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Semileptonic Branching Fractions of Charged and Neutral B Mesons

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Abstract

An examination of leptons in $\Upsilon(4S)$ events tagged by reconstructed B decays yields semileptonic branching fractions of $b_- = (10.1 \pm 1.8 \pm 1.4)\%$ for charged and $b_0 = (10.9 \pm 0.7 \pm 1.1)\%$ for neutral B mesons. This is the first measurement for charged B. Assuming equality of the charged and neutral semileptonic widths, the ratio $b_-/b_0 = 0.93 \pm 0.18 \pm 0.12$ is equivalent to the ratio of lifetimes.

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Semileptonic B decay proceeds through a coupling of the b-quark to a c- or u-quark and a $l^- \bar{\nu}$ pair (via a virtual W^-). This is known as a *spectator* process because the accompanying quark plays no direct role. In the naïve spectator model for hadronic decays, the relationship between semileptonic and hadronic widths, and thus the semileptonic branching fraction, is readily predicted [1]. Unfortunately, this simple picture does not seem to hold; for the past decade, the measured average branching fraction, $\bar{b}$, of B's in $\Upsilon(4S)$ events [2–4] has been $\sim$15% lower than predictions [1].

The hadronic width may be altered by contributions from nonspectator diagrams or by interference among final state quarks in spectator processes. Both mechanisms carry intrinsic dependences on the flavor of the spectator and do not apply to semileptonic decays. They may therefore result in unequal charged and neutral semileptonic branching fractions, b_- and b_0. The asymmetry is predicted to be less than 10% [1].

Previous measurements in $\Upsilon(4S)$ events carried several uncertainties. If the Υ(4S) decays to final states other than $B\bar{B}$, there will be an apparent shift in $\bar{b}$ [5]. Rates of exclusive decay determine $(b_- f_{+-})/(b_0 f_{00})$, where f_{+-} and f_{00} are the production fractions of neutral and charged $B\bar{B}$ events [6]. This gives b_-/b_0 if $f_{+-}/f_{00} = 1$, but the uncertainty on this assumption is a major source of systematic error. These uncertainties are minimized in *tagged* measurements where the number of B mesons in the event sample is counted directly rather than being inferred from the number of $\Upsilon(4S)$ events. We report here the measurements via tagging of b_-, b_0 and their ratio. This is a first measurement of b_-. If there is no asymmetry in semileptonic widths, then the ratio b_-/b_0 is equal to the ratio of lifetimes, which is measured at higher energies [7].

The data were collected with the CLEO II detector [8] at the Cornell Electron Storage Ring (CESR) and consist of integrated luminosities of 1.35 fb^{-1} on the $\Upsilon(4S)$ resonance and 0.64 fb^{-1} taken at a CM energy which is lower by 60 MeV (continuum). All events considered in this report are required to pass our standard hadronic criteria, which require at least 3 well-fitted charged tracks, a measured energy at least 0.15 times the CM energy and an event vertex consistent with the known interaction point.

B decays are reconstructed using three methods, (A) full reconstruction of all decay products, (B) partial reconstruction of semileptonic decay, and (C) partial reconstruction of a hadronic decay. Tag (A) gives the only measurement of b_-. All three yield b_0, where method (B) dominates statistically. Each analysis is performed both with and without a requirement that events contain a hard lepton consistent with being a primary decay product of the other B. For B^-, we need only consider leptons with charge corresponding to B^+ [9]. For $\bar{B}^0$, since B^0 mixes with $\bar{B}^0$, we accept leptons of either sign.

In tag (A), we reconstruct hadronic B decays [10] in eight modes: $D\pi^-$, $D^*\pi^-$, $D\rho^-$, $D^*\rho^-$, Da_1^-, $D^*a_1^-$, ψK and ψK^*, with charm mesons in the channels:

$$\begin{aligned}
D^{*+} &\rightarrow D^0\pi^+,\ D^+\pi^0 \\
D^{*0} &\rightarrow D^0\pi^0 \\
D^0 &\rightarrow K^-\pi^+,\ K^-\pi^+\pi^0,\ K^-\pi^+\pi^+\pi^-,\ K^0_S\pi^0,\ K^0_S\pi^+\pi^- \\
D^+ &\rightarrow K^-\pi^+\pi^+,\ K^0_S\pi^+ \\
J/\psi &\rightarrow e^+e^-,\ \mu^+\mu^-
\end{aligned}$$

and light mesons reconstructed in the channels $\pi^0\rightarrow\gamma\gamma$, $K^0_S\rightarrow\pi^+\pi^-$, $K^{*+}\rightarrow K^+\pi^0$, $K^{*+}\rightarrow K^0_S\pi^+$, $K^{*0}\rightarrow K^0_S\pi^0$, $K^{*0}\rightarrow K^+\pi^-$, $\rho^+\rightarrow\pi^0\pi^+$, $\rho^0\rightarrow\pi^+\pi^-$ and $a_1^+\rightarrow\rho^0\pi^+$.

