$\Gamma(b \rightarrow ul\nu)/\Gamma(b \rightarrow cl\nu)$ from the End Point of the Lepton Momentum Spectrum in Semileptonic B Decay

S. Behrends,(1) Jan M. Guida,(1) Joan A. Guida,(1) F. Morrow,(1) R. Poling,(1) E. H. Thorndike,(1) P. Tipton,(1) M. S. Alam,(2) N. Katayama,(2) I. J. Kim,(2) W. C. Li,(2) X. C. Lou,(2) C. R. Sun,(2) V. Tanikella,(2) D. Bortoletto,(3) A. Chen,(3) M. Goldberg,(3) R. Holmes,(3) N. Horwitz,(3) A. Jawahery,(3) P. Lubrano,(3) G. C. Moneti,(3) V. Sharma,(3) I. P. J. Shipsey,(3) P. Thoma,(3) S. E. Csorna,(4) M. D. Mestayer,(4) R. S. Panvini,(4) G. B. Word,(4) A. Bean,(5) G. J. Bobbink,(5) I. C. Brock,(5) A. Engler,(5) T. Ferguson,(5) R. W. Kraemer,(5) C. Rippich,(5) H. Vogel,(5) C. Bebek,(6) K. Berkelman,(6) E. Blucher,(6) D. G. Cassel,(6) T. Copie,(6) R. DeSalvo,(6) J. W. DeWire,(6) R. Ehrlich,(6) R. S. Galik,(6) M. G. D. Gilchriese,(6) B. Gittelman,(6) S. W. Gray,(6) A. M. Halling,(6) D. L. Hartill,(6) B. K. Heltsley,(6) S. Holzner,(6) J. Kandaswamy,(6) R. Kowalewski,(6) D. L. Kreinick,(6) Y. Kubota,(6) N. B. Mistry,(6) J. Mueller,(6) R. Namjoshi,(6) E. Nordberg,(6) D. Perticone,(6) D. Peterson,(6) M. Pisharody,(6) K. Read,(6) D. Riley,(6) A. Silverman,(6) S. Stone,(6) A. J. Sadoff,(7) P. Avery,(8) D. Besson,(8) L. Garren,(8) T. Bowcock,(9) K. Kinoshita,(9) F. M. Pipkin,(9) M. Procario,(9) Richard Wilson,(9) J. Wolinski,(9) D. Xiao,(9) P. Haas,(10) M. Hempstead,(10) T. Jensen,(10) H. Kagan,(10) and R. Kass(10)

(The CLEO Collaboration)

(1)*University of Rochester, Rochester, New York 14627*
(2)*State University of New York at Albany, Albany, New York 12222*
(3)*Syracuse University, Syracuse, New York 13210*
(4)*Vanderbilt University, Nashville, Tennessee 37235*
(5)*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213*
(6)*Cornell University, Ithaca, New York 14853*
(7)*Ithaca College, Ithaca, New York 14850*
(8)*University of Florida, Gainesville, Florida 32611*
(9)*Harvard University, Cambridge, Massachusetts 02138*
(10)*Ohio State University, Columbus, Ohio 43210*

(Received 4 May 1987)

We have used the measured yield of leptons near the end point of the momentum spectrum from semileptonic B decay to obtain an upper limit on $\Gamma(b \rightarrow ul\nu)/\Gamma(b \rightarrow cl\nu)$ and a corresponding limit on $|V_{ub}|/|V_{cb}|$.

PACS numbers: 13.20.Jf, 14.40.Jz, 14.80.Dq

The ratio $\Gamma(b \rightarrow ul\nu)/\Gamma(b \rightarrow cl\nu)$ [hereafter denoted by $(b \rightarrow u)/(b \rightarrow c)$] is related to the Kobayashi-Maskawa (KM) mixing-matrix elements V_{ub} and V_{cb}.[1] Its measurement is of considerable interest because $|V_{ub}|$ must be nonzero if *CP* nonconservation in the neutral kaon system is to be explained in terms of a phase in the KM matrix. The lepton momentum spectrum in semileptonic B decay can provide information about $(b \rightarrow u)/(b \rightarrow c)$. Since the u quark is much lighter than the c quark, the decay $B \rightarrow X_u l\nu$ is expected to have a higher end point than the decay $B \rightarrow X_c l\nu$. (Here X_u and X_c are hadronic systems containing the u and c quarks, respectively.) This principle has been exploited by Chen *et al.* (CLEO Collaboration)[2] and Klopfenstein et al. (CUSB Collaboration)[3] to obtain upper limits on $(b \rightarrow u)/(b \rightarrow c)$. The method was to fit the measured lepton spectrum over a wide momentum range to a mix of $b \rightarrow ul\nu$, $b \rightarrow cl\nu$, and $b \rightarrow c \rightarrow sl\nu$. This method is sensitive to the theoretical model for $B \rightarrow X_c l\nu$, as well as to the model for $B \rightarrow X_u l\nu$. Since $B \rightarrow X_c l\nu$ is the dominant piece of the spectrum, a small error in the model for $B \rightarrow X_c l\nu$ can lead to a large error in the fitted amount of $B \rightarrow X_u l\nu$.

