Spectra of prompt electrons from decays of $B^+$ and $B^0$ mesons and ratio of inclusive semielectronic branching fractions

Belle Collaboration

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Abstract

We present spectra of prompt electrons from decays of neutral and charged $B$
mesons. The results are based on 140 fb$^{-1}$ of data collected by the Belle detector on the $\Upsilon(4S)$ resonance at the KEKB $e^+e^-$ asymmetric collider. We tag $\Upsilon(4S) \to B\bar{B}$ events by reconstructing a $B$ meson in one of several hadronic decay modes; the semileptonic decay of the other $B$ meson is inferred from the presence of an identified electron. We obtain for charged and neutral $B$ mesons the partial rates of semileptonic decay, to electrons with momentum greater than 0.6 GeV/c in the $B$ rest frame, and their ratio $b_+/b_0 = 1.08 \pm 0.05 \pm 0.02$, where the first and second errors are statistical and systematic, respectively.

Key words: Semileptonic, B decay, inclusive
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1 Introduction

The inclusive semileptonic $B$ meson decay branching fraction $\mathcal{B}(B \to X\ell\nu)$ is a fundamental quantity that is required to fully understand $B$ meson decays. The decay is believed to be dominated by a spectator process, where the $b$ quark is coupled to a $c$ or $u$ quark and a virtual $W$ boson, while the accompanying quark in the meson, the so-called spectator, plays no direct role. Therefore, the theoretical treatment is relatively simple, and the semileptonic width $\Gamma_{\text{SL}}$ can be readily predicted. However, it has long been a puzzle that while theoretical calculations predict values of $\mathcal{B}(B \to X\ell\nu)$ higher than 12% [1], most measurements have been consistently lower, at 10–11% [2]. The discrepancy may be attributed to the uncertainty in predicting the hadronic decay width $\Gamma_{\text{had}}$, where contributions from non-spectator processes are significant. The non-spectator contribution depends on the flavor of the accompanying quark, while this is not the case for $\Gamma_{\text{SL}}$. Therefore, it may result in unequal $\mathcal{B}(B \to X\ell\nu)$ values for neutral and charged $B$ mesons, hereafter referred to as $b_0$ and $b_+$ respectively. The ratio $b_+/b_0$ is equal to the $B$ lifetime ratio $\tau_+ / \tau_0$ assuming equality in $\Gamma_{\text{SL}}$. The $B$ lifetime ratio is measured well [2]. However, only a few measurements have addressed $b_+$ and $b_0$ separately, and the uncertainties have been large due to low efficiencies for tagging neutral and charged events [3]. The deviations from unity for both the lifetime ratio and the $b_+/b_0$ ratio are predicted to be of order 10% [4].

Furthermore, measurement of $\mathcal{B}(B \to X\ell\nu)$ combined with the lifetime is one of the favored methods to determine the Cabibbo-Kobayashi-Maskawa matrix element $|V_{cb}|$ [5]. Heavy-Quark-Expansions (HQEs) [6] have become a useful tool to calculate the correction due to strong interaction effects. There have been some attempts to improve the determination of $|V_{cb}|$, by fitting the

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perturbative and non-perturbative parameters in HQEs to the data of the hadronic invariant mass ($M_X$) and the lepton energy ($E_\ell$) moments in the $B$ semileptonic decay [7]. Recently, the BaBar collaboration performed a fit to the partial $B \rightarrow X_c e\nu$ branching fraction and the $M_X$ and $E_\ell$ moments, with varied cutoffs on the lepton energy, to extract $|V_{cb}|$ and the total $B \rightarrow X_c e\nu$ branching fraction as well as the HQE parameters [8] on a consistent basis.

