Improved Measurement of $|V_{ub}|$ with Inclusive Semileptonic B Decays

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We report a new measurement of the Cabibbo-Kobayashi-Maskawa parameter $|V_{ub}|$ made with a sample of 9.7×10^6 $B\bar{B}$ events collected with the CLEO II detector. Using heavy quark theory, we combine the observed yield of leptons from semileptonic B decay in the end-point momentum interval 2.2–2.6 GeV/c with recent CLEO II data on $B \to X_s \gamma$ to find $|V_{ub}| = (4.08 \pm 0.34 \pm 0.44 \pm 0.16 \pm 0.24) \times 10^{-3}$, where the first two uncertainties are experimental and the last two are from theory.

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Measurement of the Cabibbo-Kobayashi-Maskawa (CKM) matrix element V_{ub} is one of the most challenging and important tasks in testing the standard model. This direct measurement of one side of the unitarity triangle gives information that is complementary to studies of CP violation in B decays. Semileptonic B decays are a direct route to $|V_{ub}|$ and $|V_{cb}|$. Measurements of lepton production above the kinematic limit for $B \to X_c \ell \nu$ provided the discovery of nonzero $|V_{ub}|$ [1,2] and a measurement of its value [3] that was of uncertain reliability due to its heavy reliance on theoretical models.

In this paper we report an improved inclusive measurement of $B \to X_u \ell \nu$ made with the CLEO II detector at the Cornell Electron Storage Ring (CESR). This measurement supersedes that of Ref. [3], which was based on the first tenth of our data sample. Improved background-suppression techniques help reduce the model dependence of the result. We have measured $B \to X_u \ell \nu$ over a broader momentum range than was previously possible, further reducing theoretical uncertainty, but incurring experimental uncertainty in the large $B \to X_c \ell \nu$ subtraction. We use the momentum range 2.2–2.6 GeV$/c$ as a compromise between these considerations, and present other intervals to test the stability of our result and to compare with past measurements. For extracting $|V_{ub}|$, models have been replaced with heavy quark (HQ) theory [4–10] and the CLEO-measured $B \to X_s \gamma$ photon-energy spectrum [11]. Our determination of $|V_{ub}|$ has superior precision to previous measurements, although the assumption of quark-hadron duality in the application of HQ theory is subject to an uncertainty that cannot yet be estimated with confidence.

The CLEO II detector has been described in detail [12]. Key components for this work are the tracking system, the cesium iodide calorimeter, and the muon detector. Two-thirds of our data were collected after a detector upgrade that included a silicon tracker [13], a change of drift-chamber gas from argon-ethane to helium-propane, and other improvements. We obtained an integrated luminosity of 9.13 fb^{-1} of e^+e^- annihilation data at the $\Upsilon(4S)$ resonance (ON) and 4.35 fb^{-1} at energies just below $B\bar{B}$ threshold (OFF). OFF yields are scaled by a factor of 2.06 ± 0.02 and subtracted from the ON yields to eliminate contributions of non-$B\bar{B}$ processes. We determine the scale factor by comparing ON and OFF track spectra above the B-decay kinematic limit, and confirm the result with measured luminosities. The ON sample includes 9.7×10^6 $B\bar{B}$ events.

We select electron and muon candidates using criteria that have been optimized for the measurement of charmless semileptonic B decays [14]. We use only the best-measured and best-understood central region of CLEO II ($|\cos\theta| \leq 0.71$, where θ is the angle with respect to the beam). An electron candidate must have an energy deposit in the calorimeter close in value to its measured momentum and a specific ionization consistent with that expected for an electron. The efficiency of electron selection is slightly momentum-dependent, with a value of 0.93 ± 0.03 at 2.2 GeV$/c$. Muons must penetrate seven nuclear interaction lengths of absorber material. The threshold momentum is $\sim$1.8 GeV$/c$ and the efficiency is 0.88 ± 0.03 at 2.2 GeV$/c$. Misidentification rates are measured for tagged $\pi^\pm$, $K^\pm$, and $p/\bar{p}$ tracks and averaged in proportions determined with simulated $B\bar{B}$ events. The electron and muon fake rates above 2.0 GeV$/c$ are less than 0.1% and about 0.5%, respectively.