In this Letter we use a different method of extracting $(b \rightarrow u)/(b \rightarrow c)$ from the B semileptonic decay momentum spectrum. This method has little or no sensitivity to the model for $B \rightarrow X_c l\nu$, and a simple dependence on the model for $B \rightarrow X_u l\nu$, allowing easy conversion of a result obtained with one model to one appropriate for another model.

The data are from the CLEO detector at the Cornell Electron Storage Ring (CESR). The detector,[4] event-selection criteria,[5] and lepton-identification procedures[6] have been described elsewhere. We identify electrons above 0.5 GeV/c and muons above 1.2 GeV/c. The electron yields were measured in a sample of 78 pb^{-1} of e^+e^- annihilation data on the $\Upsilon(4S)$ resonance, and 36 pb^{-1} in the continuum just below the $\Upsilon(4S)$. Muon yields were determined for this sample, and also for an earlier sample comprising 41 pb^{-1} on the $\Upsilon(4S)$ and 17

pb^{-1} below the $\Upsilon(4S)$.

Since $\Upsilon(4S)$ decays to $B\bar{B}$, leptons detected at the $\Upsilon(4S)$ resonance can come either from B decay or from the continuum under the resonance. This latter contribution is measured with data taken just below the $\Upsilon(4S)$. Our measured continuum-subtracted, efficiency-corrected electron and muon momentum spectra from the $\Upsilon(4S)$ are shown in Fig. 1.

We obtain a measurement of $(b\to u)/(b\to c)$ from the lepton yield in a momentum interval near the end point of the spectrum. This yield, $\sigma(p)$, may be written as

$$\sigma(p)=\sigma_0[Xf_u(p)+(1-X)f_c(p)], \tag{1}$$

where σ_0 is the total primary lepton yield over all momenta, X is the fraction of the total primary yield from $b\to ul\nu$, and $1-X$ is the fraction from $b\to cl\nu$. Therefore $X/(1-X)=(b\to u)/(b\to c)$ is the quantity we wish to measure. $f_c(p)$ is the fraction of the lepton spectrum from $b\to cl\nu$ that lies in the chosen momentum interval (with allowance for detector momentum resolution), and $f_u(p)$ is the fraction of the spectrum from $b\to ul\nu$ that lies in this interval. Equation (1) is readily solved to give

$$\frac{(b\to u)}{(b\to c)}=\frac{\sigma(p)/\sigma_0-f_c(p)}{f_u(p)-\sigma(p)/\sigma_0}. \tag{2}$$

Thus, $(b\to u)/(b\to c)$ can be determined from $\sigma(p)$, σ_0, $f_c(p)$, and $f_u(p)$.

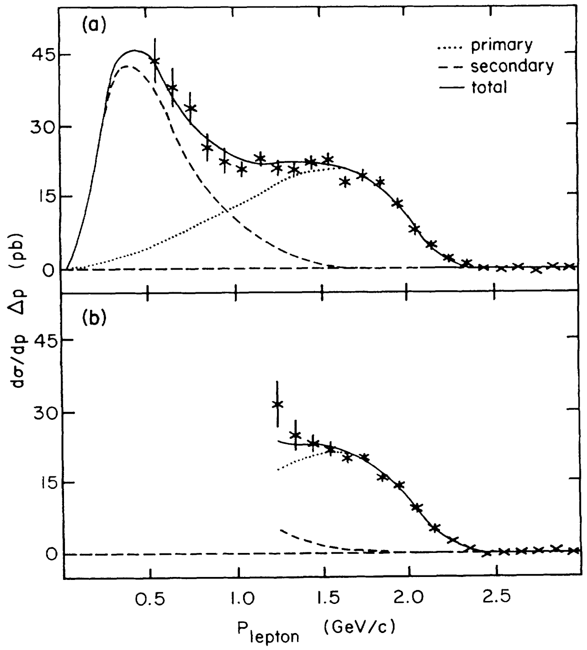

FIG. 1. Continuum-subtracted, efficiency-corrected (a) electron and (b) muon momentum spectra from the $\Upsilon(4S)$. The dotted, dashed, and solid curves are the modeled spectra for primary leptons ($B\to Xl\nu$, Ref. 7), secondary leptons ($B\to D\to Yl\nu$), and their sum.

