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Measurement of the Inclusive Electron Spectrum in Charmless Semileptonic B Decays Near the Kinematic Endpoint

The *BABAR* Collaboration

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Abstract

A preliminary result on the study of the inclusive electron spectrum in $B \to X_u e\nu$ decays above the kinematic limit for the dominant $B \to X_c e\nu$ transitions is presented. This study is performed at the PEP-II asymmetric B Factory, where B meson pairs are produced in the decay of the $\Upsilon(4S)$ resonance. For the electron momentum range of $2.3 - 2.6$ GeV/c in the $\Upsilon(4S)$ rest frame, the partial branching ratio is measured to be $\Delta\mathcal{B}(B \to X_u e\nu) = (0.152 \pm 0.014 \pm 0.014) \cdot 10^{-3}$.

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1 Introduction

The principal physics goal of the *BABAR* experiment is to establish CP-violation in B mesons and to test whether the observed effects are consistent with the prediction of the Standard Model. In this model CP violating effects are predicted from the CKM matrix of the couplings of the charged weak current to quarks. A precise determination of the matrix element $|V_{ub}|$ will place constraints on the unitarity of the CKM matrix and thus the consistency with the minimal Standard Model.

The extraction of $|V_{ub}|$ is a challenge, both theoretically and experimentally. While at the parton level weak interactions can be reliably calculated, meson decays depend on the b quark mass and its motion inside the B meson. Theoretical calculations of the semileptonic decay rate in terms of $|V_{ub}|$ rely on an operator product expansion (OPE) in inverse powers of the b quark mass [1] and thus depend on the choice of renormalization scale and include non-perturbative parameters. Experimentally, the principal difficulty is the separation of $B \to X_u e\nu$ decays from the dominant $B \to X_c e\nu$ decays. Selection criteria applied to achieve this separation generally make it difficult to translate the observed rate to the full decay rate.

In this paper we present a measurement of the inclusive electron spectrum for charmless semileptonic B decays in the momentum range of $2.3-2.6$ GeV/c as measured in the $\Upsilon(4S)$ rest frame. In the rest frame of the B meson, the kinematic endpoint of the electron spectrum for the dominant $B \to X_c e\nu$ decays is $\sim 2.3\,\mathrm{GeV}/c$ and $\sim 2.6\,\mathrm{GeV}/c$ for $B \to X_u e\nu$ decays. In the rest frame of the $\Upsilon(4S)$, the B mesons have a momentum of $\sim 0.3\,\mathrm{GeV}/c$ and thus the electron spectrum is convoluted by a spread of $\pm 0.2\,\mathrm{GeV}/c$, extending the endpoint to higher energies. Nevertheless, a narrow interval of about 300 MeV/c remains that is dominated by electrons from $B \to X_u e\nu$ transitions. This interval covers approximately 10% of the total electron spectrum for charmless semileptonic B decays. The extrapolation from the limited momentum range near the endpoint to the full spectrum is a very difficult task because the OPE breaks down in this part of phase space.

This analysis is based on the same method as previous measurements of the lepton spectrum near the endpoint [2, 3] (ARGUS), [4, 5] (CLEO).

2 Detector and Data Sample

This analysis is based on data recorded in 1999-2000 with the *BABAR* detector at the PEP-II energy asymmetric e^+e^- collider at the Stanford Linear Accelerator Center. The data sample corresponds to an integrated luminosity of 20.6 fb^{-1} that was collected at the $\Upsilon(4S)$ resonance (ON), plus an additional sample of 2.6 fb^{-1} that was recorded about 40 MeV below the $\Upsilon(4S)$ peak (OFF).

The relative normalization of the ON and OFF-peak data is $7.87 \pm 0.01 \pm 0.04$. This factor has been derived from luminosity measurements, which are based on the QED cross section for $e^+e^- \to \mu^+\mu^-$ production, corrected for the energy dependence of the cross section. The systematic error on the relative normalization is estimated to be $\sim 0.5\%$. This error accounts for small variations in the detector response and is significantly smaller than the systematic error of $\sim 1.6\%$ on the absolute $\mu^+\mu^-$ cross section measurement.

