INCLUSIVE $B \to X_{CL}\ell\nu$ DECAY SPECTRA AT BELLE AND THE DETERMINATION OF $|V_{CB}|$

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We report measurements of the inclusive electron energy spectrum and hadron invariant mass spectrum for charmed semileptonic decays of $B$ mesons in a 140 fb$^{-1}$ data sample collected with the Belle detector at the KEKB $e^+e^-$ collider. We determine the first four central moments and partial branching fraction of the electron energy spectrum for electron energy thresholds from 0.4 to 2.0 GeV, and the first two central and second non-central moments of the hadron invariant mass spectrum for lepton energy thresholds from 0.7 to 1.9 GeV. Using these measurements and Belle measurements of the photon energy moments in $B \to X_s\gamma$ decays, we determine the CKM matrix element $|V_{cb}|$, the $b$ quark mass and higher order non-perturbative parameters that appear in the Heavy Quark Expansion by performing a global fit analysis in the kinetic mass and 1S schemes.

Keywords: B physics; CKM matrix; Semileptonic decays; Heavy quarks.

1. Introduction

The most precise determinations of the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{cb}|$ are obtained using combined fits to inclusive $B$ decay distributions. These determinations are based on calculations of the semileptonic decay rate in the frameworks of the Operator Product Expansion (OPE) and Heavy Quark Effective Theory (HQET), which predict this quantity in terms of $|V_{cb}|$, the $b$-quark mass $m_b$, and non-perturbative matrix elements that enter at the order $1/m_b^2$. The spectator model decay rate is the leading term in a well-defined expansion controlled by the parameter $\Lambda_{QCD}/m_b$ with non-perturbative corrections arising to order $1/m_b^2$. The key issue in this approach is the ability to separate non-perturbative corrections and perturbative corrections (expressed in powers of $\alpha_s$). High precision comparison of theory and experiment requires a precise determination of the heavy quark masses, as well as the non-perturbative matrix elements that enter the expansion. We make use of the HQEs that express the semileptonic decay width $\Gamma_{S\ell}$, moments of the lepton energy and hadron mass spectra in $B \to X_c\ell\nu$ decays and the photon energy spectrum in $B \to X_s\gamma$ decays in terms of the running kinetic quark masses $m_b^{\text{kin}}$ and $m_c^{\text{kin}}$ as well as the 1S $b$-quark mass $m_b^{1S}$. These schemes should ultimately yield consistent results for $|V_{cb}|$. The precision of the $b$-quark mass is also important for $|V_{ub}|$, a limiting factor in the uncertainty on the unitarity triangle.

The present results are based on a 140 fb$^{-1}$ data sample collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric energy $e^+e^-$ collider, containing $1.52 \times 10^8 B\bar{B}$ pairs. An additional 15 fb$^{-1}$ data sample taken at 60 MeV below the $\Upsilon(4S)$ resonance is used to perform subtraction of background from the continuum $e^+e^- \to q\bar{q}$ process.

2. Inclusive spectral moments

We first identify hadronic events, then fully reconstruct one $B$ meson in one of several hadronic modes to determine its charge, flavour, and momentum ($B_{\text{tag}}$). The num-
ber of $B^+$ and $B^0$ candidates in the signal region, after background subtraction, is $63185 \pm 621$ (stat.) and $39504 \pm 392$ (stat.), respectively. We search for leptons produced by semileptonic $B$ decays on the non-tag side. We partially recover the effect of bremsstrahlung by searching for a photon around the electron direction. The reconstructed lepton momentum spectrum is contaminated by background processes, evaluated and subtracted from the distribution before the extraction of the moments. Backgrounds are predominantly continuum, combinatorial, cascade charm decays $b \rightarrow c \rightarrow q\ell\nu$, $J/\psi, \psi(2S)$, Dalitz decays, photon conversions, fake leptons and $B \rightarrow X_u\ell\nu$ decays. We use the LLSW model \(^{16}\) to predict the relative abundance and form factor shapes of the different components in $B \rightarrow D^{*+}\ell\nu$.

