Measurement of Charmless Semileptonic Decays of B Mesons

J. Bartelt,[1] S. E. Csorna,[1] Z. Egyed,[1] V. Jain,[1] D. S. Akerib,[2] B. Barish,[2] M. Chadha,[2] S. Chan,[2] D. F. Cowen,[2] G. Eigen,[2] J. S. Miller,[2] C. O'Grady,[2] J. Urheim,[2] A. J. Weinstein,[2] D. Acosta,[3] M. Athanas,[3] G. Masek,[3] H. Paar,[3] M. Sivertz,[3] A. Bean,[4] J. Gronberg,[4] R. Kutschke,[4] S. Menary,[4] R. J. Morrison,[4] S. Nakanishi,[4] H. N. Nelson,[4] T. K. Nelson,[4] J. D. Richman,[4] A. Ryd,[4] H. Tajima,[4] D. Schmidt,[4] D. Sperka,[4] M. S. Witherell,[4] M. Procario,[5] S. Yang,[5] R. Balest,[6] K. Cho,[6] M. Daoudi,[6] W. T. Ford,[6] D. R. Johnson,[6] K. Lingel,[6] M. Lohner,[6] P. Rankin,[6] J. G. Smith,[6] J. P. Alexander,[7] C. Bebek,[7] K. Berkelman,[7] D. Besson,[7] T. E. Browder,[7] D. G. Cassel,[7] H. A. Cho,[7] D. M. Coffman,[7] P. S. Drell,[7] R. Ehrlich,[7] M. Garcia-Sciveres,[7] B. Geiser,[7] B. Gittelman,[7] S. W. Gray,[7] D. L. Hartill,[7] B. K. Heltsley,[7] C. D. Jones,[7] S. L. Jones,[7] J. Kandaswamy,[7] N. Katayama,[7] P. C. Kim,[7] D. L. Kreinick,[7] G. S. Ludwig,[7] J. Masui,[7] J. Mevissen,[7] N. B. Mistry,[7] C. R. Ng,[7] E. Nordberg,[7] M. Ogg,[7,*] J. R. Patterson,[7] D. Peterson,[7] D. Riley,[7] S. Salman,[7] M. Sapper,[7] H. Worden,[7] F. Würthwein,[7] P. Avery,[8] A. Freyberger,[8] J. Rodriguez,[8] R. Stephens,[8] J. Yelton,[8] D. Cinabro,[9] S. Henderson,[9] K. Kinoshita,[9] T. Liu,[9] M. Saulnier,[9] F. Shen,[9] R. Wilson,[9] H. Yamamoto,[9] B. Ong,[10] M. Selen,[10] A. J. Sadoff,[11] R. Ammar,[12] S. Ball,[12] P. Baringer,[12] D. Coppage,[12] N. Copty,[12] R. Davis,[12] N. Hancock,[12] M. Kelly,[12] N. Kwak,[12] H. Lam,[12] Y. Kubota,[13] M. Lattery,[13] J. K. Nelson,[13] S. Patton,[13] D. Perticone,[13] R. Poling,[13] V. Savinov,[13] S. Schrenk,[13] R. Wang,[13] M. S. Alam,[14] I. J. Kim,[14] B. Nemati,[14] J. J. O'Neill,[14] H. Severini,[14] C. R. Sun,[14] M. M. Zoeller,[14] G. Crawford,[15] M. Daubenmeir,[15] R. Fulton,[15] D. Fujino,[15] K. K. Gan,[15] K. Honscheid,[15] H. Kagan,[15] R. Kass,[15] J. Lee,[15] R. Malchow,[15] F. Morrow,[15] Y. Skovpen,[15,†] M. Sung,[15] C. White,[15] J. Whitmore,[15] P. Wilson,[15] F. Butler,[16] X. Fu,[16] G. Kalbfleisch,[16] M. Lambrecht,[16] W. R. Ross,[16] P. Skubic,[16] J. Snow,[16] P. L. Wang,[16] M. Wood,[16] D. Bortoletto,[17] D. N. Brown,[17] J. Fast,[17] R. L. McIlwain,[17] T. Miao,[17] D. H. Miller,[17] M. Modesitt,[17] S. F. Schaffner,[17] E. I. Shibata,[17] I. P. J. Shipsey,[17] P. N. Wang,[17] M. Battle,[18] J. Ernst,[18] H. Kroha,[18] S. Roberts,[18] K. Sparks,[18] E. H. Thorndike,[18] C. H. Wang,[18] V. Chelkov,[19] J. Dominick,[19] S. Sanghera,[19] T. Skwarnicki,[19] R. Stroynowski,[19] I. Volobouev,[19] P. Zadorozhny,[19] M. Artuso,[20] D. He,[20] M. Goldberg,[20] N. Horwitz,[20] R. Kennett,[20] G.C. Moneti,[20] F. Muheim,[20] Y. Mukhin,[20] S. Playfer,[20] Y. Rozen,[20] S. Stone,[20] M. Thulasidas,[20] G. Vasseur,[20] and G. Zhu[20]

