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An Update on CLEO's Study of B Meson Decays[1]

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Abstract

This is a discussion of the main branching fractions of B Meson decays ($b \to cW^-$). A summary of what has been measured and what remains unmeasured is presented.

Introduction

The Υ family of mesons was discovered at Fermilab[1] in 1977. At that time, purely by coincidence the CESR storage ring had been designed and was under construction. Construction of the CLEO-I detector had also begun. In 1978, the existence of the $\Upsilon(1S)$ and $\Upsilon(2S)$ resonances were confirmed at the DORIS storage ring of DESY[2], and from their measurement of the $e^+e^- \to \Upsilon(1S)$ crossection, it became clear that the Υ resonances are best described as $b\bar{b}$ quark pairs, not $t\bar{t}$. CESR began operation at the end of 1979. The CLEO (and CUSB) Collaborations began data taking. In 1980, CLEO (and CUSB) published observation of the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$[3], and the $\Upsilon(4S)$[4]. The $\Upsilon(4S)$, is a much wider resonance and is believed to decay exclusively to $B\bar{B}$ mesons. Over the next six to eight years, many general properties of B meson decay were measured at DORIS and CESR. In 1988, CESR shut down and the CLEO-I detector was replaced by the CLEO-II detector. The new CLEO-II detector consists of a better resolution tracking system and electromagnetic calorimeter. Figure 1 is an illustration of the CLEO-II detector. Our understanding of the B meson decay has continued to improve with the CLEO-II detector, but today we only understand approximately 50% of the B decays. This paper is a description of the status of our understanding today compared with the Particle Data Group review published in 1996.

Understanding of B Meson Decay in 1996

In the 1996 Review of Particle Physics[5], the Particle Data Group provided a long detailed summary of what is known about the B meson branching fractions, and life times. Most of the information they reported on the B meson branching fractions came from publications of the ARGUS Collaboration at DESY and publications of CLEO at Cornell. A summary of the "largest" B meson branching fractions listed in the 1996 Review of Particle Physics is given in Table 1. In the Standard Model, the b quark decays under the weak interaction to the c or u quark. From early experiments, it was evident that the $b \to u$ interaction is more than an order of magnitude weaker than the $b \to c$ (See for example the $b \to ul\nu$ and the $B \to X_c l\nu$ branching fractions listed in Table 1.). B meson decays are usually described by the diagrams shown in figure 2 (Since the main decays are to c quarks, the diagrams shown in figure 2 do not include the $b \to u$ transitions.). The first set of branching fractions in Table 1 are the semileptonic decay modes. These are the simplest decay modes to describe. They all proceed via the tree diagram. The listed branching fractions, for example $Br(B \to Xl\nu) = (10.4 \pm 0.4)\%$, is supposed to represent the branching fraction for $l = e$ or $l = \mu$. The total semileptonic branching fraction includes $B \to Xe\nu, B \to X\mu\nu$, and $B \to X\tau\nu$. The branching fraction to electons and muons are expected to be very close to identical. However, the branching fraction to τ leptons, which have never been

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measured, are expected to be only 0.3 as large, because of the large τ mass (The factor 0.3 comes from the phase space). The sum over electron, muon and tau semileptonic decay is $2.3 \times (10.4 \pm 0.4) = (23.9 \pm 0.9)\%$.

The second group of branching fractions in Table 1 are the 2 body decays of the B meson in which the W boson materializes into a $u\bar{d}$, (i.e., π^+ or ρ^+). One notices that the B^+ branching fractions are 1.5 - 2 times larger than the B^o's. The diagrams describing the $B^+ \rightarrow \pi^+ D^o$ decay are the tree and the color supressed shown in figure 2. The $B^o \rightarrow \pi^+ D^-$ decay proceeds through the tree and the W exchange diagram. If the W exchange amplitude is as large as the color supressed amplitude, this would imply that color supressed amplitude is in phase with the tree, and the W exchange amplitude is out of phase.