To determine σ_0, we need to extrapolate the measurements to zero momentum, and to separate the primary lepton yield $B\to Xl\nu$ from the secondary lepton yield arising from $B\to D\to Yl\nu$. We do this by fitting the spectra shown in Fig. 1. Since both the D momentum spectrum in $B\to DX$ and the lepton momentum spectrum in $D\to Yl\nu$ have been measured,[8,9] the secondary lepton spectrum can be reliably modeled. For the primary lepton spectrum we have used a variety of models for $B\to X_cl\nu$ and $B\to X_ul\nu$, discussed below. The value of σ_0 is insensitive to the models used.

From these fits we find a primary lepton yield of $\sigma_0=235\pm14$ pb for the electrons, and 237 ± 14 pb for the muons. The errors are partially correlated between electrons and muons, and include contributions for the model dependence in the fitting procedure and for the uncertainty in the momentum dependence of the lepton identification efficiency.

As a check on these primary lepton yields, we use σ_0 to obtain a measurement of the B semileptonic branching ratio. We find

$$B(B\to Xl\nu)=0.110\pm0.003\pm0.005\pm0.005,$$

where the errors are due to statistical, systematic, and model-dependent uncertainties, respectively. This branching ratio agrees with the previous world average from $\Upsilon(4S)$ of 0.117 ± 0.006.[10]

The upper limit of the momentum interval for which we determine the lepton yield $\sigma(p)$ was chosen to be 2.6 GeV/c. While some leptons from $B\to X_ul\nu$ can be above this value, the fraction is small. We have used three different lower momentum limits of 2.2, 2.3, and 2.4 GeV/c. Since the maximum lepton momentum possible for $B\to X_cl\nu$ is 2.46 GeV/c, these three limits are different compromises between good statistics and dependence on the $b\to cl\nu$ model.

Table I shows our measured lepton yields, $\sigma(p)$, for the three different momentum intervals. The values given are the weighted averages of the electron and muon results, which are in good agreement. A small correction to $\sigma(p)$ has been made to eliminate the contribution from $B\to\psi X$, $\psi\to l^+l^-$.

The dominant source of error in these values of $\sigma(p)$ is the subtraction of the background due to leptons from the continuum. Therefore, we developed methods for reducing the continuum background and for determining it more precisely.

Since the B and $\bar{B}$ decays are uncorrelated, the decay products from the B which did not decay semileptonically will, on average, have a significant fraction of their momentum transverse to the lepton direction. In contrast, for a continuum event all particles, the lepton included, will tend to line up with a single axis. With this in mind, we define the variable $s_\perp$ as

$$s_\perp=\sum p_j\sin\theta_j/\sum p_i, \tag{3}$$

TABLE I. Measured values for $(b \rightarrow u)/(b \rightarrow c)$, and 90%-confidence-level upper limits on $|V_{ub}|/|V_{cb}|$, obtained for the three different lepton momentum intervals with use of the $b \rightarrow ul\nu$ models of Altarelli *et al.* (Ref. 11) and Grinstein, Wise, and Isgur (Ref. 7). Also given are the intermediate results, $\sigma(p)$ [without and with continuum suppression and fitting (CSF)], $f_c(p)$, and $f_u(p)$.

	Lepton momentum interval (GeV/c)		
	2.2–2.6	2.3–2.6	2.4–2.6
$\sigma(p)$ (pb) (without CSF)	2.32 ± 0.60	0.16 ± 0.48	-0.57 ± 0.37
$\sigma(p)$ (pb) (with CSF)	2.24 ± 0.36	0.38 ± 0.25	0.06 ± 0.17
$10^4 f_c$	79 ± 20	15 ± 6	2 ± 1
$10^4 f_u$ Altarelli	1870	1170	580
Grinstein	1460	850	400
$(b \rightarrow u)/(b \rightarrow c)$ (%) Altarelli	0.8 ± 1.5	0.0 ± 1.1	0.0 ± 1.3
Grinstein	1.0 ± 1.9	0.0 ± 1.5	0.1 ± 1.8
$\lvert V_{ub} \rvert / \lvert V_{cb} \rvert$ Altarelli	< 0.12	< 0.09	< 0.10
Grinstein	< 0.20	< 0.16	< 0.17