In this paper we report measurements of $b_0$ and $b_+$ in the electronic channel with an electron momentum requirement $p^* \geq 0.6$ GeV/c, as measured in the rest frame of the $B$ meson. These measurements are based on data collected by the Belle detector [9] at the KEKB asymmetric $e^+e^-$ collider [10], which provides copious production of $B\overline{B}$ meson pairs on the $\Upsilon(4S)$ resonance. In this analysis, one $B$ meson is fully reconstructed in one of several hadronic decay modes to determine its charge, flavor, and momentum, and is referred to as the tag side $B$ ($B_{\text{tag}}$) in the event. The semileptonic decay of the other $B$ meson, referred to as the spectrum side $B$ ($B_{\text{spec}}$), is then measured in its rest frame, determined from $B_{\text{tag}}$, without smearing due to the $B$ motion. Prompt semileptonic decays ($b \rightarrow x e\nu$) can be separated from secondary decays ($b \rightarrow c \rightarrow y e\nu$), based on the correlation between the $B_{\text{tag}}$ flavor and the electron charge. To exploit the advantages of this method requires a large sample of $B\overline{B}$ events because the full reconstruction efficiency is rather low, typically of the order of 0.1%. Our high integrated luminosity enables us to perform this measurement with higher accuracy than previously achieved.

2 Data Set and Belle Detector

The results presented in this paper are based on a 140 fb$^{-1}$ data sample accumulated on the $\Upsilon(4S)$ resonance, which contains $152.0 \times 10^6 B\overline{B}$ pairs. The center-of-mass energy is $\sqrt{s} \simeq 10.58$ GeV. An additional 15 fb$^{-1}$ data sample taken at a center-of-mass energy 60 MeV below the $\Upsilon(4S)$ resonance is used to evaluate background from the $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) process. A detailed Monte Carlo (MC) simulation, which fully describes the detector geometry and response and is based on GEANT [11], is applied to study backgrounds in the $B_{\text{tag}}$ reconstruction, backgrounds in the signal electron detection, and corrections to the signal selection efficiency due to the tagging. In the MC simulation, generic $B\overline{B}$ decays are simulated using the QQ98 generator [12].

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a three-layer silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron
flux-return located outside of the coil is instrumented to detect $K^0_L$ mesons and to identify muons (KLM). The detector is described in detail elsewhere [9].

3 Fully Reconstructed Tagging

Neutral $B_{\text{tag}}$ candidates are reconstructed in the decay modes $B^0 \rightarrow D^{*-}\pi^+$, $D^*\rho^+$, $D^*-a_1^+$ and $B^0 \rightarrow D^-\pi^+$, $D^-\rho^+$, $D^-a_1^+$. Charged $B_{\text{tag}}$ candidates are reconstructed in the decay modes $B^+ \rightarrow \overline{D}^{*0}\pi^+$, $\overline{D}^{*0}\rho^+$, $\overline{D}^{*0}a_1^+$ and $B^+ \rightarrow \overline{D}^{0}\pi^+$. The decay modes $B^+ \rightarrow \overline{D}\rho^+$ and $\overline{D}a_1^+$ are not used here because of poor purity due to large combinatorial background. Inclusion of the charge conjugate decays is implied throughout this paper.

To suppress the non-$b\bar{b}$ background processes from QED, $e^+e^- \rightarrow \tau^+\tau^-$, and beam-gas events, we select hadronic events based on the charged track multiplicity and total visible energy. The selection procedure is described in detail elsewhere [13].

Charged particle tracks are reconstructed from hits in the SVD and CDC. They are required to satisfy track quality based on their impact parameters relative to the measured profile of the interaction point (IP profile) of the two beams, and good measurements in the SVD in the direction of the beam ($z$). Charged kaons are identified by combining information on energy deposit ($dE/dx$) in the CDC, Čerenkov light yields in the ACC and time-of-flight measured by the TOF system. For the nominal requirement, the kaon identification efficiency is approximately 88% and the rate for misidentification of pions as kaons is about 8%. Hadron tracks that are not identified as kaons are treated as pions. Tracks satisfying the lepton identification criteria are removed from consideration.