(CLEO Collaboration)

[1] *Vanderbilt University, Nashville, Tennessee 37235*
[2] *California Institute of Technology, Pasadena, California 91125*
[3] *University of California, San Diego, La Jolla, California 92093*
[4] *University of California, Santa Barbara, California 93106*
[5] *Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213*
[6] *University of Colorado, Boulder, Colorado 80309-0390*
[7] *Cornell University, Ithaca, New York 14853*
[8] *University of Florida, Gainesville, Florida 32611*
[9] *Harvard University, Cambridge, Massachusetts 02138*
[10] *University of Illinois, Champaign-Urbana, Illinois 61801*
[11] *Ithaca College, Ithaca, New York 14850*
[12] *University of Kansas, Lawrence, Kansas 66045*
[13] *University of Minnesota, Minneapolis, Minnesota 55455*
[14] *State University of New York at Albany, Albany, New York 12222*
[15] *Ohio State University, Columbus, Ohio 43210*
[16] *University of Oklahoma, Norman, Oklahoma 73019*
[17] *Purdue University, West Lafayette, Indiana 47907*
[18] *University of Rochester, Rochester, New York 14627*
[19] *Southern Methodist University, Dallas, Texas 75275*
[20] *Syracuse University, Syracuse, New York 13244*

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Using the CLEO II detector and a sample of 955 000 $\Upsilon(4S)$ decays we have confirmed charmless semileptonic decays of B mesons. In the momentum interval 2.3–2.6 GeV/c we observe an excess of $107 \pm 15 \pm 11$ leptons, which we attribute to $b \to u\ell\nu$. This result yields a model-dependent range of values for $|V_{ub}/V_{cb}|$ that is lower than has been obtained in previous studies. For the inclusive spectator model of Altarelli *et al.* we find $|V_{ub}/V_{cb}| = 0.076 \pm 0.008$. Models that describe $b \to u\ell\nu$ with a limited set of exclusive final states give $|V_{ub}/V_{cb}| = 0.06 - 0.10$.

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The measurement of the Cabibbo-Kobayashi-Maskawa matrix element V_{ub} is among the principal goals of b-quark physics. A nonzero value for V_{ub} is essential for the standard model description of CP violation, and a precise determination will significantly enhance our understanding of the weak interaction. CLEO [1] and ARGUS [2] demonstrated the existence of $b \to u\ell\nu$ transitions by observing B-meson decays with leptons that were too energetic to originate from $b \to c\ell\nu$. These measurements established a value of $|V_{ub}/V_{cb}|$ of approximately 0.1. Subsequently ARGUS [3] presented preliminary evidence for the exclusive decay $B^- \to \rho^0\ell^-\overline{\nu}$, but this has not been confirmed by CLEO [4]. Thus, the inclusive results are the only undisputed evidence that V_{ub} is nonzero.

In this Letter we describe a study of B-meson semileptonic decays in the lepton momentum range 2.3–2.6 GeV/c. Our data sample was obtained with the CLEO II detector at the Cornell Electron Storage Ring and consisted of 924 pb^{-1} of e^+e^- annihilations at the $\Upsilon(4S)$ resonance (ON), and 416 pb^{-1} at total energies $\sim$ 55 MeV below the $\Upsilon(4S)$ (OFF). Our total of $955\,000 \pm 18\,000$ $B\overline{B}$ events represents a more than fourfold increase over previous inclusive measurements of $b \to u\ell\nu$. The contribution of continuum processes to our ON yields was estimated by scaling the OFF yields by 2.20 ± 0.01, the ratio of the ON and OFF luminosities, corrected for the energy dependence of the continuum cross section.

The CLEO II detector has been described in detail [5]. Crucial for this study are charged particle tracking and lepton detection. The tracking system, which measures momentum and specific ionization (dE/dx) of charged particles, consists of a 67-layer drift chamber system inside a 1.5-T solenoidal magnet. Electromagnetic energy is measured with a cesium iodide calorimeter located inside the magnet. Muons are identified with proportional counters embedded in iron.