where p_j is the momentum of the jth charged particle and θ_j is the angle between the lepton and the jth charged particle. The sum in the demoninator runs over all charged particles in the event except the lepton, while that in the numerator includes only charged particles with $45° < \theta_j < 135°$. A cut requiring $s_\perp > 0.4$ eliminates 86% of the continuum events, while losing only 30% of the $B\bar{B}$ events. The 70% efficiency for detecting $B\bar{B}$ events, used in evaluation of $\sigma(p)$, depends almost exclusively on the tracks from the B not decaying semileptonically, and thus this efficiency is insensitive to the model chosen for $B \rightarrow X_u l\nu$. This conclusion was verified by Monte Carlo simulation.

To obtain a more accurate determination of the continuum lepton spectrum near the end point, we fit the below-$\Upsilon(4S)$ lepton spectra from 1.6 to 3.0 GeV/c for muons, and 1.8 to 3.0 GeV/c for electrons. We have used three different fitting functions: a third-order polynomial (four parameters), a constant plus exponential (three parameters), and the spectrum predicted by a Monte Carlo simulation of continuum $c\bar{c}$ production with the semileptonic decay of charm (one parameter, the overall scale). All functions give similar answers. We include in our errors an allowance for differences among the fitting functions.

The values for $\sigma(p)$ obtained after these procedures are given in Table I. The combination of continuum suppression and continuum fitting substantially reduces the error on $\sigma(p)$.

The determination of $f_c(p)$, the fraction of the lepton spectrum from $B \rightarrow X_c l\nu$ in the chosen momentum interval, is the most subtle aspect of this analysis. It is here that any residual dependence on the model for $B \rightarrow X_c l\nu$ resides. Three ingredients determine f_c: the shape of the theoretical lepton spectrum for $B \rightarrow X_c l\nu$ in the B rest frame, the Doppler smearing as the lepton is boosted from the B rest frame to the laboratory frame, and the smearing of the lepton momentum due to the resolution of the detector. The last two are well understood, the first only partially. Our procedure is to fit the lepton spectra below 2.2 GeV/c with a broad range of models for $B \rightarrow X_c l\nu$ and $B \rightarrow X_u l\nu$. For each choice of models and model parameters that fit the data, we obtain a prediction for the value of f_c.

Although calculations[7] show that X_c is dominated by D and D^*, we allow for arbitrary amounts of $D\pi$ or $D^*\pi$. The reaction $B \rightarrow Dl\nu$ is described by a single form factor, and the lepton spectrum changes negligibly as that form factor is changed from a constant to that given by pole dominance. The reaction $B \rightarrow D^* l\nu$ is described by three form factors, and there is no theoretical consensus on their relative magnitudes. We use the lepton spectra suggested by Tye and Trahern,[12] Grinstein, Wise, and Isgur,[7] and Ali.[13] These three spectra differ markedly, from very stiff to very soft; spectra much stiffer than the Tye-Trahern prediction or softer than the Ali model will not fit the measured lepton spectrum. For modeling the reaction $B \rightarrow (D/D^*)\pi l\nu$, we use the lepton spectra predicted for the low-lying charmed states by Grinstein, Wise, and Isgur.[7]

For the $B \rightarrow X_u l\nu$ spectrum we use two models: the nonrelativistic, constituent-quark model of Grinstein, Wise, and Isgur,[7] and the spectator-quark model with gluon corrections due to Altarelli *et al.*[11] For the latter model the Fermi momenta of the quarks in the B are distributed as a Gaussian of width 160 MeV/c.

Fitting the lepton spectra below 2.2 GeV by many combinations of models, we obtain the values of f_c shown in Table I. The values given are the midpoints from all the combinations that give acceptable fits, and the errors are determined by the spread in the values. While the values of f_c for the models considered here lie in the ranges given, we cannot rule out the possibility that use of an as yet unknown model of $b \rightarrow ul\nu$ which has an anomalously different lepton spectrum would give a smaller value of f_c. Therefore, we emphasize that the value of f_c for the lower momentum limit of 2.4 GeV/c is negligible, independent of the $b \rightarrow cl\nu$ or $b \rightarrow ul\nu$ model used.

While f_c is largely determined from the measured lepton spectrum below the end-point region, f_u must be obtained strictly from theory. Values for f_u obtained from the models of Refs. 7 and 11 for $B \rightarrow X_u l\nu$ are shown in Table I. Additional models are considered by Guida.[14] Since the detector momentum resolution has little effect on f_u, the values for any model of $B \rightarrow X_u l\nu$ can be computed by boosting the spectrum from the B rest frame to the laboratory frame ($\beta_B = 0.06$),[15] and determining the fraction that lies in the chosen momentum interval.