We use several cuts to minimize mismeasurements and background from sources other than semileptonic decays. We veto any lepton that can be paired with another lepton of the same type and opposite charge if the pair mass is within three standard deviations of the J/ψ mass. Electrons from photon conversions are also rejected. Stringent requirements on tracking residuals, impact parameter, and the fraction of tracking layers traversed that have good hits ensure a reliable momentum measurement. The momentum-dependent track-selection efficiency is determined with a GEANT simulation [15] of signal events. Real and simulated radiative Bhabha electrons embedded in hadronic events are used to determine a correction factor accounting for the imperfect simulation. The track-selection efficiency for $B \to X_u \ell \nu$ is $\sim$0.95, with a 3% uncertainty.

Although most leptons at the $\Upsilon(4S)$ are from semileptonic B decays, continuum production contributes a large background at high momentum that can be subtracted with OFF data. To avoid degrading the precision of our $B \to X_u \ell \nu$ measurement, we use several criteria to suppress the continuum before subtraction [14]. Beam-gas, beam-wall, and some QED events are eliminated by cuts on visible energy and the event vertex. A multiplicity cut suppresses $\tau^+\tau^-$. Particles above the B-decay kinematic limit indicate continuum production or mismeasurement, so we eliminate events having a track or shower with an energy above 3.5 GeV. Two-photon and QED processes are suppressed by cutting events with missing momentum near the beam.

The continuum background remaining after this selection is primarily $e^+e^- \to c\bar{c}$. Signal and background events can be discriminated quite effectively based on "event-shape" differences: isotropic distribution of tracks and showers for $B\bar{B}$ events and back-to-back correlations for continuum $c\bar{c}$. Our previous analysis [3] relied on specific features of $B \to X_u \ell \nu$ to suppress the continuum by a factor of 70, with a signal efficiency of $\sim$0.38. Primarily because of the use of missing-momentum cuts, this efficiency depended strongly on q^2 (the squared mass of the virtual W), contributing to the model dependence of the result. The goal of this analysis is to achieve comparable suppression with reduced model dependence. This requires cuts that exploit the presence of the "other B" in signal events, rather than the details of $B \to X_u \ell \nu$. We use a neural net with inputs that are measurements of the energy flowing into eleven angular intervals defined with respect to the candidate-lepton direction. We exclude energy within 25° of the direction opposite to the lepton, where there is strong dependence on the q^2 of the decay. The net was trained with a simulated signal sample generated with the ISGW2 model [16] and a simulated background sample of continuum $e^+e^- \to q\bar{q}$. Optimized for the expected signal level, the neural net gives background rejection of a factor of 50 and signal efficiency of 0.33. Complete details of the continuum-suppression procedure are provided in Ref. [14].

The total efficiency for selecting leptons from $B \to X_u \ell \nu$ is $\sim$0.21, with about a 5% variation between 2.0 and 2.6 GeV/c. The uncertainty is about 7%, with roughly equal contributions from detector response and model uncertainties. We assess the latter by considering several models: ISGW2, the ACCMM spectator model [17,18] with various values of internal parameters, and a hybrid of these developed by CLEO. Our current procedures have less than one-third of the model-to-model variation of the previous analysis and essentially no dependence on the mass of the hadronic system X_u.

The computation of the $B \to X_u \ell \nu$ signal for the momentum interval 2.2–2.6 GeV/c is shown in Table I. The spectrum of lepton candidates from $B\bar{B}$ events is obtained by subtracting the scaled OFF momentum distribution from the ON distribution. It includes $B \to X_u \ell \nu$ and several B-decay backgrounds. Hadrons misidentified as leptons (fakes) are computed by combining the momentum-dependent misidentification probabilities with the spectrum of hadrons from $B\bar{B}$ that pass all selection requirements except for lepton identification. Leakage through the J/ψ and photon-conversion vetoes is estimated with Monte Carlo normalized to data, with systematic errors of 10% and 25%, respectively. Several other backgrounds are also estimated by Monte Carlo and are assigned conservative systematic errors: $\psi(2S)$ leptonic decays ($\pm$25%), semileptonic and leptonic decays of D and D_s ($\pm$50%), semileptonic decays to τ ($\pm$25%), and π^0 Dalitz decays ($\pm$100%).

