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Measurement of the B Semileptonic Branching Fraction with Lepton Tags

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Abstract

We have used the CLEO II detector and 2.06 fb^{-1} of $\Upsilon(4S)$ data to measure the B-meson semileptonic branching fraction. The $B \to Xe\nu$ momentum spectrum was obtained over essentially the full momentum range by using charge and kinematic correlations in events with a high-momentum lepton tag and an additional electron. We find $\mathcal{B}(B \to Xe\nu) = (10.49 \pm 0.17 \pm 0.43)\%$, with overall systematic uncertainties less than those of untagged single-lepton measurements. We use this result to calculate the magnitude of the Cabibbo-Kobayashi-Maskawa matrix element V_{cb} and to set an upper limit on the fraction of $\Upsilon(4S)$ decays to final states other than $B\bar{B}$.

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The semileptonic branching fraction of the B meson has been a persistent puzzle in heavy flavor physics. While most measurements have been below 11%, theoretical calculations have generally given 12% or higher [1]. This discrepancy has stimulated much speculation. Recent suggestions of enhancement in the decay channel $b \to c\bar{c}s$ can explain the small semileptonic branching fraction [2], but the accompanying enhancement in c-quark production cannot easily be accommodated by CLEO data [3]. Without a satisfactory theoretical explanation it is essential to continue to reexamine and refine the experimental data on semileptonic B decay.

The most precise measurements of $\mathcal{B}(B \to X\ell\nu)$ are from studies of the single-lepton momentum spectrum at the $\Upsilon(4S)$ resonance. A recent CLEO II measurement [4] has a statistical precision of better than 0.5%, but is limited by systematic effects. Primary decays ($B \to X\ell\nu$) must be separated from secondary charm decays ($b \to c \to y\ell\nu$) by fitting the spectrum with models, introducing significant theoretical uncertainty. It must also be assumed that all $\Upsilon(4S)$ decays are to $B\bar{B}$. While this is reasonable, the published upper limit on the non-$B\bar{B}$ fraction is 13% [5].

The ARGUS experiment has reported an analysis that reduced the model dependence and sensitivity to non-$B\bar{B}$ decays by using dilepton events [6]. In this letter we describe a similar analysis performed with a ten times larger data sample. High-momentum lepton tags were used to separate primary and secondary electrons, giving a nearly model- and normalization-independent measurement of the B semileptonic branching fraction, and an improved limit on $\Upsilon(4S)$ decays to non-$B\bar{B}$ final states.

Our data sample was collected with the CLEO II detector [7] at the Cornell Electron Storage Ring (CESR). It consists of an integrated luminosity of 2.06 fb^{-1} at the $\Upsilon(4S)$, with 2.2 million $B\bar{B}$ events. Continuum background was studied with 0.96 fb^{-1} at center-of-mass energies about 60 MeV below the $\Upsilon(4S)$. We identified electron candidates with momenta greater than 0.6 GeV/c by requiring an energy deposit in the CsI calorimeter consistent with the measured momentum, and dE/dx consistent with that expected for an electron. Muon candidates were charged tracks with a minimum momentum of 1.4 GeV/c that penetrated at least five nuclear interaction lengths of absorber material. Leptons were selected from the best part of the detector ($|\cos\theta| < 0.71$ for electrons and $|\cos\theta| < 0.61$ for muons), with electron and muon detection efficiencies above 90%. Hadrons with momenta greater than 1.0 GeV/c were misidentified as electrons with a probability of approximately 0.1%, while the muon misidentification probability for hadrons above 1.4 GeV/c was about 1%.

We selected events with tag leptons of momentum greater than 1.4 GeV/c. Such leptons are predominantly from semileptonic decay of one of the two B mesons in an $\Upsilon(4S)$ decay. When a tag was found, we searched for an accompanying electron with minimum momentum 0.6 GeV/c. There are three main sources of these electrons. Semileptonic decay of the other B gives an electron with charge opposite to that of the tag. Semileptonic decay of a D meson from the other B gives an electron of the same charge as the tag. Semileptonic decay of a D from the same B contributes to the unlike-sign sample, but with a kinematic signature which makes its contribution easy to isolate, as is described below. The effect of $B^0\bar{B}^0$ mixing is small and can be accounted for explicitly.