Table I gives our measured values for $(b \rightarrow u)/(b \rightarrow c)$ for the three different momentum intervals and the predictions of Refs. 7 and 11 for f_u. The values are the weighted sums of the electron and muon measurements. To get values for $(b \rightarrow u)/(b \rightarrow c)$ with use of other predictions for f_u, the functional dependencies are $(b \rightarrow u)/(b \rightarrow c) = (0.008 \pm 0.015)[0.178/(f_u - 0.009)]$, $(0.000 \pm 0.011)[0.115/(f_u - 0.002)]$, and $(0.000 \pm 0.013)[0.058/f_u]$ for the three different momentum intervals.

The dominant errors in these determinations of $(b \rightarrow u)/(b \rightarrow c)$ are from the statistical error on $\sigma(p)$ (0.009, 0.009, and 0.012 for the model of Altarelli *et al.* and the three momentum intervals) and from the model-dependent error on f_c (0.011, 0.005, and 0.002). The results for the three momentum intervals are not statistically independent.

Other errors considered,[14] and found negligible, include the error on σ_0, the effect on f_c of the uncertainties in the B-meson mass, the beam energy, and the instrumental momentum resolution, and the effect on $\sigma(p)$ of the uncertainty in the absolute momentum scale.

The quantity $(b \rightarrow u)/(b \rightarrow c)$ is related to the Kobayashi-Maskawa matrix elements V_{ub} and V_{cb} by

$$(b \rightarrow u)/(b \rightarrow c) = \rho |V_{ub}|^2/|V_{cb}|^2. \quad (4)$$

The parameter ρ accounts for differences in the phase-space factors for the decays $b \rightarrow ul\nu$ and $b \rightarrow cl\nu$ as well as differences in the wave functions, form factors, etc., of the final-state hadrons. In the model of Altarelli *et al.*[11] $\rho = 2.2$, while for the model of Grinstein, Wise, and Isgur[7] $\rho = 1.0$.

Since none of our measured values for $(b \rightarrow u)/(b \rightarrow c)$ are significantly different from zero, we give in Table I the 90%-confidence-level upper limits on $|V_{ub}|/|V_{cb}|$. The two models for $B \rightarrow X_u l\nu$ used in Table I give limits that bracket those found with other models.[14]

We gratefully acknowledge the efforts of the Cornell Electron Storage Ring (CESR) machine group. This research was supported by the National Science Foundation and the U. S. Department of Energy. Two of us (H. K. and R. Kass) thank the Department of Energy Outstanding Junior Investigator Program and one of us (K. K.) thanks the Bunting Institute for support.

---

[1] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

[2] A. Chen *et al.* (CLEO Collaboration), Phys. Rev. Lett. **52**, 1084 (1984).

[3] C. Klopfenstein *et al.* (CUSB Collaboration), Phys. Lett. **130B**, 444 (1983).

[4] D. Andrews *et al.* (CLEO Collaboration), Nucl. Instrum. Methods **211**, 47 (1983).

[5] R. Giles *et al.* (CLEO Collaboration), Phys. Rev. D **30**, 2279 (1984).

[6] K. Chadwick *et al.* (CLEO Collaboration), Phys. Rev. D **27**, 475 (1983).

[7] B. Grinstein, M. Wise, and N. Isgur, Phys. Rev. Lett. **56**, 298 (1986), and California Institute of Technology Report No. CALT-68-1311, 1986 (to be published).

[8] D. Bortoletto *et al.* (CLEO Collaboration), Phys. Rev. D **35**, 19 (1987).

[9] W. Bacino *et al.* (DELCO Collaboration), Phys. Rev. Lett. **43**, 1073 (1979).

[10] E. H. Thorndike, Ann. Rev. Nucl. Part. Sci. **35**, 195 (1985).

[11] G. Altarelli *et al.*, Nucl. Phys. **B208**, 365 (1982).

[12] S.-H. H. Tye and G. Trahern, Cornell University CLEO Collaboration Report No. CBX-85-45, 1985 (unpublished).

[13] A. Ali, Z. Phys. C **1**, 25 (1979).

[14] Joan A. Guida, Ph.D. thesis, University of Rochester, 1987 (unpublished).

[15] C. Bebek *et al.* (CLEO Collaboration), Phys Rev D (to be published).