The *BABAR* detector has been described in detail elsewhere [6]. The most important components for this study are the charged particle tracking system, consisting of a five-layer silicon detector and a 40-layer drift chamber, and the electromagnetic calorimeter assembled from 6580 CsI(Tl) crystals. Electron candidates are selected on the basis of the ratio of the energy detected in the calorimeter to the track momentum, the calorimeter shower shape, the energy loss in the drift chamber, and the angle reconstructed in the ring imaging Cherenkov detector.

The electron identification efficiency and the probabilities to misidentify a pion, kaon, or proton as an electron have been measured with clean samples of tracks that were selected from the data. This experimental information is introduced into the Monte Carlo simulation to improve the agreement with the data. Tracking efficiencies and resolution have been studied. A comparison with the simulation has revealed small differences, which have been taken into account. No significant impact of non-Gaussian resolution tails has been found in the endpoint region.

The Monte Carlo simulation of $B \to X_u e\nu$ events is based on the ISGW2 model [7]. In the current version, the hadrons X_u are represented by single particles or resonances with masses up to 1.5 GeV/c^2 and non-resonant contributions are not included. For $B \to X_c e\nu$ transitions three models are employed to simulate different decay modes. The decay to $D^* e\nu$ is modeled following a form factor based parameterization of HQET [8]; for decays to $De\nu$ and higher mass charm meson states the ISWG2 model is used. The non-resonant decays to $D^{(*)}\pi e\nu$ are modeled according to a prescription by Goity and Roberts [9].

3 Data Analysis

3.1 Event Selection

For this analysis, electron candidates are selected in the momentum range from 1.5 to 3.5 GeV/c in the $\Upsilon(4S)$ rest frame. The solid angle is restricted by the electromagnetic calorimeter coverage, defined by the laboratory polar angle range of $-0.72 < \cos\theta_{\rm lab} < 0.92$. In this momentum and angular range, the efficiency for identifying an electron has been measured to be $\epsilon_{PID} = 0.91 \pm 0.02$, while the average hadron misidentification probability is less than 0.2%. The selected electron sample is dominated by electrons from semileptonic decays of B and D mesons, non-resonant $q\bar{q}$ production and QED processes. In addition, photon conversions and Dalitz decays contribute background at low momenta and J/ψ decays contribute at higher momenta. Furthermore, there are sizable contributions from hadrons misidentified as electrons. To suppress low-multiplicity QED processes, including $\tau^+\tau^-$ pairs, the number of charged tracks per event is required to be greater than three. This background and non-resonant hadronic events are further suppressed by a restriction on the ratio of Fox-Wolfram moments $H_2/H_0 < 0.4$ [10]. In semileptonic decays, the neutrino carries a substantial momentum. In events in which the only undetected particle is this neutrino, its direction can be inferred from the missing momentum in the event, defined as the difference between the net momentum of the two colliding beam particles and the vector sum of all detected particles, charged and neutral. Therefore, the selection of these decays can be greatly enhanced by requiring that the measured missing momentum exceed 1 GeV/c and point into the detector fiducial volume. Furthermore, since the B mesons are produced almost at rest and the high momentum electron and neutrino point in nearly opposite directions, we require that the angle between the electron candidate and the missing momentum be greater than $\pi/2$. Candidate electrons are rejected if, when paired with an opposite-sign electron, the invariant mass of the pair is consistent with J/ψ mass, $3.05 < M_{e^+e^-} < 3.15$ GeV/c^2.

The detection efficiencies are estimated using Monte Carlo simulation. For the selection criteria described above, the detection efficiency for charmless semileptonic decays in the electron momentum interval of $1.5 - 2.7$ GeV/c ranges from ~ 0.4 to ~ 0.25.

3.2 Background Subtraction

The raw spectrum of the highest momentum electron in events selected by the criteria described above is shown in Figure 1a, separately for data recorded ON and OFF resonance. For the OFF-resonance data, the momenta are scaled to compensate for the 0.4% difference in the c.m.s. energies of the two data samples.