Event-selection requirements were based on standard CLEO II criteria for event multiplicity, visible energy, and an event vertex consistent with the nominal interaction point. Electron candidates were required to have both an energy deposit in the calorimeter approximately equal to the measured momentum, and dE/dx consistent with that expected for an electron. The efficiency for identifying a 2.3–2.6 GeV/c electron was $(92 \pm 4)\%$ [$(70 \pm 5)\%$] in the polar angular range $|\cos\theta| < 0.71$ [$0.71 \leq |\cos\theta| < 0.85$]. The probability of misidentifying a hadron as an electron was $(0.3 \pm 0.1)\%$. Muon candidates were identified as charged tracks with matching muon-detector hits at absorber depths of at least seven nuclear interaction lengths. The detection efficiency for a 2.3–2.6 GeV/c muon with $|\cos\theta| < 0.85$ was $(85 \pm 4)\%$, and the misidentification probability per track was $(0.7 \pm 0.3)\%$.

The observation of leptons in $\Upsilon(4S)$ decays with momenta above the $b \to c\ell\nu$ kinematic limit ($\sim$2.46 GeV/c) is model-independent evidence for $b \to u\ell\nu$. We restricted our sample to $|\cos\theta| < 0.85$, and applied stringent track-quality requirements, to eliminate mismeasured tracks. Momentum resolution was studied with μ-pair events, and by embedding isolated tracks from QED processes into hadronic events. No appreciable non-Gaussian behavior in the momentum resolution was found.

Lepton production at the $\Upsilon(4S)$ is dominated by $b \to c\ell\nu$. For momenta above 2.3 GeV/c, however, the dominant source of leptons is continuum production. To eliminate $\tau^+\tau^-$ events and other QED processes, we required at least five charged tracks, or four tracks and six or more photon showers. Additional QED background, and other events with a sizable momentum component along the beam axis, were eliminated by demanding the cosine of the polar angle of the missing momentum to be between -0.9 and 0.9. We eliminated events with a track of momentum greater than 3.5 GeV/c, or a shower with energy above 3.5 GeV, since these indicate mismeasurement or continuum production.

We suppressed leptons from continuum hadronic processes by using differences in event shape between these events and $B\overline{B}$. Our selection criteria were optimized in a Monte Carlo study. To simulate the $b \to u\ell\nu$ signal we used the models of Isgur *et al.* (ISGW) [6], Körner and Schuler (KS) [7], and Wirbel, Stech, and Bauer (WSB) [8]. These include a limited set of exclusive final states consisting of a single meson and a lepton-neutrino pair. Our main continuum-suppression tool was the Fox-Wolfram parameter [9] $R_2 = H_2/H_0$, which discriminates between more spherical $B\overline{B}$ events and more jetlike continuum events. We found the optimal requirement to be $R_2 \leq 0.2$, yielding a signal efficiency of 44%, and a continuum-suppression factor of 25. The missing momentum, $p_{\rm miss}$, provided additional discrimination against continuum processes. This quantity should be large for $b \to u\ell\nu$ events, in which a neutrino carries off appreciable momentum. By requiring $p_{\rm miss} \geq 1$ GeV/c, we reduced the continuum by a factor of 2.3, while losing less than 10% of the efficiency for the $b \to u\ell\nu$ decays considered. Since the energetic lepton and neutrino are produced roughly back-to-back, we required the lepton and missing momentum to point into opposite hemispheres. This cut rejected 25% of the remaining continuum with a negligible loss of $b \to u\ell\nu$ signal. Overall, relative to the case of no continuum suppression, these criteria (henceforth the "strict cuts") reduced continuum background by a factor of 70, while providing an efficiency for the $b \to u\ell\nu$ Monte Carlo sample of 38%.