The largest background to $B \to X_u \ell \nu$ for momenta below 2.4 GeV/c is $B \to X_c \ell \nu$. We calculate this by fitting the lepton spectra between 1.5 GeV/c and the low end of the end-point interval. Fit functions are generated with Monte Carlo simulations using models and CLEO-measured form factors [19,20]. QED radiative corrections are applied with the PHOTOS algorithm [21]. Spectra generated in the B rest frame are boosted to the lab frame using the B-momentum distribution of our data. There are four components in the fits: a mixture of D and D^* with the ratio given by exclusive branching fractions [22]; a mixture of decays to D^{**} and other higher-mass charmed mesons (ISGW2); nonresonant decays (model of Goity and Roberts [23]); and $B \to X_u \ell \nu$ (ISGW2 normalized to the end-point yield of Ref. [3]).

The proportions for the $B \to X_c \ell \nu$ components are determined by fits to the electron spectrum without the neural-net cut, because the momentum acceptance is larger and has less uncertainty than that for the muons. The resulting fit has a χ^2 of 14.9 for 11 degrees of freedom. The muons are then fitted to the same mixture, with one parameter to allow for a difference in the e/μ efficiency ratio between Monte Carlo and data. The electron and muon spectra with the neural-net cut applied are then fitted to the same mixtures, with one parameter allowing for mismodeling of the neural-net efficiency. These fits provide the $B \to X_c \ell \nu$ subtractions in Table I.

We assess the uncertainty in the $B \to X_c \ell \nu$ subtraction by varying inputs, including the D/D^* ratio, the form factors for $B \to D/D^* \ell \nu$, the relative D^{**} and nonresonant normalizations, the radiative corrections, the B-momentum scale, the normalization and models for $B \to X_u \ell \nu$, and the fit intervals. The overall uncertainty in the subtraction is the sum in quadrature of the observed variations. The largest is due to form factors.

Figure 1(a) shows the ON and scaled OFF momentum spectra. Figure 1(b) shows the background-subtracted and efficiency-corrected spectrum for $B \to X_u \ell \nu$. Statistical and systematic uncertainties have been combined in quadrature. Below 2.3 GeV/c, the $B \to X_c \ell \nu$ subtraction dominates the uncertainties, which are strongly correlated from bin to bin. The partial branching fraction for $B \to X_u \ell \nu$ ($\ell = e$ or μ) in a given momentum interval is $\Delta\mathcal{B}_u(p) = N_\ell(p)/[2N_{B\bar{B}}\epsilon(p)]$, where N_ℓ is half of the total yield of e's and μ's, $\epsilon(p)$ is the efficiency, and $N_{B\bar{B}} = (9.67 \pm 0.17) \times 10^6$ is the number of $B\bar{B}$ events. Results are given in Table II for five different end-point momentum intervals. They are in good agreement with our previous measurement [3].

To determine the charmless semileptonic branching fraction $\mathcal{B}(B \to X_u \ell \nu)$ from the partial branching fraction $\Delta\mathcal{B}_u(p)$, we need to know the true acceptance fraction $f_u(p)$ of the $B \to X_u \ell \nu$ spectrum that falls in the given momentum interval. Parton-level decays can be reliably calculated, but the observable meson-decay processes depend on the mass of the b quark and its motion inside

TABLE I. Lepton yields and backgrounds in the momentum interval 2.2–2.6 GeV/c.

	e	μ	Sum
N_{on}	4110	4857	8967
N_{off}	410	573	983
$B\bar{B}$	$3265 \pm 77 \pm 8$	$3673 \pm 85 \pm 12$	$6938 \pm 115 \pm 20$
Fakes	$15 \pm 6 \pm 4$	$194 \pm 13 \pm 58$	$209 \pm 19 \pm 58$
J/ψ	$68 \pm 4 \pm 7$	$90 \pm 5 \pm 9$	$158 \pm 6 \pm 16$
Other backgrounds	$40 \pm 8 \pm 10$	$67 \pm 6 \pm 18$	$107 \pm 10 \pm 29$
$B \to X_c \ell \nu$	$2147 \pm 23 \pm 116$	$2415 \pm 24 \pm 130$	$4562 \pm 33 \pm 246$
$B \to X_u \ell \nu$	$995 \pm 81 \pm 117$	$906 \pm 106 \pm 133$	$1901 \pm 122 \pm 256$