Also shown in Figure 1a is a fit to approximate the non-resonant background contribution. For the purpose of this fit the normalized OFF-peak data in the interval of $p_{cms} = 1.5 - 3.5$ GeV/c are combined with the ON-peak data in the interval of $p_{cms} = 2.7 - 3.5$ GeV/c above the kinematic limit for $B \to X_u e\nu$ decays. The χ^2/dof for a fit with a 4-th degree Chebyshev polynomial is 51/51. Figure 1b shows the residuals of the fitted function from the unscaled OFF-peak data. The fit significantly reduces the statistical uncertainty in the estimate of the continuum background that is to be subtracted.

The result of the subtraction of the fitted continuum background is shown in Figure 2a. Also shown are the Monte Carlo predictions of the expected signal from $B \to X_u e\nu$ decays and background contributions from all other processes, $B \nrightarrow X_u e\nu$. In this simulation, the $B \to X_u e\nu$ branching ratio is assumed to be $1 \cdot 10^{-3}$ and the relative normalization of data and Monte Carlo simulation is set by the number of electrons in the momentum interval between 1.5 and 2.3 GeV/c. The result of the subtraction of all backgrounds is shown in Figure 2b.

The number of selected events, split into three momentum intervals, together with the estimated background contributions are listed in Table 1. The intervals are chosen to emphasize differences in the background composition: the interval 2.0 and 2.3 GeV/c is dominated by semileptonic $B \to X_c e\nu$ decays, with a small contribution from hadron misidentification, the $2.3 - 2.6$ GeV/c interval is mostly populated by $B \to X_u e\nu$ decays and continuum background, while the $2.7 - 3.0$ GeV/c interval contains almost exclusively continuum background.

Table 1: The number of signal and background events and signal selection efficiencies $\epsilon(B \to X_u e\nu)$ for three different intervals in the electron momentum. $N_{\rm ON}$ refers to the number of selected electrons recorded on the $\Upsilon(4S)$ resonance, $N_{\rm OFF}$ is the fitted number of continuum background events. The $N(B \to X_c e\nu)$ and $N(B \to X_c \to e)$ refer to the Monte Carlo estimate of the remaining semileptonic background, from prompt and secondary decays (including $\psi(2S)$), respectively. $N(B \to J/\psi \to e^+e^-)$ is an estimate of J/ψ background remaining after the mass cut. $N(B \to X_c)$ is a background from hadronic B decays to charm. $N(B \to X_u e\nu)$ is the resulting number of signal electrons.

Momentum p_e (GeV/c)	$2.0 - 2.3$	$2.3 - 2.6$	$2.7 - 3.0$
$N_{\rm ON}$	$74,140 \pm 272$	$6,455 \pm 80$	$1,932 \pm 44$
$N_{\rm OFF}$	$7,749 \pm 165$	$4,051 \pm 93$	$1,903 \pm 37$
$N(B \to X_c e\nu)$	$61,158 \pm 470$	470 ± 41	0
$N(B \to J/\psi \to e^+e^-)$	666 ± 49	128 ± 22	0
$N(B \to X_c \to e)$	338 ± 35	18 ± 8	0
$N(B \to X_c)$ - mis-ID	373 ± 37	92 ± 18	4 ± 4
$N(B \to X_u e\nu)$	$3,857 \pm 572$	$1,696 \pm 133$	25 ± 57
$\epsilon(B \to X_u e\nu)(\%)$	33.9 ± 1.0	27.7 ± 1.3	28.6 ± 22.9