All events must contain at least four well-fitted charged tracks and have a ratio R_2 of second and zeroth Fox-Wolfram moments [11] less than 0.45. Leptons are required to have momentum 1.4–2.4 GeV, to be within the barrel region of the detector, and to be consistent with originating at the interaction point. Muons must penetrate at least five nuclear absorption lengths in the muon detector. Electron identification utilizes primarily the ratio of calorimetric energy to momentum and specific ionization in the drift chamber. Except in the case of direct slow pions from D^*, both the time-of-flight and dE/dx systems are used for hadron identification. Photons must be detected in regions of good calorimeter resolution and exceed a minimum energy, equal to 30 MeV for most of the detector acceptance. Candidates for π^0, K^0_S, D, D^*, and J/ψ are required to have an invariant mass (for D^* a $(D^* - D)$ mass difference) consistent with the nominal mass [12]. The K^*, ρ and a_1^+ masses are each required to be within one full decay width of the nominal mass.

From the measured components, we obtain a candidate momentum $\mathbf{p}_B = \sum \mathbf{p}_i$ and energy $E_B = \sum E_i$. We calculate $\delta(\Delta E) = (E_{\text{beam}} - E_B)/\sigma(\Delta E) = \Delta E/\sigma(\Delta E)$ and the beam-constrained mass $M_B = [E^2_{\text{beam}} - (\sum \mathbf{p}_i)^2]^{1/2}$, where E_{beam} is the beam energy and $\sigma(\Delta E)$ is calculated from the error matrices of daughter particles. To be considered further a candidate must satisfy $|\delta(\Delta E)| < 7.0$, $M_B > 5.2$ GeV. We consider charged and neutral B's separately, but all modes are otherwise combined. At most one charged and one neutral B candidate per event are allowed; for each, a χ^2 is constructed based on the agreement of its component π^0, K^0_S, D, D^* and charged hadron candidates to their hypotheses, and the candidate with the highest likelihood is selected.

Due to the spin orientation of the $\Upsilon(4S)$ produced in e^+e^- annihilation, the angle θ_B of the B momentum with the beam axis is distributed as $\sin^2\theta_B$. We require $|\cos\theta_B| < 0.95$. The "thrust angle" θ_{thr}, between the thrust axes of the B candidate and of the remainder of the event, is also examined. The distribution in $\cos\theta_{\text{thr}}$ is uniform for B decays and peaks near $|\cos\theta_{\text{thr}}| = 1$ for continuum. We require $|\cos\theta_{\text{thr}}| < 0.9$ (0.8,0.7) for $B \to X\pi$ ($B \to X\rho$, $B \to X a_1$) where X is D or D^*.

We define two regions in $|\delta(\Delta E)|$, "signal" ($|\delta(\Delta E)| < 2.5$) and "sideband" ($4.0 < |\delta(\Delta E)| < 6.5$). Looking both at data on the continuum and simulations of $B\bar{B}$ background, the signal and sideband regions are found to give similar distributions in M_B. We require that the difference between M_B and the nominal B mass be less than 6 MeV and count candidates, subtracting directly the sideband from the signal sample. We find 834 ± 42 B^- and 515 ± 31 $\bar{B}^0$ mesons. The same technique is used in events containing an identified lepton. Figure 1 (a) and (b) show the sideband superimposed on the signal for both samples. Details of this analysis are given in ref. [13].

The method (B) of partial $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ reconstruction, where the decay $D^{*+} \to D^0\pi^+$ is identified using only the π^+, has been used by CLEO II to measure $\bar{B}^0$ mixing [14]. This approach yields a large sample and exploits the extremely low energy of the D^{*+} decay; the momentum of the π^+ is scaled to obtain an approximate four-momentum $(\widetilde{E}_{D^*}, \tilde{\mathbf{p}}_{D^*})$ for the D^{*+}. The squared missing mass,

$$\widetilde{M}^2_\nu \equiv (E_{\text{beam}} - \widetilde{E}_{D^*} - E_\ell)^2 - (\tilde{\mathbf{p}}_{D^*} + \mathbf{p}_\ell)^2$$

approximates the squared mass of the neutrino.