Candidate $\pi^0$ mesons are reconstructed using $\gamma$ pairs with an invariant mass within $\pm 30 \text{ MeV}/c^2$ of the nominal $\pi^0$ mass. Each $\gamma$ is required to have a minimum energy deposit of: $E_\gamma \geq 50 \text{ MeV}$ in the barrel region of the ECL, defined as $32^\circ < \theta_\gamma < 129^\circ$; $E_\gamma \geq 100 \text{ MeV}$ in the forward endcap region, defined as $12^\circ < \theta_\gamma < 31^\circ$; $E_\gamma \geq 150 \text{ MeV}$ in the backward endcap region, defined as $131^\circ < \theta_\gamma < 155^\circ$, where $\theta_\gamma$ denotes the polar angle of the $\gamma$ with respect to the direction opposite to the positron beam. $K^0_S$ mesons are reconstructed using pairs of charged tracks that have a well reconstructed vertex that is displaced from the IP and an invariant mass within $\pm 7.6 \text{ MeV}/c^2$ of the known $K^0_S$ mass. $\rho^+$ and $\rho^0$ candidates are reconstructed in the $\pi^+\pi^0$ and $\pi^+\pi^-\pi^0$ decay modes by requiring their invariant masses to be within $\pm 150 \text{ MeV}/c^2$ of the nominal $\rho$ mass. The $\rho^+$ candidates are required to satisfy $\cos \theta_\rho \geq -0.9$, where $\theta_\rho$ is the helicity angle, defined as the angle between an axis anti-parallel to the $B$ flight direction and the $\pi^+$ flight direction in the $\rho$ rest frame. $a_1^+$ candidates are
formed from combinations of $\rho^0$ and $\pi^+$ candidates by requiring that the three tracks form a good vertex and have an invariant mass between 0.73 GeV/$c^2$ and 1.73 GeV/$c^2$.

$\bar{D}^0$ candidates are reconstructed in the four decay modes $\bar{D}^0 \rightarrow K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^-$ and $K_0^0\pi^+\pi^-$. $D^-$ candidates are reconstructed in the decay mode $D^- \rightarrow K^+\pi^-\pi^-$. The $D^0(D^-)$ candidates are required to have an invariant mass within $\pm 30 (12)$ MeV/$c^2$ of the nominal $D^0(D^-)$ mass. $\bar{D}^*$ mesons are reconstructed by pairing $\bar{D}^0$ candidates with pions, $D^{*-} \rightarrow \bar{D}^0\pi^-$ and $\bar{D}^{*0} \rightarrow \bar{D}^0\pi^0$. The $\bar{D}\pi$ pairs are required to have a mass difference $\Delta m = m_{\bar{D}\pi} - m_{\bar{D}}$ within 0.142 GeV/$c^2 < \Delta m < 0.149$ GeV/$c^2$ for $D^{+}$, and $0.140$ GeV/$c^2 < \Delta m < 0.145$ GeV/$c^2$ for $D^{*0}$. All $D^0$ candidates are used for $B$ reconstruction, regardless of whether or not the $D^0$ candidate is used to reconstruct a $D^*$ meson.

The selection of $B$ candidates is based on the beam-constrained mass, $M_{bc} = \sqrt{E_{beam}^2 - p_B^2}$, and the energy difference, $\Delta E = E_B - E_{beam}$, where $E_{beam} \equiv \sqrt{s}/2 \approx 5.290$ GeV, and $p_B$ and $E_B$ are the momentum and energy of the reconstructed $B$ in the $\Upsilon(4S)$ rest frame, respectively. The background from jet-like $e^+e^- \rightarrow q\bar{q}$ processes is suppressed by event topology based on the normalized second Fox-Wolfram moment ($R_2$) [14] and the angle between the thrust axis of the $B$ candidate and that of the remaining tracks in an event ($\cos \theta_{th}$). Requirements on $R_2$ and $\cos \theta_{th}$, as well as the $K/\pi$ selection, are tuned to suppress the background and depend on the $B_{tag}$ decay mode. We select $B_{tag}$ candidates in a signal region defined as $5.27 \text{ GeV}/c^2 \leq M_{bc} \leq 5.29 \text{ GeV}/c^2$ and $|\Delta E| \leq 0.05$ GeV.