The third group of branching fractions in Table 1 are the 2 body decays of the B meson into a $D^{(*)}D_s^{(*)}$. These exclusive two body modes add up to $\approx (5.5 \pm 2.0)\%$. The inclusive yield of D_s coming from B decays was listed as $(8.6 \pm 2.2)\%$, which implies 64% of the $B \rightarrow XD_s$ are two body.

Table 1, Summary of Major B Meson Branching Fractions known in 1996

(Numbers from PDG Review[5])

Decay Mode	B^+ (%)	B^o (%)	**Admixture** B^+ **and** B^o (%)
$B \rightarrow \bar{D}l\nu$	1.6 ± 0.7	1.9 ± 0.5	
$B \rightarrow \bar{D}^*l\nu$	5.3 ± 0.8	4.6 ± 0.3	
$B \rightarrow \bar{D}^{**}l\nu$			2.7 ± 0.7
$B \rightarrow X_cl\nu$	10.1 ± 2.3	10.3 ± 1.0	
$B \rightarrow Xl\nu$			10.4 ± 0.4
$b \rightarrow ul\nu$			$\sim 0.18 \pm 0.05$
$B \rightarrow \bar{D}\rho^+$	1.34 ± 0.18	0.78 ± 0.14	
$B \rightarrow \bar{D}^*\rho^+$	1.55 ± 0.31	0.73 ± 0.15	
$B \rightarrow \bar{D}\pi^+$	0.53 ± 0.05	0.30 ± 0.04	
$B \rightarrow \bar{D}^*\pi^+$	0.52 ± 0.08	0.26 ± 0.04	
$B \rightarrow \bar{D}D_s^+$	1.7 ± 0.6	0.7 ± 0.4	
$B \rightarrow \bar{D}^*D_s^+$	0.1 ± 0.07	1.2 ± 0.6	
$B \rightarrow \bar{D}D_s^{*+}$	1.2 ± 1.0	2.0 ± 1.5	
$B \rightarrow \bar{D}^*D_s^{*+}$	2.3 ± 1.4	1.9 ± 1.2	
$B \rightarrow XD_s^+$			8.6 ± 2.2
$B \rightarrow D^-X$			24.2 ± 3.3
$B \rightarrow \bar{D}^oX$			58.0 ± 5.0
$B \rightarrow \Psi K$	0.10 ± 0.014	0.075 ± 0.021	
$B \rightarrow \Psi K^+\pi^+\pi^-$	0.14 ± 0.06		
$B \rightarrow \Psi K^+\pi^-$		0.11 ± 0.06	
$B \rightarrow \Psi K^*$	0.17 ± 0.05	0.16 ± 0.03	
$B \rightarrow \Psi X$			1.14 ± 0.06
$B \rightarrow$ **Charm-Baryons**			6.4 ± 1.1

The inclusive decay of B mesons to $\bar{D}$ mesons in Table 1 add up to $(82.2 \pm 6.0)\%$. These include the D mesons coming from semileptonic decay of the B mesons. Most of the rest of B meson decays are into Charmonium or Charm-Baryons. Adding the 1.14 ± 0.06 and the 6.4 ± 1.1 to the $82.2 \pm 6.0\%$, one has accounted for $(89.7 \pm 6.1)\%$ of B meson decays.

Inclusive B Meson Decay Branching Fractions

During the past few years, CLEO has made many remeasurements of inclusive branching fractions in B meson decay. The most recent CLEO measurements on the inclusive branching fractions are listed in Table 2. These results are generally consistent but a little more accurate than those shown in Table 1. The separate measurement of semileptonic decays of B^+ and B^o mesons was first made via full reconstruction of the $\bar{B}$ meson hadronic decay in the event then examining how often there was a lepton coming from the remaining B meson decay[6]. Although this method was very clear and simple, it was statistically limited by the small sample of fully reconstructed B (or $\bar{B}$) mesons. The results listed in Table 2 were obtained by partial reconstruction of $\bar{B}^o \to D^{*+}l^-\nu$, $D^{*+} \to \pi^+ D^o$, detecting only the lepton and the π^+[7]. Having collected a very large sample of partially reconstructed B^os and measuring how often there is also a lepton amongst the leftover tracks coming from the other B meson decay, the semileptonic branching fraction of the B^o was determined. To obtain the $B^- \to X^o l^- \nu$ branching fraction, the result of this analysis was then combined with a previous analysis[13] in which the semileptonic branching fraction averaged over charged and neutral B mesons was measured. The result indicates the B^o branching fraction is 0.53% larger than the B^+, which is indicates the B^o lifetime is 0.53% longer than the B^+. However, the uncertainty is large enough so that the branching fractions could be equal.

