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Semileptonic Branching Fractions of Charged and Neutral B Mesons

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An examination of leptons in $Y(4S)$ events tagged by reconstructed B meson decays yields semileptonic branching fractions of $b_{-} = (10.1 \pm 1.8 \pm 1.5)\%$ 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 mesons. 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 meson 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 naive spectator model for hadronic decay, the ratio of semileptonic and hadronic widths, and thus the semileptonic branching fraction, is readily predicted [1]. Unfortunately, this simple picture may not hold; for the past decade, the average branching fraction \bar{b} of B mesons in $Y(4S)$ 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 decay. 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 $Y(4S)$ events carried several uncertainties. If the $Y(4S)$ decays to final states other than $B\bar{B}$, an apparent shift in b_- occurs [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. This error is minimized in *tagged* measurements where the number of B mesons is counted directly rather than being inferred from the number of $Y(4S)$ events. We report here such measurements of b_- , b_0 , and their ratio. This is a first measurement of b_- . If the semileptonic widths are equal, then the ratio b_-/b_0 is equal to the ratio of lifetimes 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 1.35 fb^{-1} on the $Y(4S)$ resonance and 0.64 fb^{-1} taken at a c.m. energy that is lower by 60 MeV (continuum). All events are required to pass our standard hadronic criteria, which require at least three well-fitted charged tracks, a measured energy 0.15 times the c.m. energy, and an event vertex consistent with the known interaction point.

B meson decays are reconstructed using three methods: (A) full reconstruction of all decay products, (B) partial reconstruction of a 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 mesons. For B^- , we consider only 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 meson decays [10] in eight modes

$$D\pi^-, D^*\pi^-, D\rho^-, D^*\rho^-,$$

$$Da_1^-, D^*a_1^-, \psi K, \psi K^*,$$

with charm mesons in the channels

$$D^{*+} \rightarrow D^0\pi^+, D^+\pi^0,$$

$$D^{*0} \rightarrow D^0\pi^0,$$

$$D^0 \rightarrow K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-,$$

$$K_S^0\pi^0, K_S^0\pi^+\pi^-,$$

$$D^+ \rightarrow K^-\pi^+\pi^+, K_S^0\pi^+,$$

$$J/\psi \rightarrow e^+e^-, \mu^+\mu^-,$$

and light mesons reconstructed in the channels

$$\pi^0 \rightarrow \gamma\gamma, K_S^0 \rightarrow \pi^+\pi^-, K^{*+} \rightarrow K^+\pi^0,$$

$$K^{*+} \rightarrow K_S^0\pi^+, K^{*0} \rightarrow K_S^0\pi^0, K^{*0} \rightarrow K^+\pi^-,$$

$$\rho^+ \rightarrow \pi^0\pi^+, \rho^0 \rightarrow \pi^+\pi^-, a_1^+ \rightarrow \rho^0\pi^+.$$

We require of events at least four well-fitted charged tracks and a ratio R_2 of second and zeroth Fox-Wolfram moments [11] less than 0.45. Leptons must have momentum 1.4–2.4 GeV, be within the barrel region of the detector, and be consistent with originating at the interaction point. Muons must penetrate at least five nuclear absorption lengths. Electrons are identified primarily by the ratio of calorimetric energy to momentum and specific ionization (dE/dx) in the drift chamber. Except in the case of direct slow pions from D^* , both time of flight and dE/dx 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_S^0 , D , D^* , and J/ψ must have an invariant mass (for D^* a $D^* - D$ mass difference) consistent with the nominal value [12]. The K^* , ρ , and a_1^+ masses are each required to be within one full decay width of the nominal mass.

The measured components give 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 $M_B = [E_{\text{beam}}^2 - (\sum \mathbf{p}_i)^2]^{1/2}$, where E_{beam} is the beam energy and $\sigma(\Delta E)$ is calculated from the

error matrices of daughter particles. A candidate must then satisfy $|\delta(\Delta E)| < 7.0$, $M_B > 5.2$ GeV. Charged and neutral B mesons are separated, but all modes are otherwise combined. At most one charged and one neutral B meson candidate per event are allowed; the chosen candidate is the one with the highest likelihood, based on the agreement of its component π^0 , K_S^0 , D , D^* , and charged hadron candidates with their hypotheses.

Because of the spin orientation of the $Y(4S)$ produced in e^+e^- annihilation, the angle θ_B of the B meson momentum with the beam axis is distributed as $\sin^2\theta_B$. We require $|\cos\theta_B| < 0.95$. The ‘‘thrust angle’’ θ_{thr} , the angle between the thrust axes of the B meson candidate and of the remainder of the event, is uniformly distributed in $\cos\theta_{\text{thr}}$ for B meson decays and peaks near $|\cos\theta_{\text{thr}}| = 1$ for the continuum. We require $|\cos\theta_{\text{thr}}| < 0.9$ (0.8, 0.7) for $B \rightarrow X\pi$ ($B \rightarrow X\rho$, $B \rightarrow Xa_1$) where X is D or D^* .