Figure 1 shows the distribution in $M_{bc}$ for the neutral and charged $B$ candidates in the $\Delta E$ signal region. The $M_{bc}$ signal regions, indicated by arrows in Fig. 1, contain 36974 and 36418 $B^0$ and $B^+$ candidates, respectively. The contribution from the $q\bar{q}$ process is estimated by scaling the off-resonance data by the luminosity ratio with a small correction due to the energy dependence of the cross section and found to be $2584 \pm 154$ ($2630 \pm 156$) for $B^0$ ($B^+$) candidates. The $B$ candidates remaining after the $q\bar{q}$ background subtraction contain combinatorial background from $B$ decays, where some particles are exchanged between the tag and the spectrum sides (cross-talk). We estimate the contribution from such combinatorial background to be $3221 \pm 372$ ($667 \pm 162$) for $B^0$ ($B^+$) candidates, by scaling the $M_{bc}$ distribution in the high $\Delta E$ sideband ($0.07 \text{ GeV} \leq \Delta E \leq 0.30$ GeV) with normalization to the yields in the $M_{bc}$ sideband ($M_{bc} \leq 5.26 \text{ GeV}/c^2$) after the $q\bar{q}$ background subtraction. Note that we do not apply best $B_{tag}$ candidate selection for events having multiple candidates, in order to avoid distorting the $\Delta E$ distribution. The remaining $31169 \pm 446$ ($33121 \pm 295$) $B^0$ ($B^+$) candidates, denoted as $N_{tag}(B^0)$ ($N_{tag}(B^+)$), are from $B\bar{B}$ events, and are used to normalize the lepton yield to obtain the semileptonic branching fraction. These $B_{tag}$ candidates
Fig. 1. Beam-constrained mass ($M_{bc}$) distributions for $B^0$ and $B^+$ candidates with a $|\Delta E| \leq 0.05$ GeV requirement. The solid histogram corresponds to the on-resonance data. The hatched histogram is for the off-resonance data scaled by luminosity. The dashed histogram indicates the contribution from the combinatorial background estimated by scaling the $\Delta E$ sideband (0.07 GeV $\leq \Delta E \leq 0.30$ GeV). The arrows indicate the $M_{bc}$ signal region.

may include a small fraction with incorrectly assigned $B$ charge and/or flavor due to particles that are not detected. The rate of such misassignment is found to be 0.6%(1.9%) for events with (without) electrons on the spectrum side, according to the MC simulation, and its effect on the determination of $b^+$ and $b_0$ is found to be less than 0.1%. In order to obtain the electron spectra, presented later, we apply the same background subtraction to determine the electron yield for tagged events in each electron momentum bin.

4 Electron Selection and Background Subtraction

For events passing our $B_{tag}$ selection, we search for electrons from semileptonic decays of $B_{spec}$. The electron momentum ($p^*$) is measured in the $B$ rest frame, which is found using the $B_{tag}$ momentum. Electrons are divided into two categories, based on the correlation between the electron charge ($q_e$) and $B_{tag}$ flavor ($Q_{tag}$). With the assignment $Q_{tag} = +1(-1)$ for $\overline{B}^0$ and $B^-$ ($B^0$ and $B^+$), electrons having $q_e \times Q_{tag} = +1(-1)$ are referred to as “right (wrong) sign” electrons.

Electron identification is based on a combination of $dE/dx$ in the CDC, the response of the ACC, shower shape in the ECL and the ratio of energy deposit in the ECL to the momentum measured by the tracking system [15]. The electron identification efficiency depends on the track momentum. Based on the MC simulation, the efficiencies are estimated to be about 90% in the momentum
region above 1.2 GeV/c in the $B$ rest frame, where electrons from the prompt $B$ decays dominate. The rate of pions (kaons) to be mis-identified as electrons is measured using reconstructed $K^0_S \rightarrow \pi^+\pi^-(D^{*+} \rightarrow D^0\pi^+(D^0 \rightarrow K^-\pi^+))$ and found to be less than 0.2% for electrons in the same momentum region.

For the determination of semileptonic branching fractions we use electron candidates with $p^* \geq 0.6$ GeV/c. We demand that electrons be detected in the barrel region of the associated detector system and with sufficient transverse energy for a good measurement; we make requirements on the laboratory transverse momenta with respect to the direction opposite to the positron beam, $p_t \geq 0.6$ GeV/c, and on the laboratory polar angle, $35^\circ \leq \theta \leq 125^\circ$. Radiative energy loss by electrons is corrected for by adding back energy found in ECL clusters within 3 degrees of the reconstructed momentum direction. Backgrounds from $J/\psi$ decays, photon conversions in the detector and $\pi^0$ Dalitz decays are suppressed by imposing veto conditions; we calculate invariant masses for each electron candidate when combined with opposite charge electrons ($m_{ee}$) and with additional photons ($m_{ee\gamma}$), and reject the electron if $m_{ee}$ lies within $\pm 49$ MeV/$c^2$ of the nominal $J/\psi$ mass, $m_{ee}$ is less than $100$ MeV/$c^2$ or $m_{ee\gamma}$ is within $\pm 32$ MeV/$c^2$ of the nominal $\pi^0$ mass.