The pion and lepton momenta p_π and p_ℓ are required to satisfy $p_\pi < 0.19$ GeV and $1.8 < p_\ell < 2.4$ GeV. Pion candidates are required to have a consistent specific ionization.

Background from charged B's arising from $B^- \to D^{**0}\ell\nu$ ($D^{**0} \to D^{*+}\pi^-$) is suppressed by demanding a high lepton momentum.

We examine the $\widetilde{M}_\nu^2$ distribution and select candidates in the signal region ($\widetilde{M}_\nu^2 > -2$ GeV^2). The continuum contribution is estimated using the data collected at energies off resonance, corrected for luminosity and energy differences. Background from $B\bar{B}$ events is estimated via Monte Carlo. Its shape in $\widetilde{M}_\nu^2$ is largely defined by the phase space, and the simulation is in agreement with data in the nonsignal regions and for combinations where the lepton and pion carry the same charge. Its normalization is obtained by fitting to data in the sideband region, $-20 < \widetilde{M}_\nu^2 < -4$ GeV^2. We find 7119 ± 139 tags [15]. The same procedure is applied to tagged events with a lepton. We require that the cosine of the angle between the two leptons in these events be less than 0.99, to eliminate multiply reconstructed tracks. The $\widetilde{M}_\nu^2$ distributions obtained after continuum subtraction are shown in Fig. 1, (c) and (d).

The decay chain $\bar{B}^0 \to D^{*+}\pi^-$, $D^{*+} \to D^0\pi^+$ produces a hard π^- and a soft π^+, which are used in method (C) to identify the chain without detecting the D^0 [3]. Briefly, the energy E_D of the D^0 is obtained by energy conservation. Since the D^0 and π^+ must form a D^{*+}, defining their energies fixes the angle θ between them as well as the decay angle θ^* of the π^+ in the D^{*+} rest frame relative to the D^{*+} direction in the lab. If one then calculates the maximum possible $D^{*+}\pi^-$ invariant mass M_B under these constraints, it must for a signal candidate lie in the narrow region between the actual B mass and the beam energy. Details are given in ref. [16].

Taking events with $R_2 < 0.45$, we select pairs of oppositely charged tracks compatible with the tagging mode, i.e., for which values of E_D and $\cos\theta$ are physical. The fast track must have specific ionization consistent with being a pion and not be identified as an electron or muon. Because the D^{*+} is fully polarized, the π^+ decay angle is distributed as $\cos^2\theta^*$, and we require $|\cos\theta^*| > 0.5$.

Each event is partitioned approximately into the tag B and the other B by including with the candidate the two particles (charged tracks or isolated neutral clusters) with the largest momentum component opposite the fast pion. The angle θ_{thr} is then calculated as in tag (A). We require $|\cos\ \theta_{\mathrm{thr}}| < 0.7$.

The distribution in M_B is fitted to a Gaussian plus background. The signal mean and width are obtained via Monte Carlo simulation. We define a signal region $M_B > 5.276$ GeV and a mass sideband $M_B < 5.26$ GeV. Uncorrelated track pairs from $B\bar{B}$ events give a flat distribution. Correlated pairs from $B \to D^{**}\pi^-$ ($D^{**} \to D^{*+}\pi$, $D^{*+} \to D^0\pi^+$) produce a broad peak in the signal region. The fitted background shape is the sum of this shape plus a first order polynomial. We find 822 ± 53 tags. The number of tagged events with an additional lepton is determined by counting candidates in the signal region, subtracting backgrounds from continuum, random $B\bar{B}$ combinations and $B \to D^{**}\pi^-$. To exclude secondary leptons from the undetected D^0, which are nearly opposite to the fast pion, we require the cosine of the angle between the fast pion and lepton to be greater than -0.85.

For all three tag types, additional leptons are selected in the range $1.4 - 2.4$ GeV. Background occurs when the reconstructed decay is correct but the lepton is fake (a hadron passing lepton identification) or, for neutral B's, a secondary from charmed meson decay. Fakes are assessed separately for each type of tag. In each case, events which contain candidates in the signal regions are selected. Excluding those which comprise each candidate, all tracks within the acceptances of lepton identification which fail the identification criteria are considered. These tracks, each weighted by the appropriate fake rate per track, are summed. The contribution from background candidates is estimated using events selected from the various sidebands. The fake rate as a function of momentum is determined using data taken at the $\Upsilon(1S)$, which produces very few leptons. Of all leptons from B decay with momentum above 1.4 GeV, the fraction from secondaries is found to be 0.028 ± 0.008. The fraction among detected leptons is $0.027 \pm 0.008(0.022 \pm 0.007)$ for electrons (muons). For tags (B), these factors are twice as large because the undetected D^0 may also contribute. These corrections are applied to the neutral B tags.