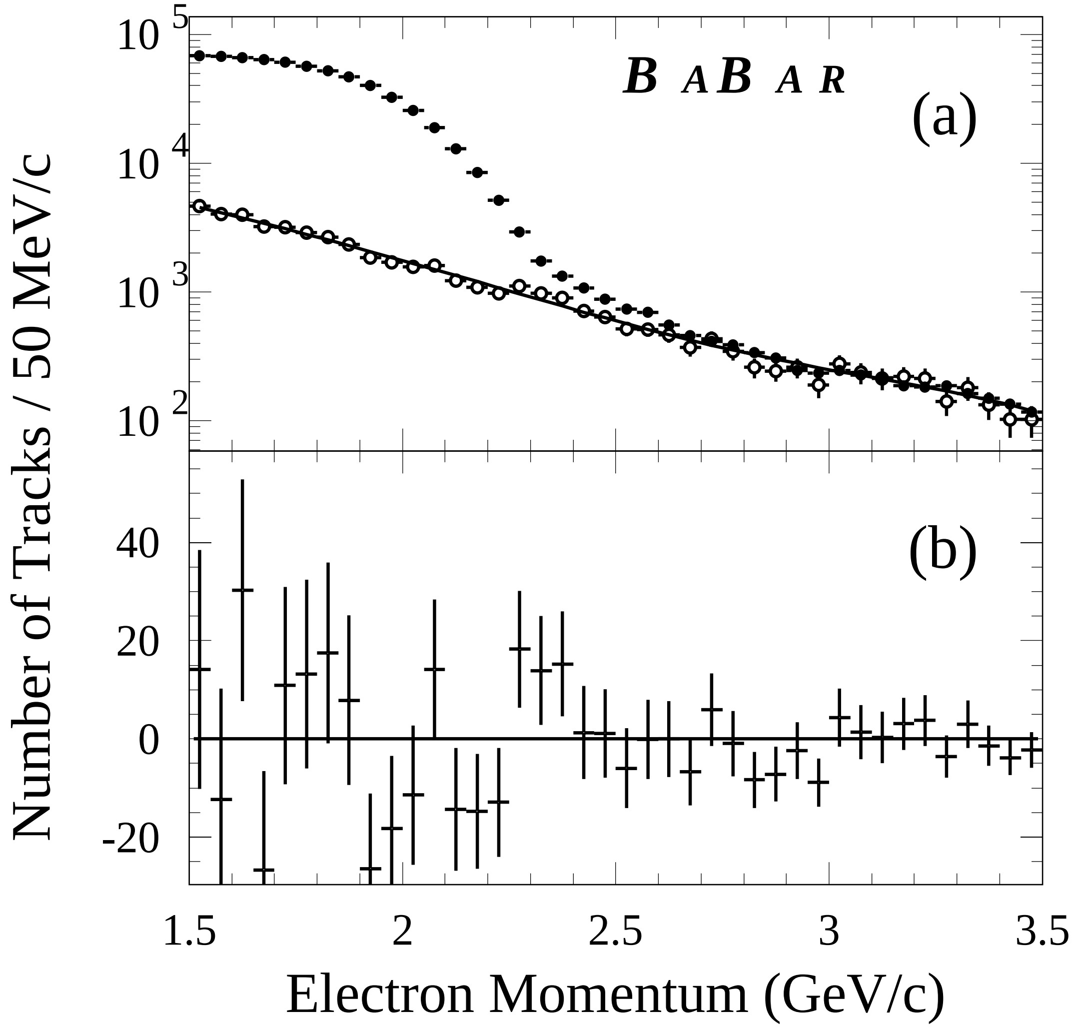

Figure 1: Electron momentum spectrum in the $\Upsilon(4S)$ rest frame: (a) ON-peak data (solid circles), OFF-peak data scaled by the ON/OFF-ratio (open circles), (b) OFF-peak data (unscaled) after the subtraction of the fitted continuum. The line show the result of a fit to the continuum spectrum (using both ON- and OFF-peak data) in the interval $p_{cms} = 1.5 - 3.5$ GeV/c with a 4-th degree Chebyshev polynomial.

3.3 Determination of $B \to X_u e\nu$ Branching Ratio

For a given interval in the electron momentum, the inclusive partial branching ratio is calculated according to

$$\Delta\mathcal{B} = \frac{N_{\rm ON} - N_{\rm OFF} - N_{B \not\to X_u e\nu}}{2\epsilon N_{B\bar{B}}}(1 + \delta_{rad}). \quad (1)$$

Here $N_{\rm ON}$ refers to the number of electrons detected ON-peak and $N_{\rm OFF}$ refers to the fitted contin-