The obtained electron spectra include events from several background processes. Table 1 summarizes the number of detected electrons and the contributions from each background source.

Backgrounds from $J/\psi$ decays, photon conversion and $\pi^0$ Dalitz decays are small after the veto. The remaining backgrounds, where one of the pair has escaped detection, are estimated by the MC simulation. The background from these processes amounts to 2.0% of the yield in the signal region. The uncertainties are evaluated from the error on each rate.

Contributions from secondary electrons from $B$ decays are modeled by the MC simulation based on Ref. [12] and branching fractions quoted in Ref. [2]. These include leptons from $\tau$ decays in processes such as $B \rightarrow X\tau^+\nu$ and $B \rightarrow D_sX$ followed by $D_s \rightarrow \tau^+\nu$. The uncertainty of their contribution is estimated based on $\mathcal{B}(b \rightarrow \tau\nu + anything) = (2.48 \pm 0.26)%$ in Ref. [2]. Another major source of secondary electrons is the $W^+ \rightarrow c\bar{s}(c\bar{d})$ processes (“upper vertex” charm) such as $B \rightarrow D_sX$, $D_s \rightarrow Y\ell^+\nu$ and $B \rightarrow D^{(*)}D^{(*)}K^{(*)}$, $D \rightarrow Y\ell^+\nu$ via $b \rightarrow \bar{c}c\bar{s}$ and a small contribution from $B \rightarrow D^{(*)}D^{(*)}$. The uncertainty of their contribution is estimated based on $\mathcal{B}(b \rightarrow \bar{c}c\bar{s}) = (22 \pm 4)%$ in Ref. [2]. The backgrounds from these processes account for 4.3% of the yield in the signal region. The uncertainties are evaluated from the errors on the associated branching fractions.

Contributions from misidentified hadrons are estimated by multiplying the measured fake rates by the number of additional hadron tracks in events con-
Table 1  
Summary of electron yields and estimated backgrounds.

|                      | $B^0$ candidate | $B^+$ candidate |
|----------------------|-----------------|-----------------|
|                      | e : right-sign  | e : wrong-sign  |
| on-resonance data    | 2007.0 ± 44.8   | 967.0 ± 31.1    |
|                      | 2520.0 ± 50.2   | 450.0 ± 21.2    |
| scaled off resonance | 9.2 ± 9.2       | 0.0 ± 9.2       |
|                      | 9.2 ± 9.2       | 0.0 ± 9.2       |
| estimated combinatorial | 78.6 ± 10.5   | 33.9 ± 5.5      |
|                      | 31.9 ± 6.9      | 12.7 ± 3.3      |
| estimated background | 130.7 ± 1.3     | 73.9 ± 1.1      |
| from $J/\psi$        | 2.8 ± 0.1       | 2.9 ± 0.1       |
|                      | 3.0 ± 0.1       | 3.0 ± 0.1       |
| from Dalitz or conv. | 25.7 ± 0.4      | 25.9 ± 0.4      |
|                      | 27.7 ± 0.4      | 27.5 ± 0.4      |
| from $\tau$          | 42.7 ± 0.5      | 10.1 ± 0.2      |
|                      | 52.6 ± 0.6      | 0.8 ± 0.1       |
| from upper vertex     | 50.9 ± 0.5      | 27.3 ± 0.4      |
|                      | 60.5 ± 0.6      | 9.5 ± 0.2       |
| hadron fakes         | 8.6 ± 1.0       | 7.7 ± 0.9       |
|                      | 10.5 ± 0.3      | 5.8 ± 0.2       |
| bkg. subtracted      | 1788.5 ± 47.4   | 859.2 ± 34.0    |
|                      | 2324.4 ± 51.4   | 390.7 ± 23.3    |
| after mixing corr.   | 2063.7 ± 62.3   | 584.0 ± 46.3    |
| after eff. corr.     | 3298.6 ± 104.2  | 1067.3 ± 80.8   |
|                      | 3736.7 ± 84.0   | 713.5 ± 42.6    |

Taining selected $B_{\text{tag}}$. Here, the hadrons are obtained by imposing a lepton identification veto on charged tracks. Misidentified hadrons are distributed mainly in the momentum region below 1.5GeV/c, and amount to 0.4%(1.0%) over the whole momentum range of the right(wrong) sign spectra.