The efficiency for geometric acceptance, track reconstruction and identification is found to be 65.1% (50.7%) for electrons (muons). Requirements on dilepton opening angle and event characteristics result in effective adjustmentments of -1.7%, -1.1% and -12% for (A), (B) and (C), respectively. Dependences of tagging efficiencies on the decay charge multiplicity of the other B in an event result in effective increases of 6% for (A) and 3% for (B) and (C). To extrapolate the spectrum to lower momenta, we use the model of Isgur et al. ($ISGW$), [17] which predicts that three exclusive modes dominate, $B \rightarrow D\ell\nu$, $B \rightarrow D^{*}\ell\nu$ and $B \rightarrow D^{**}\ell\nu$. Based on our fit to the inclusive lepton spectrum, [4] we take their proportions to be 24.5/54.5/21. For electrons (muons) the fraction of the spectrum above 1.4 GeV is found to be 48.1% (51.4%). Assuming $e - \mu$ universality, we average the electron and muon totals. Shown in Table I are the raw numbers of tags with and without leptons, corrections, and branching fractions.

The systematic uncertainties in efficiencies for tracking, lepton identification and lepton spectrum extrapolation are common to all of the analyses and are found to be 2.0%, 2.5% and 8%, respectively. The effect of the lepton spectrum is simulated by varying the percentage of $B \rightarrow D^{**}\ell\nu$ from 0% to 30% in the ISGW model. Uncertainties due to fitting methods and functions are determined by varying the techniques and shapes used to fit signals and backgrounds. Selection of events and candidates add uncertainties which are estimated via Monte Carlo. The uncorrelated systematic uncertainties are summarized in Table II.

We average the $\bar{B}^0$ measurements, using the quadratic sum of statistical and uncorrelated systematic errors to determine relative weights. The results are

$$b_- = (10.1 \pm 1.8 \pm 1.4)\%,$$
$$b_0 = (10.9 \pm 0.7 \pm 1.1)\%.$$

Both are consistent with the CLEO II average inclusive branching fraction, $(10.9 \pm 0.1 \pm 0.3)\%$ [4]. The ratio is

$$\frac{b_-}{b_0} = 0.93 \pm 0.18 \pm 0.12.$$

The error due to uncertainty in f_{+-}/f_{00} is less than 1%. This result is in agreement with our other result and with that of ARGUS [6], which assume that $f_{+-}/f_{00} = 1$. It is consistent with the world average lifetime ratio of 1.10 ± 0.11 [7] as well as with theoretical expectations, and is of comparable significance to existing individual measurements.

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TABLES

TABLE I. Numbers of tags without (all) and with (e, μ) additional leptons. Tag types are described in the text. Subtraction of estimated fakes (a) and secondaries (b) yields the number of detected primary leptons (c), which is corrected for efficiency to obtain (d). The electron and muon values are averaged to obtain N_ℓ, and the branching fraction B.

	B^- (A)	$\bar{B}^0$ (A)	$\bar{B}^0$ (B)	$\bar{B}^0$ (C)
all	834 ± 42	515 ± 31	7119 ± 139	822 ± 53
e	32.0 ± 6.8	23.0 ± 5.3	271.9 ± 22.1	25.8 ± 6.2
(a)	0.17 ± 0.05	0.13 ± 0.04	1.5 ± 0.4	0.1 ± 0.02
(b)	—	0.7 ± 0.2	14.6 ± 4.3	0.7 ± 0.2
(c)	31.8 ± 6.8	22.3 ± 5.3	255.8 ± 22.5	25.0 ± 6.2
(d)	97.2 ± 20.8	68.0 ± 16.2	826.0 ± 72.7	90.9 ± 22.5
μ	21.0 ± 5.4	21.0 ± 5.4	197.7 ± 20.2	19.6 ± 5.5
(a)	1.1 ± 0.3	0.9 ± 0.3	8.3 ± 2.5	0.5 ± 0.1
(b)	—	0.5 ± 0.2	8.3 ± 2.7	0.4 ± 0.1
(c)	19.9 ± 5.4	19.7 ± 5.4	181.1 ± 20.5	18.7 ± 5.5
(d)	73.0 ± 19.8	72.1 ± 19.9	702.5 ± 79.6	81.7 ± 24.0
N_ℓ	84.6 ± 14.3	69.6 ± 12.5	767.5 ± 53.5	86.6 ± 16.3
B	10.1 ± 1.8	13.5 ± 2.6	10.5 ± 0.8	10.2 ± 1.9

TABLE II. Uncorrelated systematic errors, given as percent of signal.