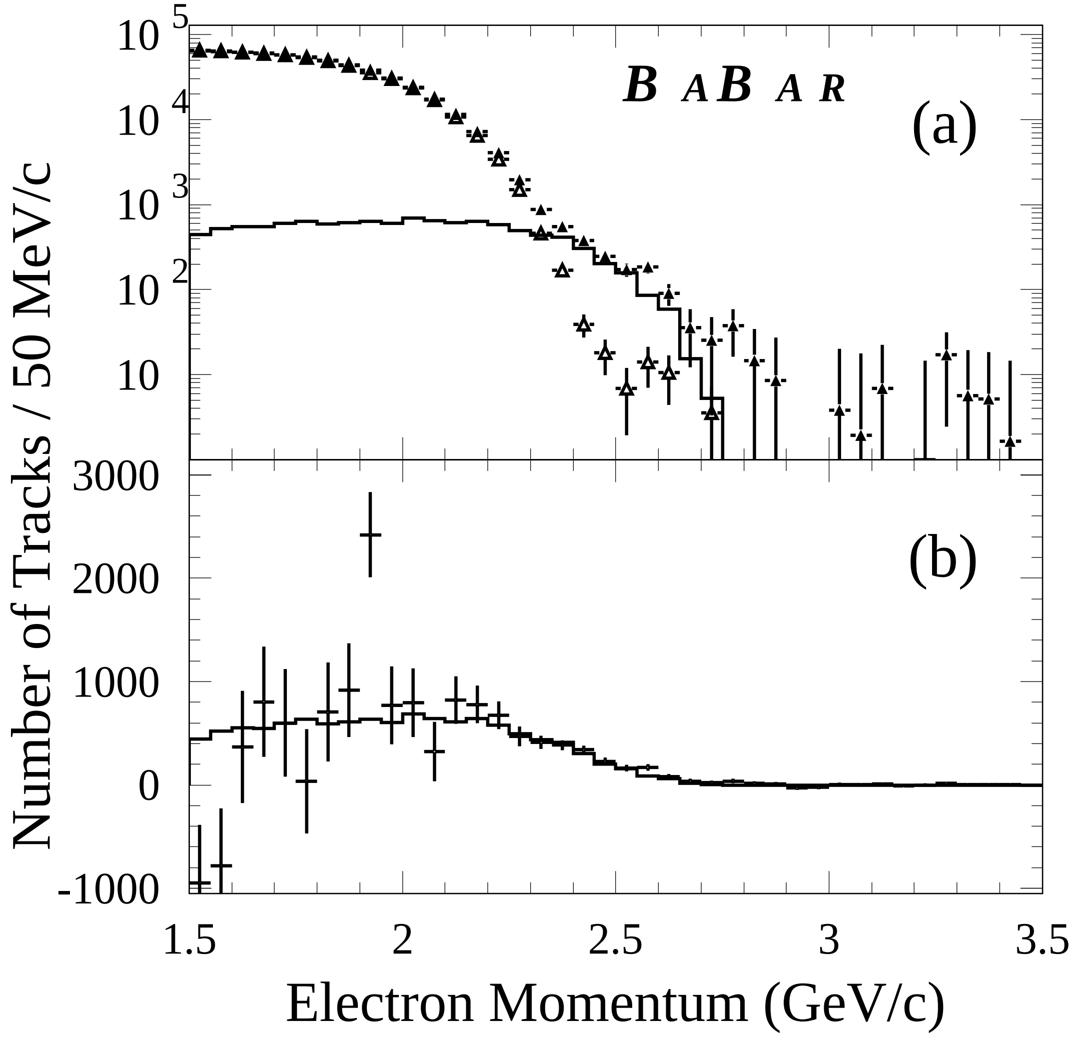

Figure 2: The electron momentum spectrum in the $\Upsilon(4S)$ rest frame: (a) ON-peak data after continuum subtraction (solid triangles), and MC predicted background from $B\bar{B}$ events ($B \nrightarrow X_u e\nu$) (open triangles). (b) ON peak data after subtraction of continuum and Monte Carlo predicted ($B \nrightarrow X_u e\nu$) backgrounds (data points with statistical errors). For comparison, the histograms show the expected signal spectrum from $B \to X_u e\nu$ decays.

uum background in a specified momentum interval, $N_{B\nrightarrow X_u e\nu}$ is the background from $B\bar{B}$ events derived from Monte Carlo simulation normalized to the total number of electrons in the momentum range $1.5-2.3$ GeV/c, ϵ is the total efficiency for detecting a signal electron from $B \to X_u e\nu$ decays (including bremsstrahlung in detector material), and δ_{rad} accounts for the distortion of the electron spectrum due to final-state radiation. This last is a momentum dependent correction, derived from the Monte Carlo simulation, amounting to $\sim 11\%$ in the range $2.3-2.6$ GeV/c. As the overall normalization the total number of produced $B\bar{B}$ events is used, $N_{B\bar{B}} = (22,630 \pm 19 \pm 362) \cdot 10^3$.

