Limit on the $b \to u$ Coupling from Semileptonic B Decay

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We have used the momentum spectrum of leptons produced in semileptonic B-meson decays to set a 90%-confidence-level upper limit on $\Gamma(b \to ul\nu)/\Gamma(b \to cl\nu)$ of 4%. We also measure the semileptonic branching fractions of the B meson to be $(12.0 \pm 0.7 \pm 0.5)\%$ for electrons and $(10.8 \pm 0.6 \pm 1.0)\%$ for muons.

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Studies of B-meson decay provide an ideal way to examine the weak-interaction properties of the b quark. In the standard model,[1] the b quark can decay to a virtual W^- and either a u quark or a c quark. Semileptonic decays occur when the W^- transforms into a lepton-antineutrino pair, and the lepton momentum spectrum can be used to determine whether the b decays predominantly to u or to c. In this Letter we report the results of a study of B-meson semileptonic decay which has been made with the CLEO detector at the Cornell Electron Storage Ring (CESR).

The data for this analysis consist of 40.6 pb^{-1} (148 000 hadronic events) collected at the $\Upsilon(4S)$ resonance[2] and 17.1 pb^{-1} (45 000 hadronic events) of continuum data collected at energies below the resonance. The $\Upsilon(4S)$ sample includes 42 200 $B\bar{B}$ events.[3] The CLEO detector and our hadronic event selection cuts have previously been described in detail.[4,5] Those detector components which are used in this analysis are described below.

The interaction region is surrounded by a three-layer cylindrical proportional chamber and a large seventeen-layer drift chamber in a 1-T magnetic field. Outside the drift chamber are eight identical octants containing detectors for particle identification. Each octant has a three-layer planar drift chamber, proportional chambers to measure specific ionization (dE/dx), a time-of-flight scintillation counter array, and a twelve-radiation-length (proportional tube and lead) shower detector. The octants are surrounded by an iron hadron filter (0.5–1 m thick) on which are mounted planar drift chambers for muon identification.

We select electrons in hadronic events by searching for charged tracks which match with signals in the dE/dx chambers and in the electromagnetic shower detector. The energy deposited in the dE/dx chambers must be consistent with that expected for an electron, and both the energy deposited and the pattern of shower development in the shower detector must be characteristic of an electron. The overall electron detection efficiency is the product of four factors: geometrical acceptance (0.47), track reconstruction efficiency (0.95 ± 0.01), the efficiency of the electron identification algorithm (0.25 ± 0.1 at 0.7 GeV/c rising to 0.70 ± 0.03 above 2 GeV/c), and the relative efficiency for selecting semileptonic decay events compared to typical $B\bar{B}$ events (0.94 ± 0.02).

The probability for a hadron to be misidentified as an electron has been determined with data collected at the $\Upsilon(1S)$ resonance. The three-gluon decays of the $\Upsilon(1S)$, which are expected to produce very few leptons, are preferentially selected with an event-shape cut. With these events we measure the misidentification probability to be approximately 8×10^{-3} per hadronic track.

Muon candidates are charged tracks which match hits in the muon drift chambers within 0.32 m. Because the hadron filter is not uniform in thickness, the minimum momentum muon which can penetrate the iron varies with direction from 1.1 to 2.0 GeV/c; we use a minimum momentum cut of 1.2 GeV/c. The muon detection efficiency is the product of geometrical acceptance (0.75), track detection and projection efficiency (0.85 ± 0.03), muon drift chamber efficiency (0.86 ± 0.03), and the relative event selection efficiency described above (0.94 ± 0.02).

We estimate the contamination among our muon candidates from random matches between hadron tracks and muon chamber hits by comparing tracks and hits from different events. This contribution, about 2.5% of all candidates, is subtracted from the observed candidate yields. Misidentified hadrons among the remaining muon candidates (due to decays in flight and punchthrough) are estimated with $\Upsilon(1S)$ data. We find misidentification probabilities ranging from 4×10^{-3} at 1.2 GeV/c to 12×10^{-3} above 2.4 GeV/c.

After subtracting the lepton contribution of non-$B\bar{B}$ events (estimated with the below-resonance continuum data), and misidentified hadrons, we find 3750 electrons and 2115 muons from B-meson decay. The efficiency-corrected momentum spectra for these leptons are shown in Fig. 1. The shape of these spectra provides striking evidence of the dominance of the $b \to c l \nu$ decay mode over $b \to u l \nu$. For a b decay to c, the lepton must be accompanied by a charmed meson. Since the mass of the lightest charmed meson (the D) is 1.87 GeV, this imposes a maximum lepton momentum of 2.5 GeV/c. For a b decay to u it is likely that hadronic systems of much smaller mass would accompany the lepton, so that any excess of leptons above 2.5 GeV/c would constitute evidence for $b \to u l \nu$. Our spectra show no such evidence. Since current understanding of B decay is inadequate to provide a unique theoreti-