At the $\Upsilon(4S)$, the B and the $\bar{B}$ are produced nearly at rest. There is little correlation between the directions of a tag lepton and an accompanying electron if they are the daughters of different B mesons. If they originate from the same B, however, there is a tendency for the tag lepton and the electron to be back-to-back. The strength of the correlation depends on the electron momentum p_e, and we studied the distribution of p_e versus the opening angle $\cos\theta_{\ell e}$ to optimize the separation. For unlike-sign pairs we applied the diagonal cut $p_e + \cos\theta_{\ell e} > 1$ (p_e in GeV/c), which suppresses the background of dileptons from the same B by a factor of 25, while retaining 67% of the opposite-B electron signal.

Systematic effects that may be introduced by this cut have been studied with a Monte Carlo simulation using the ISGW form-factor model [8] for the decay modes $B \to D\ell\nu$, $B \to D^*\ell\nu$, and $B \to D^{**}\ell\nu$, with an additional component to account for higher multiplicity nonresonant decays. The signal efficiency was found to vary insignificantly among these channels, while the background of lepton-tag pairs from the same B varies somewhat from mode to mode. The dominant background mode is $D^*\ell\nu$, while $D\ell\nu$, $D^{**}\ell\nu$, and nonresonant decays contribute much less, because of smaller branching fractions and softer lepton spectra. Reasonable variations in the fractions of the individual modes give an uncertainty in this same-side background of 15%.

The raw $\Upsilon(4S)$ electron spectra for the unlike-sign sample with the diagonal cut applied, and for the like-sign without that cut, are shown in Fig. 1. The raw yield and background subtractions are summarized in Table I. The continuum contribution was subtracted by scaling the lepton yields in the off-resonance data by 2.12 ± 0.01, the ratio of the on- and off-resonance integrated luminosities, corrected for the energy dependence of the continuum cross section. Fakes are hadrons that were misidentified as leptons. Their contributions have been calculated using misidentification probabilities and hadron track momentum spectra found in data. The fake correction is small ($< 3\%$ for the unlike-sign sample), with an estimated uncertainty of 50%.

Leptons from J/ψ's produced in B decays and electrons from π^0 and η decays to $e^+e^-\gamma$ were vetoed by using the invariant mass of oppositely charged lepton pairs. Electrons from photon conversions in the beam pipe and drift chamber walls were also suppressed. Residual backgrounds from these processes were estimated by Monte Carlo simulation, as was the smaller contribution of leptonic ψ' decays. Leptons from $B \to X\tau^-\bar{\nu}_\tau$ were also estimated by Monte Carlo, assuming a branching fraction of 2.5%, consistent with the Standard Model and recent measurements [9]. The uncertainties in these backgrounds were taken to be 20%. The background contribution of D_s and Λ_c decays was studied with a simulation tuned to match measured rates and momentum spectra [10,11]. The production of Λ_c included 20% $c\bar{c}s$ production through $B \to \Xi_c\Lambda_c(m\pi)$ in addition to the dominant $B \to \Lambda_c\bar{p}(\bar{n})(m\pi)$. The uncertainty for both of these contributions was estimated to be 30%. Secondary leptons can occasionally have momenta above 1.4 GeV/c and contribute false tags. In the CLEO II study of the B-meson single-lepton spectrum [4], we found that approximately 2.8% of the identified leptons above 1.4 GeV/c are secondary, with an estimated uncertainty of 25%.

