bar{c}s$ as much as D_s has. If true, it would significantly wider the B hadronic width since we have assumed it to be negligible in Table 1.

3 Measurement of $b \rightarrow \bar{D}X$ with Lepton Tags

CLEO conducted searches for such additional $b \rightarrow c\bar{c}s$ decays as $B \rightarrow D\bar{D}KX$. A high momentum lepton tag was used to tag the flavor of one of

Table 2: Measured fraction of charm in B decays.

B decay to	B(%)
D^0	61.9 ± 2.6
D^+	23.8 ± 2.1
D_s	10.3 ± 1.4
J/ψ	0.82 ± 0.08
ψ'	0.35 ± 0.05
χ_{c1}	0.37 ± 0.07
χ_{c2}	0.25 ± 0.10
η_c	< 0.9 (95% C.L.)
Λ_c	6.4 ± 2.3
Ξ_c^-	1.5 ± 0.7
Ξ_c^0	2.4 ± 1.3
total	111.1 ± 4.6

the two B mesons in $\Upsilon(4S)$ events, similar to the analysis mentioned earlier that looked for an additional lepton in each event. This time, a D (D^0 and D^+) or \bar{D} (\bar{D}^0 and D^-) was looked for. The charge and kinematic correlations of the lepton and D mesons would reflect the production mechanism of the D mesons.

In each $\Upsilon(4S)$ decay, a $B(\bar{b}q)$ and $\bar{B}(b\bar{q})$ pair is produced. Let's look at the case when the $B\bar{B}$ system is not mixed first and do the trivial correction for the 8% of mixing later. Suppose that we have a ℓ^+ tag with momentum greater than 1.5 GeV/c. It then is most likely from the B meson through $B \rightarrow \bar{D}X\ell^+\nu$. In addition, if a D meson is observed, it must be from $\bar{B} \rightarrow DX$. If a \bar{D} meson is observed instead, it could be either the \bar{D} from the B semileptonic decay that accompanied the lepton, or otherwise from the process $\bar{B} \rightarrow D\bar{D}KX$, the signal we are looking for. These two contributions must be distinguished to identify the latter. This was done by utilizing the kinematic characteristics of the two \bar{D} production processes as follows.

The $B\bar{B}$ system is produced right above its threshold near rest at the $\Upsilon(4S)$ energy. The

particles from the B and those from the \bar{B} are not kinematically related. As a result, the distribution of the opening angle between signal \bar{D} from the \bar{B} and the lepton from the B is uniform. The \bar{D} that accompanies the lepton tends to go to opposite hemispheres of the lepton since they are both from the same B and the lepton carries a high momentum. The resulting opening angle distribution is therefore peaked at 180 degrees. By fitting the $\cos(\ell^+, \bar{D})$ distribution with this peaking and the flat components we would be able to obtain the amount of \bar{D} from each processes.

With this strategy, we searched through 3.55 fb^{-1} of data collected by the CLEO-II detector [9] at the CESR e^+e^- collider, of which 1.14 fb^{-1} was collected from right below the $B\bar{B}$ threshold to represent the continuum background underneath the $\Upsilon(4S)$ peak. The remaining 2.41 fb^{-1} of data collected on the resonance contains approximately 2.4 million $B\bar{B}$ pairs. Electron candidates are identified by requiring an energy deposit in the CsI(Tl) calorimeter close to the measured momentum and dE/dx consistent with the expected ionization of electrons. Muons are identified by matching charged tracks with hits in two out of three muon chambers at five nuclear interaction length or more. The D^0 and D^+ candidates are reconstructed from $D^0 \rightarrow K^-\pi^+$ and $D^+ \rightarrow K^-\pi^+\pi^+$. Consistency with dE/dx and time of flight are required for these charged K and π candidates. Due to a poor resolution of such particle identification, a kaon could be misidentified as a pion and vice versa. In the case of D^0 , if both K and π are misidentified this could give the wrong flavor for the charmed meson. Thus we further require in this case that the K is not consistent with π and π not K , which reduces the probability of misidentifying the charm flavor to a much lower level.

The observed angular distributions of ℓ^+ and \bar{D}^0 or D^- from data are plotted in Fig 3 after background subtractions including continuum, fake lepton tags, a small remaining misidentified D^0 and

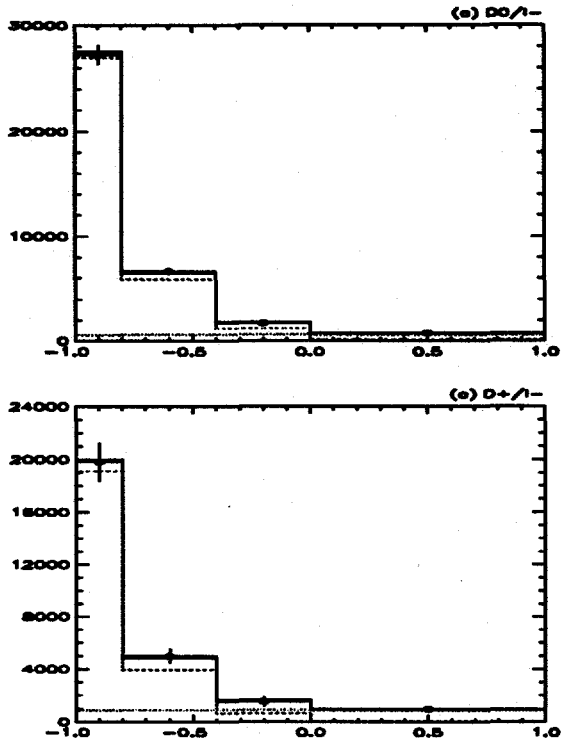


Figure 3: $\cos(\ell^+, \bar{D}^0)$ (upper) and $\cos(\ell^+, D^-)$ (lower) from data (charge conjugate implied).