There is considerable uncertainty about the detailed properties of B-meson decays mediated by $b \to u\ell\nu$. In the exclusive models most of the leptons above 2.3 GeV/c are produced in decays with final states $\rho\ell\nu$ and $\omega\ell\nu$ ($\sim$ 70% for ISGW). These models also predict that most decays have large values of q^2, which measures the mass

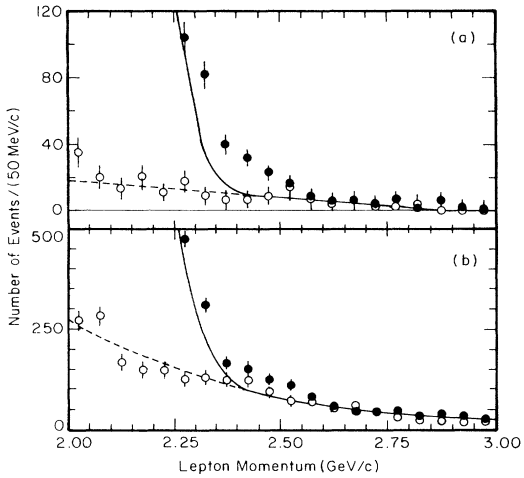

FIG. 1. Lepton spectra for (a) strict and (b) $R_2 < 0.3$ continuum suppression. Filled points are ON data, and open points are scaled OFF. Dashed curves are fits to OFF data. Solid curves show sum of predicted $b \to c\ell\nu$ and fitted OFF.

squared of the virtual W. Both the inclusive model of Altarelli *et al.* (ACCMM) [10], and the hybrid approach suggested by Ramirez *et al.* (RDB) [11], yield more events at low q^2 than the exclusive models, which ignore non-resonant multipion final states. Since the efficiency of stringent continuum suppression depends on q^2, we must assess possible model dependence in our selection efficiency. To do this we have also analyzed our data with a cut of $R_2 < 0.3$ and no requirements on either the magnitude or direction of the missing momentum. This cut suppressed the continuum by a factor of 7, while giving an efficiency of 72% for the exclusive $b \to u\ell\nu$ Monte Carlo sample described above.

Figure 1 shows the momentum spectra for the ON and scaled OFF samples. Both continuum-suppression procedures give clear signals for lepton production beyond the $b \to c\ell\nu$ end point. We estimated the remaining continuum background by fitting the OFF spectra to smooth functions. Good fits were obtained for a variety of functions and fit intervals. The fit results were consistent with directly measured yields. The systematic uncertainty in the continuum subtraction was estimated from the spread among the results of these fits.

The yields of lepton candidates in the 2.4–2.6 GeV/c momentum range are summarized in Table I. Background from misidentified hadrons (fakes) was estimated by multiplying the number of hadron tracks by the fake probabilities. Leptons from $B \to J/\psi X$ were suppressed by excluding any lepton accompanied by an oppositely charged track with which it formed a mass within 60 MeV of the $J\psi$. We used a Monte Carlo simulation, normalized by our observed $J\psi$ yield, to estimate the leakage through this veto and the contribution of $B \to \psi' X$.

We calculated the contribution of $b \to c\ell\nu$ decays by fitting the spectra below the end-point region to models of $b \to c\ell\nu$ [6,8]. Theoretical spectra were corrected for QED effects [12], boosted into the lab using B-momentum measurements from fully reconstructed decays, and smeared to account for momentum resolution. We fitted our electron and muon spectra to the theoretical predictions over the momentum intervals 1.6−2.2 and 1.9−2.2 GeV/c, respectively. The small contribution from $b \to u\ell\nu$ was ignored. From the fit results we determined the $b \to c\ell\nu$ contributions to the signal bins, with systematic uncertainties reflecting differences among models and reasonable variations in the radiative corrections, boost, and momentum resolution. We also have considered other sources of leptons from B decays, including $B \to D \to \ell$ and leptonic decays of vector mesons. These make a very small contribution to the observed yields of high-momentum leptons, and have been included with the $b \to c\ell\nu$ entries.

TABLE I. Lepton yields and backgrounds in momentum interval 2.4–2.6 GeV/c.

	Strict cuts	$R_2 < 0.3$
$N_{\rm ON}$	80	463
$N_{\rm OFF}$(direct)	16	161
$N_{\rm OFF}$(fit)	14.8 ± 2.2 ± 3.0	143.9 ± 6.8 ± 6.8
Excess	47.4 ± 10.2 ± 6.6	146.4 ± 26.2 ± 15.0
Fakes	1.7 ± 0.7 ± 0.5	3.7 ± 2.1 ± 0.9
$J/\psi, \psi'$	1.4 ± 0.4	8.1 ± 1.8
$b \to c\ell\nu$	1.3 ± 0.6	6.2 ± 2.0
$b \to u\ell\nu$	43.0 ± 10.2 ± 6.7	128.4 ± 26.3 ± 15.3