After background corrections the electron spectra consist of primary B semileptonic decays and secondary charm semileptonic decays. In both cases the tag and the electron are from different parent B's. The unlike-sign and like-sign electron momentum spectra can be expressed in terms of the primary and secondary branching fractions as

$$\frac{dN_{+-}}{dp} = N_\ell \eta \epsilon \left[\frac{d\mathcal{B}(b)}{dp}(1-\chi) + \frac{d\mathcal{B}(c)}{dp}\chi \right], \text{ and} \tag{1}$$

$$\frac{dN_{\pm\pm}}{dp} = N_\ell \eta \left[\frac{d\mathcal{B}(b)}{dp}\chi + \frac{d\mathcal{B}(c)}{dp}(1-\chi)\right], \tag{2}$$

where η is the momentum-dependent efficiency of electron identification, and ϵ is the momentum-dependent efficiency of the diagonal cut. The number of tags, $N_\ell = 246,465 \pm 739$, was determined by counting leptons above 1.4 GeV/c, subtracting backgrounds, and correcting for the relative efficiency for selecting dilepton events compared to single-lepton events ($(97.9 \pm 0.5)\%$). The correction for $B\bar{B}$ mixing is given by $\chi = f_0\chi_0$, where f_0 is the branching fraction for $\Upsilon(4S)$ decay into $B^0\bar{B}^0$, and χ_0 is the mixing parameter. We used $\chi = 0.080 \pm 0.012$, the average of ARGUS [12] and CLEO [13] measurements made with dileptons at the $\Upsilon(4S)$.

The primary and secondary electron spectra (Fig. 2) were obtained by solving Eqs. (1) and (2). Integrating the primary spectrum from 0.6 to 2.6 GeV/c, we found the partial branching fraction, $\mathcal{B}(B \to Xe\nu, p > 0.6\ \mathrm{GeV}/c) = (9.85 \pm 0.16 \pm 0.40)\%$. The systematic error includes the contributions which have been described, a 2% uncertainty in the electron detection efficiency, and a 1% uncertainty in tracking efficiency. There is no model dependence. To obtain the overall semileptonic branching fraction it is necessary to correct for the undetected portion of the spectrum below 0.6 GeV/c. Using theoretical models [8,14], and including the effects of internal and external bremsstrahlung, we estimated the undetected fraction to be $(6.1 \pm 0.5)\%$. With this correction the B-meson semileptonic branching fraction is found to be $\mathcal{B}(B \to Xe\nu) = (10.49 \pm 0.17 \pm 0.43)\%$.

If the semileptonic branching fractions for charged and neutral B mesons differ, the lepton-tagged measurement of $\mathcal{B}(B \to Xe\nu)$ could be systematically higher than one made with generic $\Upsilon(4S)$ decays [4]. Nonspectator effects that could produce such a difference are expected to be small, and this is supported by measurements of the B^0 and $B^\pm$ lifetimes [15], and of $\mathcal{B}(B^- \to D^{*0}\ell^-\bar{\nu})$ and $\mathcal{B}(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu})$ [16]. Utilizing 90% confidence level limits from these measurements, we find that the systematic upward shift in the lepton-tagged branching fraction can be no greater than 1.5% of the measured value.

Because of the lepton tag used in this measurement, we did not need to assume that all $\Upsilon(4S)$ decays are to $B\bar{B}$ final states. The agreement between the overall rate for lepton production and the rate in tagged events is evidence that the fraction f of non-$B\bar{B}$ decays is small. The background-corrected single-electron spectrum can be expressed as

$$\frac{dN_{\pm}}{dp} = 2N_{\Upsilon(4S)}(1-f)\eta \left[\frac{d\mathcal{B}(b)}{dp} + \frac{d\mathcal{B}(c)}{dp}\right], \tag{3}$$

where $N_{\Upsilon(4S)} = 2,143,400 \pm 4500$ is the number of $\Upsilon(4S)$ events. By comparing the integrated single-lepton yield in the momentum interval $0.6 - 2.6$ GeV/c ($350,460 \pm 1726$) with that in tagged events, as given by Eqs. (1) and (2) ($14,384 \pm 221$ for unlike-sign and 5321 ± 98 for like-sign), we find $f = (-0.11 \pm 1.43 \pm 1.07)\%$, or $f < 3.4\%$ at 95% confidence level. Allowing for possible lepton production in non-$B\bar{B}$ decays, primarily through charmed and charmonium mesons, increases this limit to 4%.