The inclusive decays to D mesons in table 2 are the result of observing how often it was possible to reconstruct a D^o (via $D^o \to K^-\pi^+$) and how often it was possible to reconstruct D^+ (via $D^+ \to K^-\pi^+\pi^+$) in a set of events coming from $\Upsilon(4S)$ decay. The same analysis was used to measure the inclusive B branching fraction to D^{*+} and D^{*o} by measuring how often it is possible to reconstruct a D^{*+} and how often a D^{*o}. One should understand the inclusive D branching fractions include D mesons coming from D^* decays.

Normally, the D mesons from $\bar{B}$ meson decay originate from the b quark transition, $b \to cW^-$. However, $\bar{D}$ mesons can come from $\bar{B}$ meson decay by the $W^- \to \bar{c}s$. Both the tree and the color supressed diagrams (see figure 2) can lead to $\bar{D}$ from $\bar{B}$ decays. A measurement of how often the $\bar{B}$ meson decays to a D meson and how often to a $\bar{D}$ meson has been made[9]. This was carried out by using the fact that the $\Upsilon(4S)$ decays to $B\bar{B}$. One of the two B mesons is tagged via the sign of the lepton in its semileptonic decay. Only high momentum leptons ($p_l > 1.4$ GeV/c) are used, to eliminate lepton from semileptonic D decay. The other B meson is assumed to have the opposite flavor (Corrections are made for the $B^o \leftrightarrow \bar{B}^o$ mixing of the neutral B mesons). Having tagged the flavor of one of the B mesons, the D meson coming from that same B meson is known to have an explicit flavor. This D meson, which comes from the tagged B meson, is identified via the angular correlation. Since the lepton has a momentum greater than 1.4 GeV/c, the D meson must be moving at an angle greater than 90^o away from the lepton in order to conserve momentum. The D mesons from the other B meson are isotropic, so the flavor of the D mesons in the same hemisphere as the lepton was studied. From the numbers in Table 2, one sees that 90% of the D mesons from B decay come from the c quark that originates from the $b \to cW^-$ transition and 10% come from the W boson.

The $B \to XD_s$ inclusive branching fractions were measured by studying the number of D_s mesons and their momentum spectrum at the $\Upsilon(4S)$ No attempt was made to tag the flavor of the B meson or its charge. From the D_s momentum spectrum it was concluded that the D_s is almost always coming from the W boson. To obtain the branching fraction, 12.11%, it was assumed that the B^+ and B^o branching fraction to D_s are the same. This value is significantly larger than the 1996 PDG value (see Table 1.).

The most interesting new inclusive result is the measurement of the B decay to ηX[12]. The 17.6% branching fraction is much larger than one might expect. Some of the η mesons come from the D and D_s mesons that are in the B meson decay. The contribution from feed down has been estimated from the inclusive $B \rightarrow \bar{D}^o, D^-$, and D_s branching fractions and the inclusive η branching fractions of each of these three charm mesons. The branching fraction estimates are $\mathcal{B}r(B \rightarrow \bar{D}X \rightarrow \eta X') = (2.5 \pm 0.5)\%$, and $\mathcal{B}r(B \rightarrow D_s X \rightarrow \eta X') = (2.8 \pm 0.6)\%$. Subtracting these leads to the conclusion $(12.3 \pm 1.8)\%$ of B decays