5 Semileptonic Decay Spectra

The spectra after the above background subtraction contain electrons from prompt semileptonic $B$ decays and from secondary semileptonic charm decays (“lower vertex” charm). After background subtraction, the number of right(wrong) sign electrons is $1789 \pm 47$ ($859 \pm 34$) for events tagged with $B^0$, and $2324 \pm 51$ ($391 \pm 23$) for those tagged with $B^+$. For events tagged with a $B^+$, electrons with the right and wrong signs correspond to those from prompt $B$ and secondary charm decays, respectively. For events tagged with a $B^0$, the effect of $B^0$-$\overline{B}^0$ mixing is taken into account, by solving the following equations for $N_p$ and $N_s$, the number of electrons from prompt and secondary semileptonic decays, respectively:

$$N_{\text{right}} = N_p(1 - \chi_d) + N_s\chi_d$$
\[ N_{\text{wrong}} = N_p \chi_d + N_s (1 - \chi_d), \]

where \( N_{\text{right}} \) and \( N_{\text{wrong}} \) are the numbers of right- and wrong-sign electrons and \( \chi_d = 0.186 \pm 0.004 \) [2] is the \( B^0-B^0 \) mixing probability.

The electron detection efficiency is corrected for detector acceptance, tracking and electron selection efficiencies, where the correction is evaluated with the MC simulation. We also take into account a correlation due to the difference in the event tagging efficiency between events where the \( B_{\text{spec}} \) decays semileptonically and those where it decays hadronically. This effect is referred to hereafter as “tag bias”. In the MC simulation, it is found that the difference depends on track multiplicity in the event, which alters the detection efficiency of charged, \( \pi^0 \) and \( K^0_S \) particles used for the \( B_{\text{tag}} \) reconstruction. The tag bias effect is estimated from the change of semileptonic decay fraction in the tagged sample using the generator information in the MC simulation, which is 8%(6%) for \( B^0(B^+) \). Figure 2 shows the \( p^* \) spectra from the prompt \( B \) and the secondary semileptonic decays obtained separately for \( B^0 \) and \( B^+ \).

The differential branching fractions \( d\mathcal{B}/dp \) are obtained from the number of electrons, normalized by \( N_{\text{tag}}(B^0) \) or \( N_{\text{tag}}(B^+) \). Table 2 shows obtained differential branching fraction for each bin. Both in Figure 2 and Table 2, the errors are statistical only. The analysis of systematic uncertainties presented in detail in Section 6 shows that they are momentum independent and the common systematic error of 3.4% and 3.6% can be ascribed to all the bins for \( B^0 \) and \( B^+ \), respectively.

The partial branching fractions for the electron channel, integrated over the momentum region above 0.6 GeV/c, are \( b_0(p^* \geq 0.6 \text{ GeV}/c) = (9.83 \pm 0.34)\% \) and \( b_+(p^* \geq 0.6 \text{ GeV}/c) = (10.62 \pm 0.25)\% \) for \( B^0 \) and \( B^+ \), respectively. Their average and ratio are found to be \( b(p^* \geq 0.6 \text{ GeV}/c) = (10.34 \pm 0.20)\% \), and \( b_+/b_0(p^* \geq 0.6 \text{ GeV}/c) = 1.08 \pm 0.05 \).

### 6 Systematic Error

The systematic uncertainties on the partial semileptonic branching fractions are evaluated separately for \( b_0 \) and \( b_+ \), and are summarized in Table 3.

The uncertainty in \( N_{\text{tag}} \) is associated mainly with the procedure for the combinatorial background subtraction described earlier. After applying the same procedure on the simulated data and comparing the number of obtained tagged candidates with the true number, the systematic uncertainty due to \( N_{\text{tag}} \) determination is estimated to be 1.0–1.9%.