While our determination of the semileptonic branching fraction did not involve fitting the lepton momentum spectrum with theoretical models, such fits allow comparison with the predictions of those models, and with the results of our single-lepton analysis [4]. Good fits and consistent results were obtained for the ACCMM spectator model [14] and for a modified version of the ISGW model [8] in which the proportion of B semileptonic decays to $D^{**}\ell\nu$ was allowed to float (Fig. 2).

The branching fraction $\mathcal{B}(b \to c \to ye\nu)$ was determined from the secondary electron spectrum. This spectrum was fitted to model predictions of the charm semileptonic momentum spectra, boosted according to measured D^0 and D^+ momentum distributions [17]. For the ACCMM model [14], with charm-decay parameters tuned to agree with DELCO data [18], the result is $\mathcal{B}(b \to c \to ye\nu) = (7.8 \pm 0.2 \pm 1.2)\%$, while the result for the ISGW model [8] is $\mathcal{B}(b \to c \to ye\nu) = (8.3 \pm 0.2 \pm 1.2)\%$. These branching fractions do not include the contributions of charmed baryons or D_s, which have been treated as background in our analysis. Within errors the secondary charm semileptonic branching fraction is consistent with expectations, and with CLEO II single-lepton measurements.

The B-meson inclusive branching fraction is related to the CKM matrix elements V_{ub} and V_{cb} by $\mathcal{B}(B \to X\ell\nu)/\tau_B = \gamma_c|V_{cb}|^2 + \gamma_u|V_{ub}|^2$, where the factors γ_c and γ_u must be obtained from theory. The term involving V_{ub} makes a negligible contribution [19]. While the computation of γ_c is straightforward for any given model, an assumed uncertainty of 20% has been conventional. With the ACCMM model ($\gamma_c = 39 \pm 8$ ps^{-1}), our semileptonic branching fraction measurement and a B-meson lifetime of (1.61 ± 0.04) ps [15] lead to $|V_{cb}| = 0.041 \pm 0.001 \pm 0.004$. The first error combines all experimental uncertainties, both statistical and systematic. It is much smaller than the second error, which is the theoretical uncertainty in the computation of γ_c. With the ISGW model ($\gamma_c = 41 \pm 8\ ps^{-1}$), we find $|V_{cb}| = 0.040 \pm 0.001 \pm 0.004$. Shifman *et al.* [20] have asserted that the uncertainty in determining $|V_{cb}|$ from the inclusive rate can be reduced if experimental and theoretical constraints on the quark-mass difference $m_b - m_c$ are taken into account. Following their prescription, we find $|V_{cb}| = 0.040 \pm 0.001 \pm 0.002$. The size of the uncertainty remains somewhat controversial, however, with other analyses similar in approach leading to overall uncertainties in $|V_{cb}|$ of 10% or more [21].

In conclusion, we have used events with an electron and a high-momentum lepton tag to measure $\mathcal{B}(B \to Xe\nu) = (10.49 \pm 0.17 \pm 0.43)\%$, in agreement with other measurements, and below most theoretical expectations. This measurement is largely model-independent, and is insensitive to non-$B\bar{B}$ decays of the $\Upsilon(4S)$. By comparing the electron yield in tagged events with the total single-electron yield, we set a 95% confidence level upper limit on the fraction of non-$B\bar{B}$ decays of 4%. We have used our results to extract the CKM parameter $|V_{cb}|$ for different theoretical approaches.

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TABLES

TABLE I. Yield of lepton-tagged electrons and corrections with statistical and systematic errors, summed over the momentum interval 0.6 – 2.6 GeV/c.