Table 2, Inclusive B Meson Branching Fractions from CLEO

Decay Mode	Branching Fraction (%)	Reference
Semileptonic Decays		
$B^+ \rightarrow X^o l^+ \nu$	$10.25 \pm 0.57 \pm 0.65$	[7]
$B^o \rightarrow X^- l^+ \nu$	$10.78 \pm 0.60 \pm 0.69$	[7]
Inclusive Decays to D mesons		
Assuming an Equal Admixture of $B^o\bar{B}^o$ and B^+B^-		
$B \rightarrow D^o X + \bar{B} \rightarrow D^o X$	$63.6 \pm 1.4 \pm 2.6$	[8]
$B \rightarrow D^+ X + \bar{B} \rightarrow D^+ X$	$23.5 \pm 0.9 \pm 2.4$	[8]
$B \rightarrow D^{*o} X + \bar{B} \rightarrow D^{*o} X$	$24.7 \pm 1.2 \pm 2.5$	[8]
$B \rightarrow D^{*+} X + \bar{B} \rightarrow D^{*+} X$	$23.9 \pm 1.5 \pm 1.7$	[8]
Inclusive Flavor Sensitive Decays to D mesons		
(lv) for D meson from $b \rightarrow c$, (uv) for D meson from $W^- \rightarrow \bar{c}s$		
$\bar{B} \rightarrow D^o X + \bar{B} \rightarrow D^+ X$ **(lv)**	79.2 ± 3.9	[9]
$\bar{B} \rightarrow \bar{D}^o X + \bar{B} \rightarrow D^- X$ **(uv)**	7.9 ± 2.2	[9]
Inclusive B $\rightarrow D_s$ Decays		
$B^+ \rightarrow D_s^+ X = B^o \rightarrow D_s^+ X$	$12.11 \pm 0.39 \pm 1.63$	[10]
Inclusive B $\rightarrow$ Charmonium Decays		
$B \rightarrow \Psi X = \bar{B} \rightarrow \Psi X$	$1.12 \pm 0.04 \pm 0.06$	[11]
$B \rightarrow \Psi X = \bar{B} \rightarrow \Psi X$ **Direct**	0.80 ± 0.08	[11]
$B \rightarrow \Psi' X = \bar{B} \rightarrow \Psi' X$	$0.34 \pm 0.04 \pm 0.03$	[11]
$B \rightarrow \chi_{c1} X = \bar{B} \rightarrow \chi_{c1} X$	$0.40 \pm 0.06 \pm 0.04$	[11]
$B \rightarrow \chi_{c2} X = \bar{B} \rightarrow \chi_{c2} X$	$0.25 \pm 0.10 \pm 0.03$	[11]
$B \rightarrow$ **Charmonium (total)**	1.79 ± 0.15	**from above**
Inclusive B Decays to ηX		
$(B \rightarrow \eta X)$	$17.6 \pm 1.1 \pm 1.2$	[12]

produce η mesons directly. η mesons are often described as partly an $s\bar{s}$ resonance, but this 12.3% branching fraction is much larger than the incusive $\mathcal{B}r(B \rightarrow \phi X) = (3.5 \pm 0.7)\%$[5].

Exclusive B Meson Decay Branching Fractions

The sum of all the exclusive branching fractions listed in Table 1 add up to $(15.6 \pm 2.1)\%$, (16.6% for B^+, 17.4% for B^o). In recent years, many other 2 body final states have been searched for. Most of these are "rare B decays"[14]. The exclusive final states listed in Table 1 have been remeasured. The new CLEO results for these and a few others are given in Table 3. There have been several new measurements of semileptonic decays. For the $b \rightarrow c$ final states, there have been no serious changes. The $D_1^o l\nu$ has been measured. There have also been measurements of the $b \rightarrow u$ final states, $\pi l\nu$ and $\rho l\nu$. The branching fractions of the exclusive $b \rightarrow cl\nu$ final states that have been observed add up to 7.0% which is only $\sim$ 67% of the inclusive branching fraction. The observed $b \rightarrow u$ final states add up to 0.043% compared with the inclusive rate of 0.18% from Table 1, i.e., only $\sim$ 25% of the $b \rightarrow ul\nu$ is understood.