We define two regions in $|\delta(\Delta E)|$, ‘‘signal’’ [$|\delta(\Delta E)| < 2.5$] and ‘‘sideband’’ [$4.0 < |\delta(\Delta E)| < 6.5$]. In 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 meson mass be less than 6 MeV and count candidates, subtracting directly the sideband from the signal sample. We find $834 \pm 42 B^-$ and $515 \pm 31 \bar{B}^0$ mesons. The same technique is used in events containing an identified lepton. Figures 1(a) and 1(b) show the sideband superimposed on the signal for both samples. Details are given in Ref. [13].

The method (B) of partial $\bar{B}^0 \rightarrow D^{*+}\ell^-\bar{\nu}$ reconstruction, where the decay $D^{*+} \rightarrow D^0\pi^+$ is identified using only the π^+ , has been used to measure \bar{B}^0 mixing [14]. It

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 $(\tilde{E}_{D^*}, \tilde{\mathbf{p}}_{D^*})$ for the D^{*+} . The squared missing mass,

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

approximates the squared mass of the neutrino.

We require five well-fitted charged tracks. The pion and lepton momenta p_π and p_ℓ must satisfy $p_\pi < 0.19$ GeV and $1.8 < p_\ell < 2.4$ GeV. Pion candidates are required to have a consistent dE/dx . Background from $B^- \rightarrow D^{*0}\ell^- \nu$ ($D^{*0} \rightarrow D^{*+}\pi^-$) is suppressed by demanding a high lepton momentum.

We examine the \tilde{M}_ν^2 distribution and select candidates in the signal region ($\tilde{M}_\nu^2 > -2$ GeV²). The continuum data, corrected for luminosity and energy differences, are used to estimate the nonresonant contribution. Background from $B\bar{B}$ events is estimated via Monte Carlo simulation. Its shape in \tilde{M}_ν^2 is largely defined by the phase space, and the simulation is in agreement with data in the nonsignal region and for combinations of leptons and pions with the same charge. Its normalization is obtained by fitting to data in the sideband, $-20 < \tilde{M}_\nu^2 < -4$ GeV². We find 7119 ± 143 tags [15]. The same procedure is applied to tagged events with an additional lepton. The cosine of the angle between the two leptons in these events is required to be less than 0.99, to eliminate multiply reconstructed tracks. The \tilde{M}_ν^2 distributions after continuum subtraction are shown in Figs. 1(c) and 1(d).

The decay chain $\bar{B}^0 \rightarrow D^{*+}\pi^-$, $D^{*+} \rightarrow D^0\pi^+$ produces a hard π^- and a soft π^+ , which are used in method (C) to identify it 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^+ form a D^{*+} , their energies define 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. The maximum possible $D^{*+}\pi^-$ invariant mass M_B under these constraints must, for a signal decay, lie in the narrow region between the actual B mass and the beam energy. Details are given in Ref. [3].

We require $R_2 < 0.45$ and 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 dE/dx consistent with being a pion and not be identified as an electron or muon. Because the D^{*+} is polarized, the π^+ decay angle is distributed as $\cos^2\theta^*$. We require $|\cos\theta^*| > 0.5$. Each event is partitioned approximately into the tag B and the other B by including with the tag 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 $|\cos\theta_{\text{thr}}| < 0.7$.

The distribution in M_B is fitted by a Gaussian plus background. The signal mean and width are obtained via Monte Carlo simulation. Uncorrelated track pairs from $B\bar{B}$ events give a flat distribution. Correlated pairs

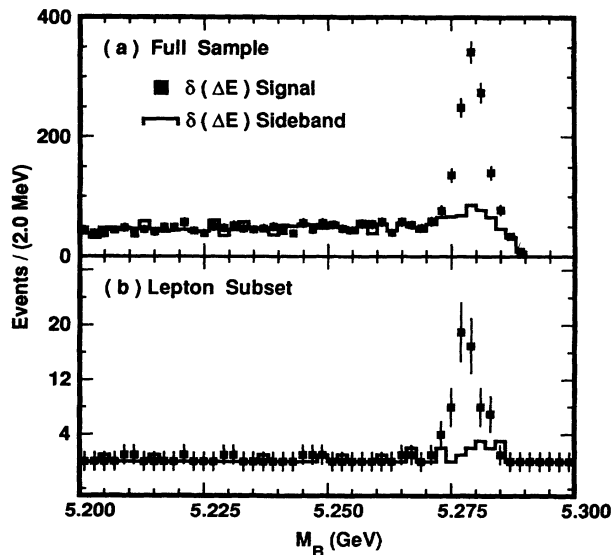


FIG. 1. Tag samples, without and with additional lepton required. (a), (b) B^- , method (A), M_B distributions; (c), (d) \bar{B}^0 , method (B), \tilde{M}_ν^2 distributions.