	Unlike Sign $p_e + cos(\ell, e) > 1$	Like Sign no cut
ON $\Upsilon(4S)$ e Yield	13115 ± 115	7699 ± 88
Continuum	$1365 \pm 54 \pm 7$	$637 \pm 37 \pm 3$
Fake tag ℓ	$141 \pm 2 \pm 71$	$85 \pm 1 \pm 43$
Fake e	$214 \pm 3 \pm 107$	$540 \pm 8 \pm 270$
Leptons from J/ψ and ψ'	$238 \pm 6 \pm 48$	$154 \pm 4 \pm 31$
e from π^0 or η	$52 \pm 5 \pm 10$	$158 \pm 9 \pm 32$
e from γ conv.	$56 \pm 5 \pm 11$	$152 \pm 8 \pm 30$
$B \to X\tau, \tau \to Y\ell$	$270 \pm 11 \pm 54$	$70 \pm 5 \pm 14$
Leptons from Λ_c or D_s	$307 \pm 13 \pm 87$	$183 \pm 8 \pm 39$
Secondary Tags	$205 \pm 10 \pm 51$	$401 \pm 13 \pm 100$
e from same B	$329 \pm 13 \pm 49$	–
Total Background	$3177 \pm 60 \pm 186$	$2380 \pm 43 \pm 299$
Net e yield	$9938 \pm 129 \pm 186$	$5319 \pm 98 \pm 299$