Table 3, Exclusive B meson Decay Branching Fractions from CLEO

Decay Mode	B^+ (%)	B^o (%)	**Reference**
Semileptonic Decays			
$B \rightarrow Dl\nu$	$1.94 \pm 0.15 \pm 0.34$	$1.87 \pm 0.15 \pm 0.32$	**[15]**
$B \rightarrow D^* l\nu$	$5.13 \pm 0.54 \pm 0.64$	$4.49 \pm 0.32 \pm 0.39$	**[16]**
$B \rightarrow D_1^o l\nu$	$0.56 \pm 0.13 \pm 0.09$	?	**[17]**
$B \rightarrow \pi l\nu$		$0.018 \pm 0.004 \pm 0.004$	**[18]**
$B \rightarrow \rho l\nu$		$0.025 \pm 0.004 \pm 0.007$	**[18]**
Exclusive Two Body Charm Decays			
$B \rightarrow D\rho$	$1.35 \pm 0.12 \pm 0.15$	$0.81 \pm 0.11 \pm 0.18$	**[19]**
$B \rightarrow D^*\rho$	$1.68 \pm 0.21 \pm 0.28$	$0.74 \pm 0.10 \pm 0.14$	**[19]**
$B \rightarrow D\pi$	$0.55 \pm 0.04 \pm 0.05$	$0.29 \pm 0.04 \pm 0.06$	**[19]**
$B \rightarrow D^*\pi$	$0.434 \pm 0.033 \pm 0.038$	$0.281 \pm 0.011 \pm 0.022$	**[20]**
$B \rightarrow DD_s^+$	$1.26 \pm 0.22 \pm 0.29$	$0.87 \pm 0.24 \pm 0.22$	**[21]**
$B \rightarrow DD_s^{*+}$	$0.87 \pm 0.27 \pm 0.20$	$1.00 \pm 0.35 \pm 0.25$	**[21]**
$B \rightarrow D^* D_s^+$	$1.40 \pm 0.43 \pm 0.39$	$0.93 \pm 0.23 \pm 0.19$	**[21]**
$B \rightarrow D^* D_s^{*+}$	$3.10 \pm 0.88 \pm 0.75$	$2.03 \pm 0.50 \pm 0.43$	**[21]**
$B \rightarrow D^- D^+$		< 0.12	**[22]**
$B \rightarrow D^{*\pm} D^{\mp}$		< 0.18	**[22]**
$B \rightarrow D^{*-} D^{*+}$		< 0.22	**[22,26]**
Exclusive B $\rightarrow$ Charmonium Decays			
$B \rightarrow \Psi K$	$0.102 \pm 0.008 \pm 0.007$	$0.085 \pm 0.013 \pm 0.006$	**[23]**
$B \rightarrow \Psi K^*$	$0.141 \pm 0.023 \pm 0.024$	$0.132 \pm 0.017 \pm 0.017$	**[23]**
$B \rightarrow \Psi \pi$	0.0056 ± 0.0027	< 0.0058	**[24]**
$B \rightarrow \Psi \rho$	< 0.077	< 0.025	**[24]**
$B \rightarrow \Psi \omega$		< 0.027	**[24]**

The exclusive two body charm decays in which the W boson materializes as a π, ρ or D_s have been remeasured. Most of the results agree with the earlier measurements and are more accurate. The remeasurements on $B \to \Psi K^{(*)}$ have similar results.

Summary- What Fraction of B Meson Decays are "Understood"

Theoretically, the Semileptonic decays of B mesons are the easiest to understand, because there is only one hadronic vertex. Originally[25], the semileptonic branching fraction was estimated to be approximately 16%. After independent measurements at DORIS, CESR, and LEP, we find the branching fraction is significantly smaller. The generic average of the CLEO measurements gives the inclusive branching fraction,

$$\mathcal{B}r(\bar{B} \to Xl\nu) = (10.5 \pm 0.89)\%.$$

Although using QCD corrections, theorists have recently suggested the B semileptonic branching fraction could be as low as 12%, the CLEO result is a theoretical challenge. Furthermore, only a fraction of the of the hadronic content of the semileptonic decays have been measured. Summing over the measured charm hadronic states, one has

$$\mathcal{B}r(\bar{B} \to (D + D^* + D^{**})l\nu) = (7.00 \pm 0.85)\%$$

Therefore, we understand $(7.00 \pm 0.85)/(10.5 \pm 0.89) = (67.0 \pm 13.7)\%$ of semileptonic branching fractions.