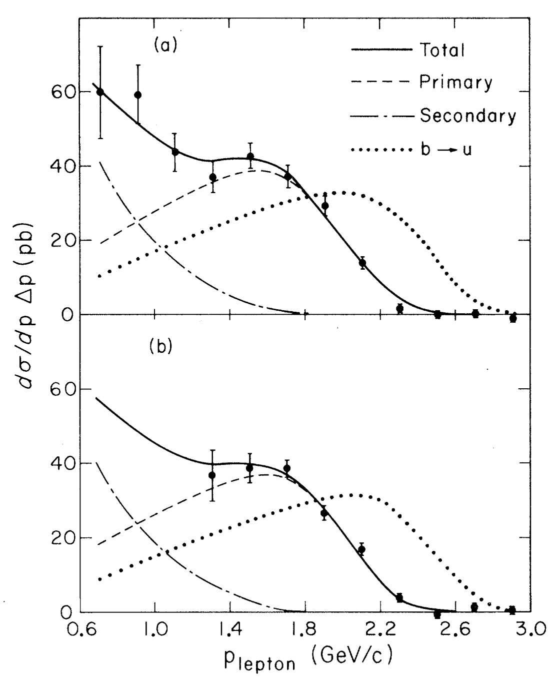

FIG. 1. The efficiency-corrected momentum spectra for (a) electrons and (b) muons from B-meson decay. The curves are Monte Carlo calculations of the lepton spectra based on model II (described in the text). The primary leptons are produced directly in semileptonic B decays ($b \to c l \nu$), and the secondary leptons are produced in semileptonic decays of D mesons produced in B decays. Also shown for comparison are the calculated spectra for semileptonic B decays by $b \to u l \nu$.

cal spectrum, we have considered four different models of B decay by $b \to cl\nu$. These models provide descriptions of both semileptonic B decay and semileptonic D decay, since some of the leptons we observe (especially at momenta below 1 GeV/c) are produced by $B \to D \to l$. The B mesons are assumed to have a momentum[2] of 0.4 GeV/c, and the D momentum spectrum is made to agree with the measured D^0 momentum spectrum.[6] The models of semileptonic D decay have been adjusted to agree with the data of Bacino *et al.*[7]

In model I,[8] B and D decay with the same $V-A$ current structure as $\mu \to e\nu\bar{\nu}$. The meson masses rather than the quark masses are assumed in calculating the lepton spectra. The decay $b \to cl\nu$ is described as a combination of $B \to Dl\nu$ and $B \to D^*l\nu$, with the relative proportions determined by fitting our data. In this model a combination of 50% $D \to Kl\nu$ and 50% $D \to K^*l\nu$ fits the data of Ref. 7.

Model II[9] also assumes a $V-A$ current for semileptonic B and D decay. It used a spectator quark model with quark masses $m_c = 1.7$ GeV and $m_s = 0.3$ GeV. The initial state b and the light spectator quark (assumed to have a mass of 0.15 GeV) are in relative motion with momentum $2p_f$, where p_f is Gaussian distributed with $\sigma = 0.15$ GeV/c. The mass of the b quark is not fixed, but is allowed to vary to conserve momentum and energy. QCD corrections are applied to the lepton spectrum.

Model III[10] describes B decay as a mixture of $B \to Dl\nu$ and $B \to D^*l\nu$. The treatment of $B \to Dl\nu$ and $D \to Kl\nu$ is identical to $K \to \pi l\nu$. Only the vector component of the hadronic current contributes to the decay. The form factor is assumed to be constant. For the decay $B \to D^*l\nu$ and $D \to K^*l\nu$, all form factors (one vector, three axial-vector) are assumed to be constant, and $F_A = -F_V$. For semileptonic D decay we used 75% $D \to Kl\nu$ and 25% $D \to K^*l\nu$.

Model IV[11] differs from model III only in the calculation of $B \to D^*l\nu$. The hadronic current is taken to be proportional to the D^* polarization. The only form factor involved in the decay is F_A, and it is assumed to be constant.

For each model we have performed fits to the muon and electron spectra assuming no $b \to ul\nu$ contribution by using a fitting function

$$G(p) = c_1 G_{B \to D}(p) + c_2 G_{B \to D^*}(p) + c_3 G_{D \to X}(p),$$

where $G_{B \to D}$, $G_{B \to D^*}$, and $G_{D \to X}$ are the expected spectra for the various contributions folded with the resolution of the drift-chamber tracking system. We have estimated this resolution by a Monte Carlo simulation which includes position resolution in the drift chamber, track-finding errors, and the effect of material between the interaction point and the drift chamber. The term $G_{D \to X}$ includes both the contribution of leptons from semileptonic decays of D's from B decays, and the much smaller contribution of leptons from the decay of τ's produced by $B \to \tau\bar{\nu}_\tau X$. For model II, instead of separate D and D^* terms, there is only a single $b \to c$ term.