The differential branching ratio as a function of the electron momentum in the $\Upsilon(4S)$ rest frame is shown in Figure 3. Integrated over the interval from 2.3 to 2.6 GeV/c, the partial branching ratio is (statistical error only):

$$\Delta\mathcal{B}(B \to X_u e\nu) = (0.152 \pm 0.014) \cdot 10^{-3}. \quad (2)$$

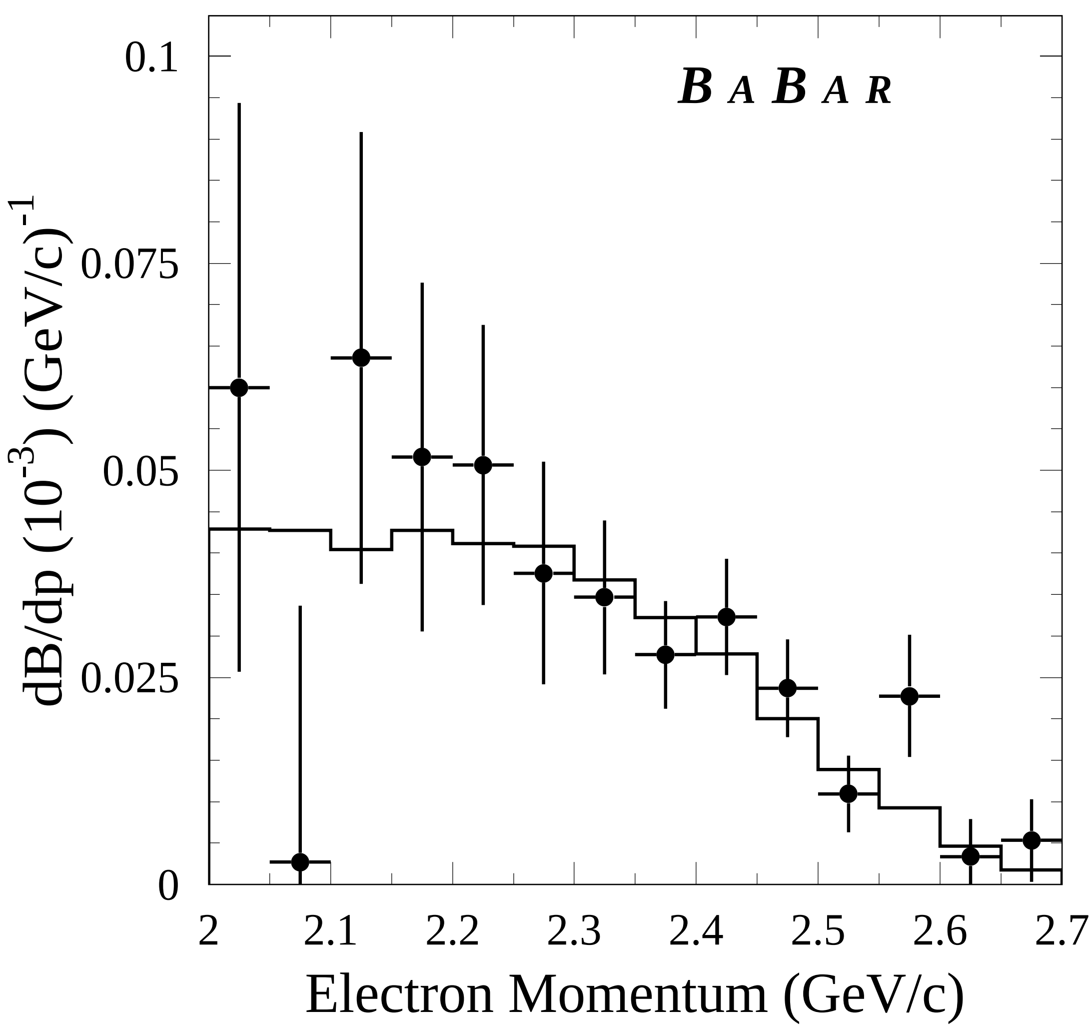

Figure 3: The branching ratio $\mathcal{B}(B \to X_u e\nu)$ as a function of the electron momentum in the $\Upsilon(4S)$ rest frame. The data (statistical errors only) are compared to a prediction (solid line) based on the ISGW2 model assuming a total inclusive branching ratio of $1 \cdot 10^{-3}$ for $B \to X_u e\nu$ decays with X_u masses up to 1.5 GeV/c^2. The spectrum is corrected for final-state radiation and bremsstrahlung.

3.4 Systematic Errors

The following sources of systematic errors have been considered:

- the Monte Carlo simulation of the signal events and the impact on the detection efficiency,
- continuum background subtraction,
- the subtraction of all other backgrounds based on Monte Carlo simulation of the production process and the detector simulation,
- the uncertainty of the B meson momentum spectrum in the $\Upsilon(4S)$ rest frame.

The systematic error introduced by the efficiency estimation for the signal events is caused by uncertainties in simulation of event selection (4%), the track reconstruction (1%), and the electron identification efficiencies (2%). The error on the selection efficiency depends not only on the accuracy of the detector model, but also on the adequacy of the ISGW2 model on which the event generation is based. The latter error has been estimated from the impact of the variation (within their current uncertainties) of individual branching ratios for B meson decays and variation of the event selection cuts. The total systematic error on the efficiency amounts to 5%.

An error in the continuum background subtraction can be introduced by the choice of the fitting function and the fitting procedure. The impact of the choice of the function has been estimated by trying different functional forms, such as an exponential function and Chebyshev polynomials. Possible differences in continuum spectra in ON-peak and OFF-peak data have been assessed by including or excluding ON-peak data above $B \to X_u e\nu$ kinematic limit in the fit. The observed variations in the number of continuum events leads us to attribute a 2% systematic uncertainty on the number of continuum events. This is equivalent to 5% systematic error in the number of signal events.