\bar{D}^0 , and detection efficiency corrections. In both the charged and neutral D cases, a peaking component is clearly visible though dominated by the uniform component. By fitting these two components in these plots and similar ones for $\cos(\ell^+, D)$, we obtain the yields in Table 3. Now the effect of $B^0 \bar{B}^0$ mixing can be corrected by substituting these numbers into the following equation, where x is the D momentum normalized to beam energy, and $\chi = 8\%$ the $B\bar{B}$ mixing probability.

$$\begin{bmatrix} \frac{dN(b \rightarrow \bar{D})}{dx} \\ \frac{dN(b \rightarrow D)}{dx} \end{bmatrix} = \begin{bmatrix} 1 - \chi & \chi \\ \chi & 1 - \chi \end{bmatrix} \begin{bmatrix} \frac{dN(\bar{D})}{dx} \\ \frac{dN(D)}{dx} \end{bmatrix}$$

We obtain the final result of the fraction of $B \rightarrow$

$D\bar{D}KX$ through $b \rightarrow c\bar{c}s$:

$$\frac{\Gamma(\bar{B} \rightarrow \bar{D}X)}{\Gamma(\bar{B} \rightarrow DX)} = (10.7 \pm 2.9 \pm 1.8)\%$$

where the first error is statistical and the second one systematic that includes the uncertainties in the fraction of fake lepton tags, the probability of misidentifying kaons and pions, and the uncertainties in the D detection efficiencies. Using the result of an independent CLEO measurement of inclusive $B \rightarrow D$ decay without the lepton tag, $\mathcal{B}(B \rightarrow D \text{ or } \bar{D}) = (88 \pm 3)\%$ we obtain the final result $\mathcal{B}(\bar{B} \rightarrow \bar{D}) = (8.1 \pm 2.6)\%$. Note, however, this does not change the total fraction of charm from B decays shown in Table 2 as the D^0 and D^+ contributions in the table were measured from simple charm counting that included both the D and \bar{D} .

Table 3: Fitting results of D and \bar{D} contributions from B and \bar{B} decays in units of thousand events.

	from B	from \bar{B}
\bar{D}	276.0 ± 7.5	48.6 ± 6.1
D	2.9 ± 5.5	225.4 ± 7.3

4 Impact on Measurements at $\Upsilon(4S)$ and Z^0

This is the first observation of \bar{D} in b decays, or the production of the wrong charm flavor. It makes up almost half of the 20% missing hadronic width of the B , though not as much compared to Dunietz's estimate. Furthermore, the addition of such decays has profound implications on existing and ongoing measurements both at the $\Upsilon(4S)$ and Z^0 resonances not only in B but also in electroweak physics, as all experiments except SLD have assumed that this decay did not happen.

One direct impact is on the measurement of $\mathcal{B}(B \rightarrow X\ell\nu)$ with lepton tags discussed earlier. This process adds an additional background from $\bar{B} \rightarrow \bar{D} \rightarrow \ell^-$ to the primary lepton spectrum at very low momenta. Consequently this correction should bring all results down by a certain amount. This correction to the $\Upsilon(4S)$ experiments ARGUS and CLEO is luckily small, 0.03-0.05% on the 10.0-10.5% results due to a 0.6 GeV/c detector momentum cut off on electrons. The LEP measurements took advantage of the boost of the B from Z^0 decays. They used P_T perpendicular to the B direction, and thus measured the lepton spectra down to zero. The full background from $\bar{B} \rightarrow \bar{D} \rightarrow \ell^-$ must be subtracted now. This 0.4-0.7% subtraction incidentally brings the LEP results from slightly above 11% into agreement with CLEO and ARGUS [8].

For the same reason, this will also have corrections on electroweak measurements such as R_c or possibly some small impact even on R_b , according to Dunietz's calculation. The world average dominated by LEP has been close to 3 standard deviations away from the standard model expectations. The CLEO observation of \bar{D} production in \bar{B} decays helps in clearing up the background.

Theoretically this observation provides new insight of the B decay mechanism. We need to re-examine our assumptions on the decay modes and re-calibrated the calculation of their branching fractions. Further experimental work in determining exclusive decay modes will also be beneficial.

5 Summary

We discussed the problem in heavy quark physics that the measured semileptonic branching fraction of the B meson being 20% below QCD expectations based on the latest measurements and developments on operator product expansion. This is primarily a 20% shortage of our understanding of the B hadronic width. CLEO for the first time

observed $(8.1 \pm 2.6)\%$ \bar{D} production in \bar{B} decays. This confirms recent theoretical predictions that the process $b \rightarrow c\bar{c}s$ contributes more than the observed $B \rightarrow D_s$, and thus closes the 20% by half. The understanding of the remaining 10% depends both on further experimental and theoretical development.

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