From the CLEO measurement of the flavor dependence of the decay of B mesons to D mesons, we know the $\mathcal{B}r(\bar{B} \to DX) = (79.2 \pm 3.9)\%$ (i.e., from $b \to c$ at the lower vertex). Assuming the exclusive semileptonic branching fractions to τ's are 0.3 times the branching fractions to electrons and/or muons, and adding the exclusive semileptonic decays to e's, μ's, and τ's, we have for the total exclusive semileptonic branching fraction

$$\mathcal{B}r(\bar{B} \to D^{(*,**)}(e + \mu + \tau)\nu) = (2.3 \times (7.00 \pm 0.85) = (16.1 \pm 2.0)\%$$

The exclusive two body decays resulting in a D meson add up to

$$\mathcal{B}r(\bar{B} \to D\pi + D^*\pi + D\rho + D^*\rho + DD_s + D^*D_s + DD_s^* + D^*D_s^*) = (8.8 \pm 1.2)\%$$

(This was calculated from the numbers in Table 3, averaging over B^+ and B^o.) Putting the above numbers together, the inclusive $B \to DX$ decays are "understood" at the level,

$$\mathcal{B}r(\bar{B} \to D^{(*)}(l\nu + \pi + \rho + D_s)) = (16.1 \pm 2.0) + (5.73 \pm 1.17) + (3.07 \pm 0.35) = (24.9 \pm 1.8)\%$$

This is $(24.9 \pm 1.8)/(79.2 \pm 3.9) = 0.31 \pm 0.03$ of the inclusive D mesons coming from the $b \to c$ vertex.

The average of exclusive final states with charmonium that have been measured add up to $\sim (0.23 \pm 0.03)\%$. The exclusive baryon final states have not yet been fully reconstructed. Therefore, we have an exclusive understanding of $(24.9 \pm 1.8 + 0.23 \pm 0.03) = (25.1 \pm 1.8)\%$ of the B decays.

In terms of inclusive branching fractions, in the $\bar{B} \to DX$ decays, the X represents $l\nu X'$, $D_s X''$, and X'''. Here X' includes the π's coming from D^* or D^{**} which we know something about, but X'' and X''' are not known. From the value of the branching fraction $\bar{B} \to DX = (79.2 \pm 3.9)\%$, we calculate,

$$\begin{aligned} \mathcal{B}r(\bar{B} \to DX''') &= \bar{B} \to D(X - l\nu X' - D_s X'') \\ &= (79.2 \pm 3.9) - (2.3 \times (10.5 \pm 0.89)) - (12.1 \pm 1.7) \\ &= (42.9 \pm 4.7)\% \end{aligned}$$

This means we know nothing about $(42.9/79.2) = 54\%$ of the inclusive $B \to DX$ decays.

The total inclusive branching fractions, (excluding the "rare" decays) add up to

$$\begin{aligned} \mathcal{B}r(B \to DX + charmonium X' + baryons X'') &= (79.2 \pm 3.9) + (1.8 \pm 0.2) + (6.4 \pm 1.1) \\ &= (87.4 \pm 4.1)\% \end{aligned}$$

CLEO has recently made many measurements of rare decays (and upper limits of rare decays)[14]. However, the total sum of the measured modes and the upper limits on rare B decay branching fractions is less than 2×10^{-3}, so there is no need to includes these at this time. The conclusion is one must invent non-rare decay modes and look for them.

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26. Recently there has been a measurement of the branching fraction, $\mathcal{B}r(B \to D^{*-}D^{*+}) = (7.8^{+5.4}_{-3.8} \pm 1.5) \times 10^{-4}$. This has been submitted to the Van Couver conference, CLEO CONF 98-07; ICHEP98 849.