The $b \to c$ background consists of electrons and misidentified hadrons (see Table 1). The dominant contribution are electrons from semileptonic $B \to X_c e\nu$ decays. There is also a much smaller contribution of secondary electrons from $B \to X_c \to X_s e\nu$ and $B \to \psi(2S) \to ee$ decays, but very few with momenta above 2.3 GeV/c. The error in the estimate of prompt lepton background arises primarily from the uncertainty in the decay dynamics and the branching fractions of the individual decay modes. The impact of these uncertainties (4%) is estimated by variation of these branching ratios within their current uncertainties. In addition, the uncertainty in the electron identification (2%) has been included. The systematic error (28%) on the background from misidentified hadrons arises from both the uncertainty in the spectrum of charged hadrons above 2.3 GeV/c and the overall uncertainty on the mis-identification probabilities for pions and kaons. In addition, there is a small correction for electrons from J/ψ decays that are not vetoed by the mass requirement; the uncertainty in this correction is 20%. Background from photon conversions and Dalitz decays have been analyzed and found to be negligible above 1.5 GeV/c. The total systematic error on the Monte Carlo based $b \to c$ background subtraction is estimated to be 6%, translating to a relative error of 3% on the number of signal events.

Since the $\Upsilon(4S)$ mass is so close to the threshold for $B\bar{B}$ production, the B meson momentum and thereby the endpoint of the electron spectrum from $B \to X_c e\nu$ decays is highly sensitive to the total energy of the colliding beams. Thus variations of the colliding beam energy introduces a systematic error in the $B \to X_c e\nu$ background subtraction. These variations are included in the Monte Carlo simulations, and the impact of the difference between data and Monte Carlo is studied using a sample of fully reconstructed B mesons. The comparison of the measured and simulated momentum distributions, currently limited by statistics, shows that the systematic error from this effect does not exceed 5%.