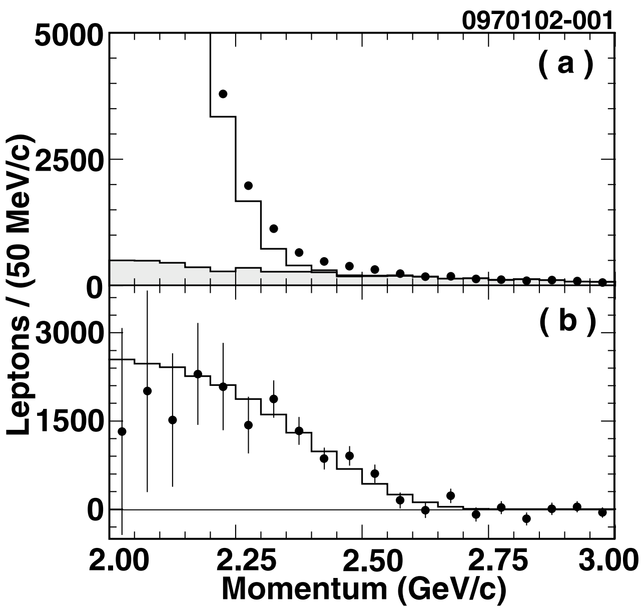

FIG. 1. (a) Lepton spectra for ON (points) and scaled OFF (shaded histogram). The unshaded histogram is the sum of the scaled OFF and B-decay backgrounds. (b) Background-subtracted efficiency-corrected lepton spectrum for $B \to X_u \ell \nu$ (points). The histogram is the $B \to X_u \ell \nu$ spectrum predicted with the measured $B \to X_s \gamma$ spectrum.

the B meson. These properties have been described in recent years with HQ theory under the assumption of quark-hadron duality [4–10]. A light-cone shape function can be convoluted with the $b \to u \ell \nu$ spectrum to obtain the spectrum for $B \to X_u \ell \nu$. The shape function depends on nonperturbative QCD and has not yet been calculated from first principles. To leading order, the same shape function describes *all* b-to-light transitions, in particular also relating $B \to X_s \gamma$ to $b \to s \gamma$.

We have recently measured the photon-energy spectrum in $B \to X_s \gamma$ [11]. Three two-parameter descriptions of the shape function [7,8] are used to fit this spectrum over the range $1.5 < E_\gamma < 2.8$ GeV. All shape functions give good fits. We use the best-fit parameters and error ellipses to calculate the $B \to X_u \ell \nu$ lepton-momentum spectra and determine f_u and its uncertainty, following Ref. [9]. We compute the effect of QED radiative corrections on f_u with PHOTOS. The resulting values of f_u are given in Table II. The systematic uncertainty includes contributions from the subtraction of B-decay processes other than $B \to X_s \gamma$, the choice of scale for evaluating α_s, radiative corrections, and differences among the shape functions.

We extract $|V_{ub}|$ by averaging the nearly identical formulations of Hoang *et al.* [24] and Uraltsev [25]:

$$|V_{ub}| = (3.07 \pm 0.12) \times 10^{-3} \times \left[\frac{\mathcal{B}(B \to X_u e \nu)}{0.001} \frac{1.6\ \text{ps}}{\tau_B} \right]^{1/2}.$$