The uncertainty due to the tag bias correction is estimated to be 1.3% from the
Fig. 2. Momentum spectra in the $B$ meson rest frame of electrons from prompt semileptonic $B$ decay (open squares) and secondary semileptonic charm decay (closed circles) for $B^0$ and $B^+$ tagged events. The vertical scale shows the differential branching fraction ($dB/dp$).

Table 2
Differential branching fractions of $B^0$ and $B^+$ for each bin. The last column shows their ratio. The errors are statistical only. The common systematic error of 3.4%, 3.6% and 1.9% can be ascribed to all the bins for $B^0$, $B^+$ and $B^+/B^0$, respectively.

| $p$ (GeV/c) | $B^0$       | $B^+$       | $B^+/B^0$   |
|------------|-------------|-------------|-------------|
| 0.6–0.8    | 0.0234 ± 0.0071 | 0.0362 ± 0.0040 | 1.547 ± 0.502 |
| 0.8–1.0    | 0.0401 ± 0.0053 | 0.0503 ± 0.0047 | 1.253 ± 0.203 |
| 1.0–1.2    | 0.0656 ± 0.0056 | 0.0648 ± 0.0042 | 0.987 ± 0.106 |
| 1.2–1.4    | 0.0889 ± 0.0061 | 0.0831 ± 0.0045 | 0.934 ± 0.082 |
| 1.4–1.6    | 0.0925 ± 0.0058 | 0.0985 ± 0.0048 | 1.065 ± 0.085 |
| 1.6–1.8    | 0.0829 ± 0.0055 | 0.0913 ± 0.0046 | 1.101 ± 0.091 |
| 1.8–2.0    | 0.0700 ± 0.0050 | 0.0742 ± 0.0041 | 1.060 ± 0.096 |
| 2.0–2.2    | 0.0271 ± 0.0031 | 0.0304 ± 0.0026 | 1.121 ± 0.160 |
| 2.2–2.4    | 0.0010 ± 0.0007 | 0.0019 ± 0.0007 | 1.892 ± 1.408 |
| 2.4–2.6    | 0.0001 ± 0.0002 | 0.0005 ± 0.0003 | 3.912 ± 5.849 |

uncertainties of the charged particle and photon multiplicity dependence in the $B_{tag}$ reconstruction. We find multiplicity difference between data and the simulation to be about 0.1 for charged particles and 0.2 for photons. These differences propagate to the reconstruction efficiencies of charged particles, $\pi^0$ and $K^0_S$, and hence the $B_{tag}$ which is reconstructed based on 8.1 charged
particles, $2.7\,\pi^0$ and $1.1\,K_S^0$ per event on average. We add another $1.8%(1.6\%)$ uncertainty due to the statistics in the MC simulation to determine the tag bias correction factor for $B^0(B^+)$.

The uncertainty on the tracking efficiency is determined based on a study using $D^{*-} \rightarrow D^0(\rightarrow K_S^0\pi^+\pi^-)\pi^+$ decays. In this study, the yield of fully reconstructed $D^*$ mesons is to be compared to that using partial reconstruction, where one pion from $K_S^0$ is not used. A $\pm1.0\%$ uncertainty is assigned for the tracking efficiency by taking the difference of the yield ratio between the experimental data and the MC simulation.

The uncertainty on the electron identification efficiency is one of the largest sources of systematic error. It is estimated to be $\pm2.1\%$ from the difference between the efficiency determined from the MC simulation and that based on a sample of simulated tracks embedded in beam data. The uncertainty on the fake electron rate is studied by comparing the fake rates measured with $K_S^0 \rightarrow \pi^+\pi^-$ decays in real data and in the MC simulation. The uncertainty on $b_0$ and $b_+$ is estimated to be $\pm0.1\%$.

The uncertainties on the background subtractions from $J/\psi$ decays, converted electrons, $\tau$ decays, and the “upper vertex” processes are evaluated from the error on each rate, as described above. The uncertainty in $b_0$ and $b_+$ for the “upper vertex” processes is $(0.5 - 0.6)\%$.

The uncertainty from the mixing probability $\chi_d$ is determined based on its quoted error in Ref. [2], and contributes $\pm0.4\%$ to the systematic error on $b_0$.

The uncertainty in the continuum subtraction is attributed to the normalization between on- and off-resonance data, and is estimated to be $\pm0.1\%$ based on the error of the relative luminosity measurement.