In summary, Table 2 contains list of systematic errors for the momentum range from 2.3 to 2.6 GeV/c; the total systematic error on the partial branching ratio measurement for this momentum range is $\sim 9\%$.

Table 2: Systematic error on the $\Delta\mathcal{B}$ for the momentum range from 2.3 to 2.6 GeV/c. All numbers are given in percent.

contribution	$\delta x/x$	$\delta(\Delta\mathcal{B})/\Delta\mathcal{B}$
efficiency $\epsilon(B \to X_u e\nu)$	5	5
continuum subtraction	2	5
background $B \to X_c e\nu$	4	1
background $B \to J/\psi \to e^+e^-$	20	2
background $B \to X_c$ - mis-ID	28	2
B movement	5	5
$N_{B\bar{B}}$	1.6	1.6
radiative corrections	10	1
total	–	9

4 Conclusion

The result of this analysis, the fully corrected differential branching ratio as a function of the electron momentum in the $\Upsilon(4S)$ rest frame, is presented in Figure 3. Integrating over the interval from 2.3 to 2.6 GeV/c results in the partial branching ratio

$$\Delta\mathcal{B}(B \to X_u e\nu) = (0.152 \pm 0.014 \pm 0.014) \cdot 10^{-3}. \quad (3)$$

This result agrees very well with the measurement by the CLEO collaboration [5]. The measured electron spectrum in the endpoint region is well reproduced by the ISGW2 model.

5 Extraction of $|V_{ub}|$ based on CLEO Measurements

To determine the charmless semileptonic branching fraction $\mathcal{B}(B \to X_u e\nu)$ from the partial branching fraction $\Delta\mathcal{B}(\Delta p)$, one needs to know the fraction $f_u(\Delta p)$ of the spectrum that falls into the momentum interval Δp. Heavy Quark theory describes the Fermi-motion of the quarks inside the meson in terms of a shape function that depends on non-perturbative QCD. To leading order, the same shape function describes all $b \to q\ell\nu$ transitions (here q represents any light quark).

The CLEO collaboration [11] has recently used the measurement of the inclusive photon spectrum from $b \to s\gamma$ transitions to derive the parameters describing the shape function and to calculate the lepton momentum spectrum for $B \to X_u e\nu$ transition. They quote a value of $f_u(\Delta p) = 0.074 \pm 0.014 \pm 0.009$ for the interval Δp from 2.3 to 2.6 GeV/c.

Relying on the CLEO measurement, the result presented here translates into a total branching ratio of

$$\mathcal{B}(B \to X_u e\nu) = (2.05 \pm 0.27_{exp} \pm 0.46_{f_u}) \cdot 10^{-3}. \quad (4)$$

Based on studies developed independently by two groups [12]-[17], we adopt the following relationship for the extraction of $|V_{ub}|$ from the total branching fraction [18] (revised most recently at the 2002 CKM workshop)

$$|V_{ub}| = 0.00445 \left(\frac{\mathcal{B}(B \to X_u l \nu)}{0.002} \frac{1.55\text{ps}}{\tau_b} \right)^{1/2} (1.0 \pm 0.020 \pm 0.052), \quad (5)$$

where the first error arises from the uncertainty in the OPE expansion, and the second from the uncertainty in the b quark mass, assuming $m_b(1\,\text{GeV}) = 4.58 \pm 0.09\,\text{GeV}$. Based on this expression and our measurement of the branching fraction, we find

$$|V_{ub}| = (4.43 \pm 0.29_{exp} \pm 0.25_{OPE} \pm 0.50_{f_u} \pm 0.35_{s\gamma}) \cdot 10^{-3}. \quad (6)$$

Here the first error is the measurement uncertainty from the combined statistical and systematic error, and the second refers to the uncertainty on the extraction of $|V_{ub}|$ from the branching ratio as stated above. The remaining errors are taken from the CLEO analysis: the third refers to the determination of f_u and the fourth represents an estimate of the validity of the assumption that the shape function can be extracted from the $b \to s\gamma$ spectrum. The uncertainty due to the theoretical assumption of quark-hadron duality remains unquantifiable.

The *BABAR* collaboration is planning to develop this and other methods for extracting the total branching ratio and $|V_{ub}|$ in the near future.

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