In the momentum range 2.4–2.6 GeV/c the strict-cut analysis yields an excess of $43.0 \pm 10.2 \pm 6.7$ leptons which we attribute to $b \to u\ell\nu$. For $R_2 < 0.3$, the $b \to u\ell\nu$ signal is $128.4 \pm 26.3 \pm 15.3$ leptons. This is a model-independent demonstration of $b \to u\ell\nu$, since the $b \to c\ell\nu$ contribution above 2.4 GeV/c is very small. We measured the lepton yield between 2.3 and 2.4 GeV/c to increase our efficiency in measuring $|V_{ub}|$. While this bin has more $b \to c\ell\nu$ background, our procedure allows it to be calculated reliably. Observed lepton totals and background estimates are given in Table II. For our strict cuts, the total yield due to $b \to u\ell\nu$ in the 2.3–2.6 GeV/c range is $107 \pm 15 \pm 11$ leptons.

Several models were used to extract $|V_{ub}/V_{cb}|$ from the

TABLE II. Lepton yields and backgrounds in momentum interval 2.3–2.4 GeV/c.

	Strict cuts	$R_2 < 0.3$
$N_{\rm ON}$	122	474
$N_{\rm OFF}$(direct)	7	114
$N_{\rm OFF}$(fit)	10.1 ± 1.2 ± 1.4	107.1 ± 4.0 ± 4.2
Excess	99.8 ± 11.4 ± 3.1	238.4 ± 23.5 ± 9.2
Fakes	5.2 ± 0.6 ± 1.8	22.7 ± 1.6 ± 8.0
$J/\psi, \psi'$	2.2 ± 0.5	11.7 ± 2.3
$b \to c\ell\nu$	28.1 ± 2.5	105.9 ± 8.3
$b \to u\ell\nu$	64.3 ± 11.4 ± 4.4	98.1 ± 23.6 ± 14.9

TABLE III. Calculations of $d(p)$ for various models, and corresponding efficiencies and values of $\Delta B_{ub}(p)$ and $|V_{ub}/V_{cb}|^2$.

Model	$d(p)$	Strict cuts Efficiency	Strict cuts $10^6\Delta B_{ub}(p)$	Strict cuts $10^2\|V_{ub}/V_{cb}\|^2$	$R_2 < 0.3$ Efficiency	$R_2 < 0.3$ $10^6\Delta B_{ub}(p)$	$R_2 < 0.3$ $10^2\|V_{ub}/V_{cb}\|^2$
			$p = 2.4–2.6$ GeV/c				
ISGW	0.05	0.21±0.02	53±12±9	0.94±0.28	0.41±0.03	82±17±11	1.46±0.37
KS	0.19	0.22±0.02	51±12±9	0.25±0.07	0.43±0.03	78±16±11	0.39±0.10
WSB	0.11	0.20±0.02	56±13±10	0.47±0.14	0.40±0.03	83±17±12	0.69±0.18
ACCMM	0.12	0.16±0.01	70±16±12	0.53±0.16	0.37±0.03	89±18±12	0.68±0.17
			$p = 2.3–2.4$ GeV/c				
ISGW	0.06	0.25±0.02	67±12±7	1.07±0.23	0.44±0.04	57±14±10	0.90±0.27
KS	0.16	0.27±0.03	62±11±7	0.37±0.08	0.44±0.04	57±14±10	0.34±0.10
WSB	0.10	0.26±0.03	64±11±7	0.58±0.13	0.44±0.04	57±14±10	0.51±0.15
ACCMM	0.13	0.20±0.02	82±15±9	0.60±0.13	0.42±0.03	59±15±10	0.43±0.13

$b \to u\ell\nu$ signal (Table III). In addition to the exclusive models, we used an inclusive calculation based on ACCMM with simple fragmentation [13]. We determined efficiencies for detecting $b \to u\ell\nu$ with full Monte Carlo simulations for each model. Systematic uncertainty in the efficiencies comes from tracking (5%), lepton detection (5%), and continuum suppression (5% for the strict cuts and 2.5% for $R_2 < 0.3$). Averaging over electrons and muons, we determined $\Delta B_{ub}(p)$, the partial branching ratio for $b \to u\ell\nu$ decays in the specific momentum interval. This is related to $|V_{ub}/V_{cb}|^2$ by

$$\left|\frac{V_{ub}}{V_{cb}}\right|^2 = \frac{\Delta B_{ub}(p)}{d(p)B_{cb}},$$

where B_{cb} is the $b \to c\ell\nu$ branching ratio (10.8±0.6% [14]), and $d(p)$ is a theoretical parameter [15].