The lepton spectra are well fitted by all models except for model IV (see Table I). Averaging the results of models I, II, and III, we find semileptonic branching fractions[12] for the mixture of $B^\pm$ and B^0 produced in $\Upsilon(4S)$ decay to be

$$B(B \to e\nu X) = (12.0 \pm 0.7 \pm 0.5)\%,$$

$$B(B \to \mu\nu X) = (10.8 \pm 0.6 \pm 1.0)\%,$$

where the first error is statistical and the second systematic. The systematic errors arise from theoretical, efficiency, and background uncertainties. The electron and muon results are consistent with each other and with previous measurements.[5,13,14] Quark counting with phase-space corrections leads to a prediction of 17% each for electrons and muons. QCD corrections[15] from gluon exchange among the final-state quarks and the contributions of nonspectator decays of the B^0 reduce this to about 12%. Our measurements are consistent with this prediction.

The spectral fits also provide information about semileptonic D decays in $B\bar{B}$ events. Leptons from this source are mostly below 1 GeV/c, and so we only measure $B \to D \to e\nu X$. We find from the first three models that $B(B \to D \to e\nu X) = (11.7$

TABLE I. The results of fits to the electron and muon momenta spectra.

Model	χ^2/D.F.	$B(B \to eX)$ (%)	$B(B \to \mu X)$ (%)	$B(B \to D \to eX)$ (%)
I	17.9/17	11.9 ± 0.7	10.8 ± 0.6	12.0 ± 2.6
II	17.2/18	11.9 ± 0.7	10.5 ± 0.6	11.3 ± 2.4
III	18.8/17	12.1 ± 0.7	11.1 ± 0.7	11.8 ± 2.6
IV	38.3/17	14.6 ± 0.9	13.4 ± 0.8	4.9 ± 2.7

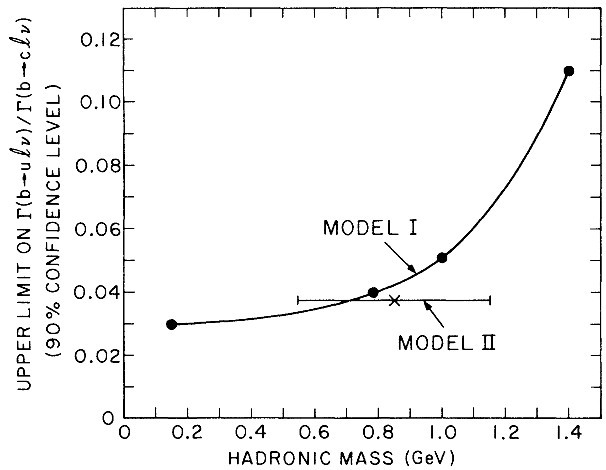

FIG. 2. The 90%-confidence-level upper limits on $\Gamma(b \rightarrow ul\nu)/\Gamma(b \rightarrow cl\nu)$ obtained from fits of the electron and muon data by models I and II.

± 2.5)% (statistical error only). We estimate that 10% of this amount comes from the decay of τ's from $B \rightarrow \tau\bar{\nu}_\tau X$. On the basis of 1.15 D's per B decay,[16] we infer a D semileptonic branching ratio of (9 ± 3)%, consistent with previous measurements.[7,17]

The lepton momentum spectra are well fitted by models which assume no b decays to u. We set quantitative limits on the amount of $b \rightarrow ul\nu$ which the spectra can accommodate by refitting with a function which includes a term for B decay by $b \rightarrow ul\nu$. Among our previous models, model II can describe $b \rightarrow ul\nu$ by assuming $m_u = 0.15$ GeV. For comparison we consider a variation of model I in which $b \rightarrow ul\nu$ decays are treated as $B \rightarrow l\nu X$ with $m_X = m_\pi$, m_ρ, 1.0 GeV, and 1.4 GeV. The results of these fits are shown in Fig. 2. From model II we conclude that $\Gamma(b \rightarrow ul\nu)/\Gamma(b \rightarrow cl\nu)$ is less than 4% (90% confidence). Model I supports this limit up to $m_X \cong 0.9$ GeV. This upper limit is stronger than has previously been published,[13] and leads to a limit on the ratio of Kobayashi-Maskawa matrix elements $|V_{bu}|/|V_{bc}| < 0.14$ (90% confidence).[18]

This limit in conjunction with the recent measurements of the B lifetime[19] greatly restricts the allowed range of the mixing parameters. The b lifetime can be related to the measured semileptonic branching fraction and the semileptonic width[20] by $\tau_b = \hbar B(B \rightarrow l\nu X)/\Gamma(b \rightarrow l\nu X)$, where

$$\Gamma(b \rightarrow l\nu X) = (G_F^2 m_b^5/192\pi^3)\{0.45|V_{bc}|^2 + |V_{bu}|^2\}.$$

In terms of the mixing angles θ_1, θ_2, and θ_3, we can write $V_{bu} = s_1 s_3$ and $V_{bc} = c_1 c_2 s_3 + s_2 c_3 e^{-i\delta}$ ($c_i = \cos\theta_i$, $s_i = \sin\theta_i$). To set limits on s_2 and s_3 we take our upper limit of 0.14 on $|V_{bu}|/|V_{bc}|$ and a conservative lower limit on τ_b (from Mark II detector group) of 0.6×10^{-12} and find $s_2 < 0.09$ and $s_3 < 0.06$. We can also use an upper bound on τ_b (from MAC detector group) of 2.7×10^{-12} sec to show that $s_2 > 0.009$.

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