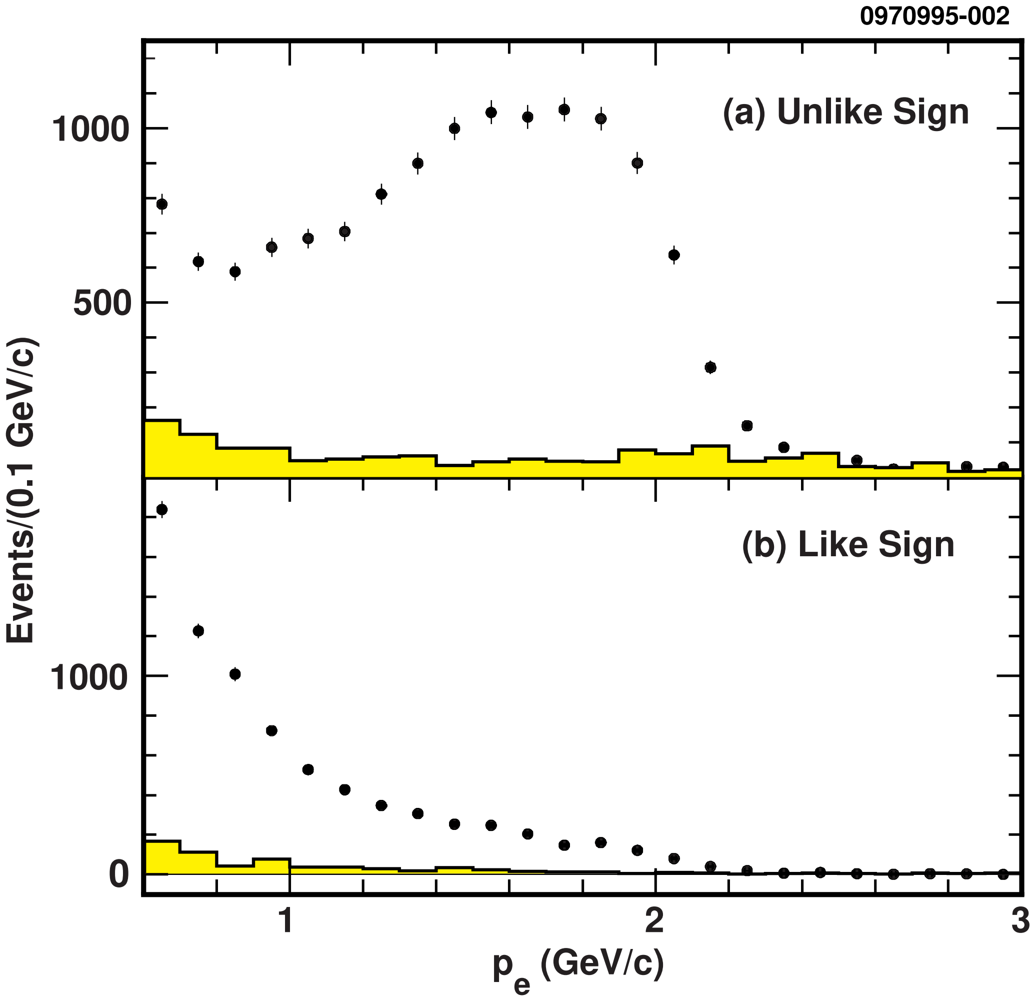

FIG. 1. Momentum spectra for electrons with (a) unlike-sign tags satisfying the diagonal cut, and (b) like-sign tags without that cut. The points and the histograms represent $\Upsilon(4S)$ and continuum data, respectively.

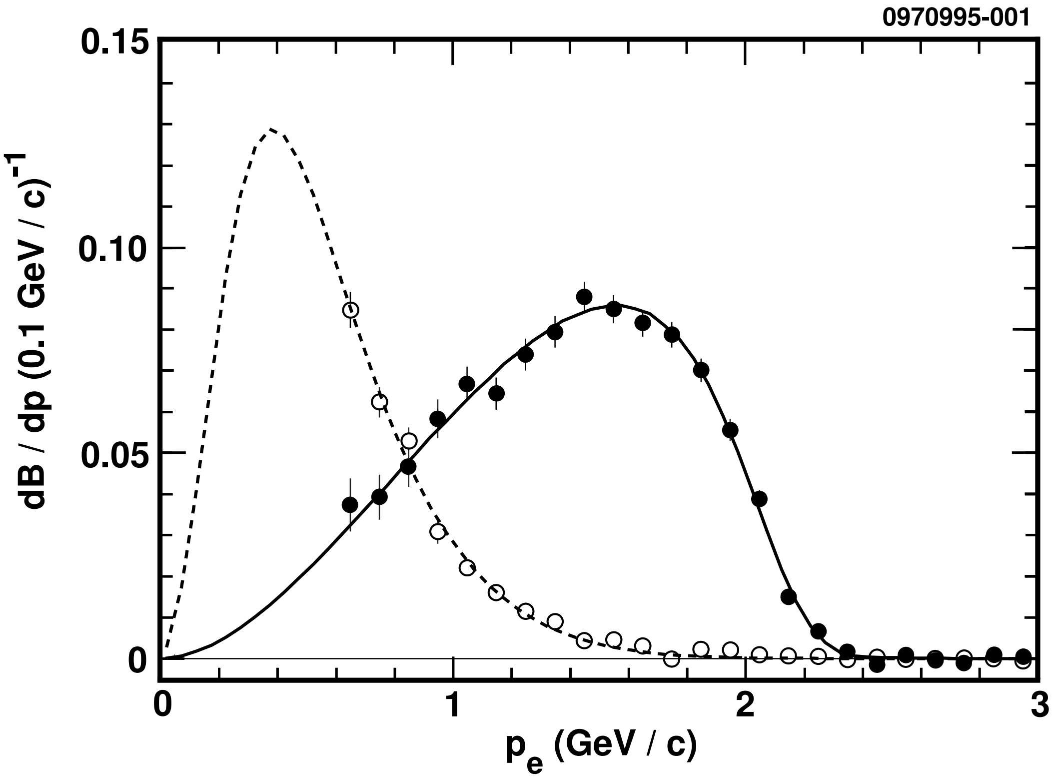

FIG. 2. Spectra of electrons from $B \rightarrow Xe\nu$ (filled circles) and $b \rightarrow c \rightarrow y\ell\nu$ (open circles) obtained by solving Eqs. (1) and (2). The curves show the best fit to the modified ISGW model, with 23% $B \rightarrow D^{**}\ell\nu$.