from $B \rightarrow D^{**}\pi^-$ ($D^{**} \rightarrow D^{*+}\pi$, $D^{*+} \rightarrow D^0\pi^+$) produce a broad peak in the signal region, $M_B > 5.276$ GeV. The fitted background shape is the sum of this plus a first-order polynomial. We find 822 ± 53 tags. Events with a lepton and a tag in the signal region are counted, then backgrounds from the continuum, random $B\bar{B}$ combinations, and $B \rightarrow D^{**}\pi^-$ are subtracted. To exclude leptons from the undetected D^0 , the angle between the lepton and fast pion is required to have a cosine 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 mesons, a secondary from charmed meson decay. Fakes are assessed separately for each type of tag. For each candidate in the signal region, all remaining tracks in the event within the acceptances of lepton identification which fail the criteria are considered. These tracks, each weighted by the appropriate fake rate, 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 $Y(1S)$, which produces very few leptons. Of all detected leptons from B meson decay with momentum above 1.4 GeV, the fraction from secondaries is found to be 0.027 ± 0.008 (0.022 ± 0.007) for electrons (muons). These corrections are applied to the neutral B meson tags. For tags (B), the values are doubled because the undetected D^0 may also contribute.

The efficiency for geometric acceptance, track reconstruction and identification is found to be 65.1% (50.7%) for electrons (muons). Requirements on opening angles and event characteristics result in effective adjustments of -1.7% , -1.1% , and -12% for tags (A), (B), and (C). Dependences of tagging efficiencies on the decay charge multiplicity of the other B mesons 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) [16], in which 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 - μ universality, we average the electron and muon totals. Shown in Table I are the numbers of tags with and without leptons, corrections, and branching fractions.

The systematic uncertainties on efficiencies for tracking, lepton identification, and 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 $B \rightarrow D^{**}\ell\nu$ from 0% to 30% in the ISGW model. Uncertainties due to fitting procedures are determined by varying the techniques and shapes used. Selection of events and candidates adds uncertainties which are estimated via Monte Carlo simula-

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 two values of (d) are averaged to obtain N_e , 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 ± 143	822 ± 53
e	32.0 ± 6.8	23.0 ± 5.3	271.9 ± 22.7	25.8 ± 6.2
(a)	0.17 ± 0.05	0.13 ± 0.04	1.5 ± 0.4	0.1 ± 0.02
(b)	—	0.6 ± 0.2	14.6 ± 4.3	0.7 ± 0.2
(c)	31.8 ± 6.8	22.3 ± 5.3	255.8 ± 23.1	25.0 ± 6.2
(d)	97.2 ± 20.8	68.0 ± 16.2	801.2 ± 72.4	88.2 ± 21.9
μ	21.0 ± 5.4	21.0 ± 5.4	197.7 ± 20.7	19.6 ± 5.5
(a)	1.1 ± 0.3	0.9 ± 0.3	8.3 ± 2.5	0.5 ± 0.1
(b)	—	0.4 ± 0.1	8.3 ± 2.7	0.4 ± 0.1
(c)	19.9 ± 5.4	19.7 ± 5.4	181.1 ± 21.0	18.7 ± 5.5
(d)	73.0 ± 19.8	72.1 ± 19.9	681.5 ± 79.1	79.3 ± 23.3
N_e	84.6 ± 14.3	69.6 ± 12.5	746.8 ± 53.4	84.0 ± 15.9
B	10.1 ± 1.8	13.5 ± 2.6	10.5 ± 0.8	10.2 ± 1.9

tions. The uncorrelated systematic errors 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

$$b_- = (10.1 \pm 1.8 \pm 1.5)\%$$

$$b_0 = (10.9 \pm 0.7 \pm 1.1)\%$$

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

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

This agrees with our other result and with that of ARGUS [6], which assume that $f_{+-}/f_{00} = 1$. Its error due to uncertainty in f_{+-}/f_{00} is less than 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.

TABLE II. Uncorrelated systematic errors (% 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	—	—
No. tags	5.5	6.3	2.6	4.6
No. tags with leptons	4.3	5.7	7.1	5.6
Tagging efficiency	5.7	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	11.7	11.7	8.3	8.9

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