The overall systematic errors are evaluated by adding these errors in quadrature. The systematic error on the ratio $b_+/b_0$ is small because several sources of systematic error cancel in the ratio. The remaining sources of systematic error are mainly $N(B_{tag})$ estimation $(1.9\%)$ and mixing $(0.4\%)$. The overall systematic errors on the partial branching fractions are $3.6\%$ for $b_+$, $3.4\%$ for $b_0$ and $1.9\%$ for $b_+/b_0$.

7 Results and Summary

Including the above systematic errors, the partial semileptonic branching fractions are
Table 3
Contributions to the systematic error.

| Source                | $\Delta b_0/b_0$ (%) | $\Delta b_+ / b_+$ (%) | $\Delta \frac{b_+}{b_0} / \frac{b_+}{b_0}$ (%) |
|-----------------------|----------------------|------------------------|----------------------------------------|
| $N_{\text{tag}}$     | $\pm 1.0$            | $\pm 1.9$              | $\pm 1.9$                               |
| Tag-bias              | $\pm 2.2$            | $\pm 2.1$              | $-$                                     |
| Tracking              |                      | $\pm 1.0$              | $-$                                     |
| PID efficiency        |                      | $\pm 2.1$              | $< 0.1$                                 |
| Hadron fakes          |                      | $\pm 0.1$              | $< 0.1$                                 |
| $e$ from $J/\psi$     |                      | $< 0.1$                | $< 0.1$                                 |
| $e$ from conversion   |                      | $< 0.1$                | $< 0.1$                                 |
| $e$ from $\tau$       |                      | $\pm 0.3$              | $< 0.1$                                 |
| $e$ from upper vertex | $\pm 0.6$            | $\pm 0.5$              | $< 0.1$                                 |
| Mixing                | $\pm 0.4$            | $-$                    | $\pm 0.4$                               |
| Continuum subtraction |                      | $\pm 0.1$              | $\pm 0.1$                               |
| Total                 | $\pm 3.4$            | $\pm 3.6$              | $\pm 1.9$                               |

$b_0(p^* \geq 0.6 \text{ GeV/c}) = (9.83 \pm 0.34 \pm 0.33)\%$
$b_+(p^* \geq 0.6 \text{ GeV/c}) = (10.62 \pm 0.25 \pm 0.39)\%$

and their average and ratio are found to be

$$b(p^* \geq 0.6 \text{ GeV/c}) = (10.34 \pm 0.20 \pm 0.36)\%$$
$$b_+ / b_0(p^* \geq 0.6 \text{ GeV/c}) = 1.08 \pm 0.05 \pm 0.02.$$  

These average values are calculated with weights determined by the statistical error of each subsample.

The average partial branching fraction $b$ is consistent with our previous measurement [16], with the overall error improved by 15%, and it is also consistent with recent measurements on the $\Upsilon(4S)$ resonance by BaBar and CLEO [17] with the same minimum momentum requirement. Our results are the most precise separate determinations of $b_+, b_0$ and their ratio $b_+/b_0$. The observed $b_+/b_0$ ratio is consistent with the $B^+/B^0$ lifetime ratio $\tau_+/\tau_0 = 1.086 \pm 0.017$ [2]. Furthermore, as shown in Table 2, the ratio of the differential branching fraction for each momentum bin is consistent with $\tau_+/\tau_0$. There is no indication that the naive expectation of equal $\Gamma_{\text{SL}}$ for charged and neutral $B$ mesons break down in the measured range of electron momentum.

The present analysis method using fully reconstructed tags can be extended to a separate determination of the $M_X$ and $E_\ell$ moments in the $B^+$ and $B^0$
semileptonic decays. The partial branching fractions obtained in the present
work can be used as part of a combined fit of HQE parameters to the full set
of the moments to determine the total branching fraction as well as $|V_{cb}|$. In
contrast to measurements based on samples with $B^+/B^0$ admixtures, such an
approach will help to eliminate the uncertainty in $|V_{cb}|$ due to the production
ratio of $B^+$ and $B^0$ on the $\Upsilon(4S)$ resonance $(f_+/f_0)$, and will also provide
a useful cross check of assumptions behind the HQE theory, such as quark-
hadron duality. These extensions to this analysis will be reported in future
articles.

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