For the B lifetime, we use $\tau_B = 1.60 \pm 0.02$ ps [22]. Results for $|V_{ub}|$ (Table II) show excellent agreement among the five momentum ranges. The best overall precision (15%) is obtained for the 2.2–2.6 GeV/c interval. The first two uncertainties on $|V_{ub}|$ are from the determinations of $\Delta\mathcal{B}_u(p)$ from the end-point measurement and of f_u from $B \to X_s \gamma$ (combined statistical and systematic). The third is the average of the uncertainties given in Refs. [24,25] for computing $|V_{ub}|$ from the branching fraction. Both $\mathcal{B}(B \to X_u \ell \nu)$ and $|V_{ub}|$ are subject to an additional theoretical uncertainty associated with the assumption that $B \to X_s \gamma$ can be used to compute the spectrum for $B \to X_u \ell \nu$. This is valid to leading order, with corrections at order Λ_{QCD}/M_B. Taking $\Lambda_{\text{QCD}}/M_B \approx 0.1$, we preliminarily estimate this error by varying the shape function parameters by $\pm 10\%$ [26]. This is given as the fourth uncertainty on $|V_{ub}|$ in Table II. Reference [14] provides a detailed explanation, allowing reevaluation of $|V_{ub}|$ and its uncertainties as the theoretical picture clarifies.

For comparison, we also determine f_u with models of $B \to X_u \ell \nu$. Available exclusive models are limited in the final states included, while inclusive models have uncertain internal parameters. Neither type provides a solid basis for assessing the theoretical uncertainty. For ISGW2 and ACCMM (spectator mass $m_{sp} = 150$ MeV/c^2, Fermi momentum $p_F = 300$ MeV/c), we find $|V_{ub}|$ in the 2.2–2.6 GeV/c interval to be 20% smaller than the result given above. Replacing the default ACCMM parameters (chosen for consistency with past analyses) with values we have obtained by fitting the $B \to X_s \gamma$ spectrum [11] to a spectator parameterization [27] gives better agreement. The parameter values are $m_{sp} \simeq 230$ MeV/c^2 and $p_F \simeq 440$ MeV/c, leading to a $|V_{ub}|$ that is ~5% smaller than our result.

In conclusion, we have measured the CKM parameter $|V_{ub}|$ to be $(4.08 \pm 0.63) \times 10^{-3}$. This result has smaller

TABLE II. Results for five momentum intervals. Uncertainties on the yields, acceptance fraction f_u, and branching fractions are statistical and systematic. The first uncertainty on the total branching fraction is from $\Delta\mathcal{B}_u(p)$ and the second is from f_u. The first two uncertainties on $|V_{ub}|$ are from the branching fraction and the third and fourth are from theory.

p (GeV/c)	Yield	$\Delta\mathcal{B}_u(p)$ (10^{-4})	f_u	$\mathcal{B}(B \to X_u \ell \nu)$ (10^{-3})	$\lvert V_{ub}\rvert$ (10^{-3})
2.0–2.6	3538 ± 279 ± 1470	4.22 ± 0.33 ± 1.78	0.266 ± 0.041 ± 0.024	1.59 ± 0.68 ± 0.28	3.87 ± 0.83 ± 0.35 ± 0.15 ± 0.12
2.1–2.6	2751 ± 191 ± 584	3.28 ± 0.23 ± 0.73	0.198 ± 0.035 ± 0.020	1.66 ± 0.39 ± 0.34	3.95 ± 0.46 ± 0.40 ± 0.16 ± 0.16
2.2–2.6	1901 ± 122 ± 256	2.30 ± 0.15 ± 0.35	0.130 ± 0.024 ± 0.015	1.77 ± 0.29 ± 0.38	4.08 ± 0.34 ± 0.44 ± 0.16 ± 0.24
2.3–2.6	1152 ± 80 ± 61	1.43 ± 0.10 ± 0.13	0.074 ± 0.014 ± 0.009	1.94 ± 0.22 ± 0.43	4.27 ± 0.24 ± 0.47 ± 0.17 ± 0.34
2.4–2.6	499 ± 57 ± 14	0.64 ± 0.07 ± 0.05	0.037 ± 0.007 ± 0.003	1.74 ± 0.24 ± 0.38	4.05 ± 0.28 ± 0.45 ± 0.16 ± 0.45

overall uncertainty than previous measurements and represents a major step forward, both in the quality of the experimental data and in the use of QCD theory together with the measured $B \to X_s \gamma$ photon-energy spectrum rather than phenomenological models.

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