	B^- (A)	$\bar{B}^0$ (A)	$\bar{B}^0$ (B)	$\bar{B}^0$ (C)
Event selection	1.7	1.7	0.5	4.1
Single tag/event	7.2	5.0	–	–
# tags	4.8	6.5	2.6	4.6
# tags with leptons	3.4	5.1	7.1	5.6
Tagging efficiency	6.0	6.0	3.0	3.0
Secondary leptons	–	0.8	1.6	0.8
Fake leptons	0.1	0.2	0.2	0.2
Total uncorrelated	11.2	11.5	8.3	8.9

FIGURES

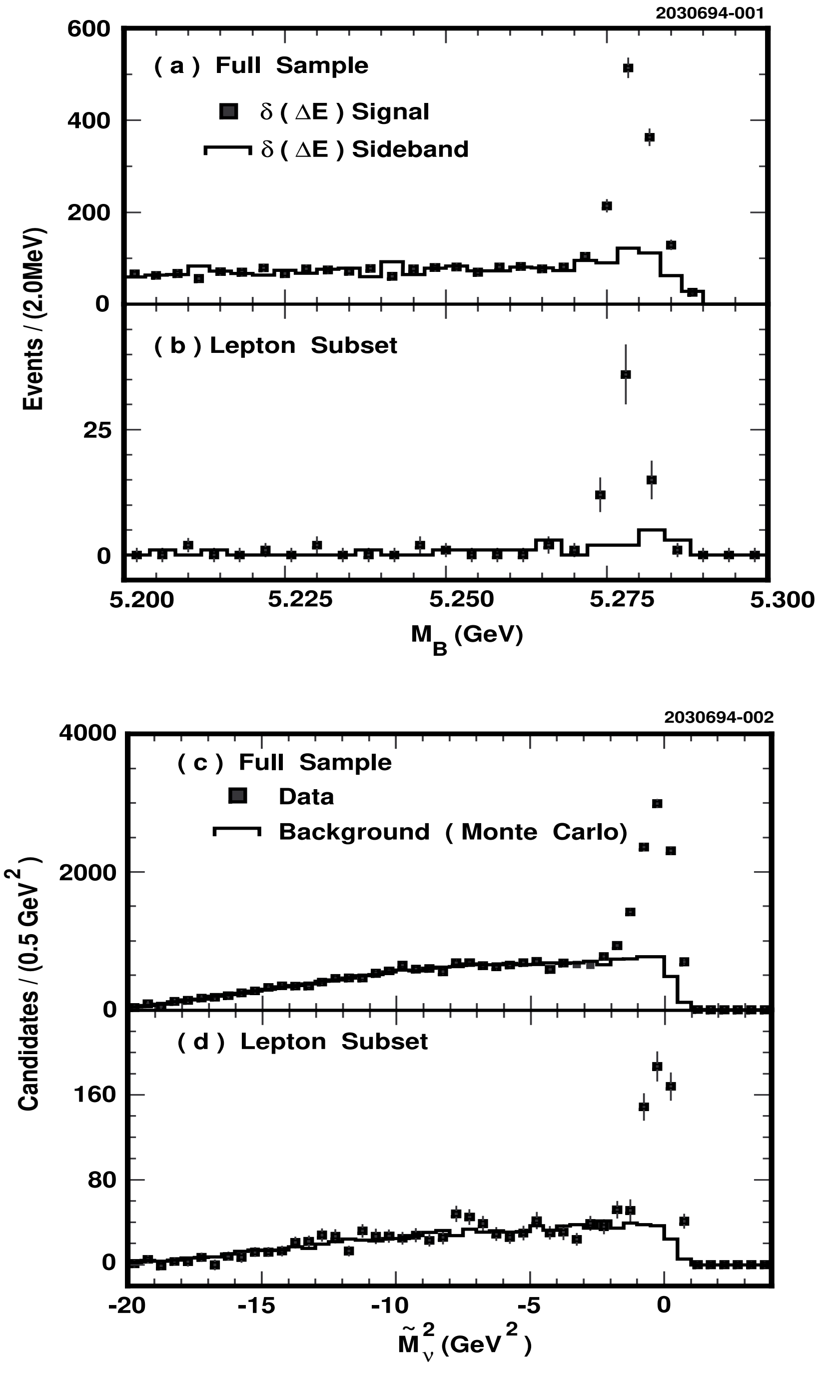

FIG. 1. Tag samples, without and with additional lepton required. (a), (b): B^-, method (A), M_B distributions; (c), (d): $\bar{B}^0$, method (B), $\widetilde{M}_\nu^2$ distributions.