Table III shows reasonable consistency between the 2.3–2.4 and 2.4–2.6 GeV/c momentum bins. The small differences between the strict cuts and $R_2 < 0.3$ are consistent with being statistical fluctuations, but could hint at inadequacies in the models. The consistency of the two continuum-suppression procedures demonstrates that our strict-cut analysis does not introduce severe model dependence into the determination of $|V_{ub}/V_{cb}|$. A much more significant uncertainty is the model-to-model variation of $d(p)$, reflecting inconsistent predictions for the $b \to u\ell\nu$ decay rate and spectral shape.

The results of our strict-cut analysis for the full 2.3−2.6 GeV/c momentum range are summarized in Table IV. For the ACCMM model, we find $\Delta B_{ub}(p) = (154 \pm 22 \pm 20) \times 10^{-6}$, and $|V_{ub}/V_{cb}| = 0.076 \pm 0.008$. The exclusive models give $|V_{ub}/V_{cb}| = 0.06 - 0.10$. The limited set of final states in the exclusive models raises concerns about their appropriateness for extracting $|V_{ub}/V_{cb}|$. The inclusive approach averages over all $b \to u\ell\nu$ decays, but does not explicitly include single-meson final states which must contribute near the end point. Reference [11] proposed a hybrid with exclusive techniques for small hadronic recoil energy, and an inclusive approach for large recoil. We constructed such a hybrid from our ISGW and ACCMM Monte Carlo samples. We found some sensitivity to the choice of parameters, and values of $|V_{ub}/V_{cb}|$ between 0.065 and 0.075. Because the model dependence is mostly in $d(p)$, our measurements of $\Delta B_{ub}(p)$ can be used to estimate $|V_{ub}/V_{cb}|$ with models besides those discussed here. Ball *et al.* have used QCD sum rules and our results to obtain $|V_{ub}/V_{cb}| \approx 0.08$ [16].

TABLE IV. Partial branching fractions, $|V_{ub}/V_{cb}|^2$, and $|V_{ub}/V_{cb}|$ in 2.3–2.6 GeV/c interval for strict cuts.

Model	$10^6\Delta B_{ub}(p)$	$10^2\|V_{ub}/V_{cb}\|^2$	$\|V_{ub}/V_{cb}\|$
ISGW	121 ± 17 ± 15	1.02 ± 0.20	0.101 ± 0.010
KS	115 ± 16 ± 15	0.31 ± 0.06	0.056 ± 0.006
WSB	122 ± 17 ± 16	0.53 ± 0.11	0.073 ± 0.007
ACCMM	154 ± 22 ± 20	0.57 ± 0.11	0.076 ± 0.008

Our measurements of $|V_{ub}/V_{cb}|$ are consistent with upper limits from an exclusive search for $b \to u\ell\nu$ [4]. The new $|V_{ub}/V_{cb}|$ values are considerably smaller than those of previous inclusive studies. Using the ISGW model, CLEO [1] reported $|V_{ub}/V_{cb}|^2$ measurements of $(3.6 \pm 1.0) \times 10^{-2}$ and $(2.2 \pm 0.6) \times 10^{-2}$, for the momentum intervals 2.4–2.6 and 2.2–2.6 GeV/c, respectively. Correcting these measurements to use the B_{cb} value of Ref. [14], we find that our new results differ by 1.5 to 2.5 standard deviations. While comparisons with ARGUS [2] are more difficult, we estimate that our results are smaller by approximately 2.5 standard deviations.

In conclusion, we have confirmed charmless semileptonic decays of B mesons. The values of $|V_{ub}/V_{cb}|$ which we find are smaller than those of previous inclusive studies. Extraction of $|V_{ub}/V_{cb}|$ continues to be limited by theoretical uncertainties. As the CLEO II data sample grows, detailed studies of $b \to u\ell\nu$ signal events should allow discrimination among the theoretical alternatives.

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* Permanent address: Carleton University, Ottawa,

Canada K1S 5B6.
† Permanent address: INP, Novosibirsk, Russia.

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[15] For any model, $\Gamma(b \to u\ell\nu) = |V_{ub}|^2\gamma_u$ and $\Gamma(b \to c\ell\nu) = |V_{cb}|^2\gamma_c$, where Γ is the total width for the given semileptonic decay. If $f_u(p)$ is the fraction of the $b \to u\ell\nu$ momentum spectrum in the specified momentum interval, then $d(p) = f_u(p)\gamma_u/\gamma_c$.
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