2.1. Electron Energy Spectrum

To measure the moments of the electron energy spectrum, we determine the true electron energy spectrum by unfolding \(^{13}\) the measured spectrum for distortions by various detector effects, in the $B$ meson rest frame, $E_e^B$. The unfolded spectrum is corrected for QED radiative effects using PHOTOS \(^{17}\). Belle measures the the $B^0$ and $B^+$ weighted average partial branching fractions $B(B \rightarrow X_e\ell\nu)_{E_\ell>E_{\text{min}}}$ and the first four moments of the electron energy spectrum in $B \rightarrow X_e\ell\nu$, $(\langle E_\ell \rangle)_{E_\ell>E_{\text{min}}}$, $(\langle E_\ell - \langle E_\ell \rangle \rangle^2)_{E_\ell>E_{\text{min}}}$, $(\langle (E_\ell - \langle E_\ell \rangle) \rangle^3)_{E_\ell>E_{\text{min}}}$, and $(\langle (E_\ell - \langle E_\ell \rangle) \rangle^4)_{E_\ell>E_{\text{min}}}$, for electron energy thresholds, $E_{\text{min}}$, from 0.4 to 2.0 GeV \(^{12}\) (Fig. 1). The principal systematic errors originate from event selection, electron identification, background estimation and signal model dependence. The independent partial branching fractions at $E_{\text{cut}}=0.6$ GeV are $\Delta B(B^+ \rightarrow X_e\ell\nu)=0.10.34 \pm 0.23$(stat.)$\pm 0.25$(sys.)% and $\Delta B(B^0 \rightarrow X_e\ell\nu)=9.80 \pm 0.29$(stat.)$\pm 0.21$(sys.)%; consistent with our previous measurements \(^{19}\). The $\Delta B(B^+ \rightarrow X_e\ell\nu)/\Delta B(B^0 \rightarrow X_e\ell\nu)$ ratio, at $E_{\text{cut}}=0.4$ GeV, is $1.07 \pm 0.04$(stat.)$\pm 0.03$(sys.), consistent with the $B^+/B^0$ lifetime ratio \(^{18}\).

2.2. Hadron Mass Spectrum

The 4-momentum $p_X$ of the hadronic system $X$ recoiling against $\ell\nu$ is determined by summing the 4-momenta of the remaining charged tracks and unmatched clusters. Events with particles missing in the reconstruction are rejected by requiring $|M_{\text{miss}}^2| < 3 \text{ GeV}^2/c^4$. To improve the resolution in $M_X^2$, we constrain the neutrino mass to zero, and recalculate the 4-momentum of the $X$ system, $p'_X = (p_{\text{LER}} + p_{\text{HER}}) - p_{B_{\text{tag}}}$, where LER and HER refer to the low energy and high energy beams, respectively. We measure the $M_X^2$ spectrum in from 0 to 15 GeV$^2/c^4$, and unfold the finite detector resolution in this distribution to a range.
of $M_X^2$ to about 15 GeV$^2$. The bin width is 1 GeV$^2$, except around the narrow states, $(D, D^*, D_1$ and $D_2)$ where smaller bin sizes are chosen. Belle measures the first, second central and second non-central moments of the unfolded $M_X^2$ spectrum in $B \to X_c \ell \nu$, $\langle M_X^2 \rangle_{E_\ell > E_{\text{min}}}$, $\langle (M_X^2 - \langle M_X^2 \rangle)^2 \rangle_{E_\ell > E_{\text{min}}}$ and $\langle M_X^2 \rangle_{E_\ell > E_{\text{min}}}$ for lepton energy thresholds, $E_{\text{min}}$, from 0.7 to 1.9 GeV \(^{14}\) (Fig. 2). Principal systematic errors originate from background estimation, unfolding and signal model dependence.}

3. HQE parameters

Using these measurements and Belle measurements of the photon energy moments in $B \to X_c \gamma$ decays \(^{20}\), we determine the CKM matrix element $|V_{cb}|$, and HQE parameters by performing global fit analyses in the kinetic and 1S schemes \(^{15}\). We exclude measurements that do not have corresponding theoretical predictions and those with high cutoff energies (i.e. semileptonic moments with $E_{\text{min}} > 1.5$ GeV and photon energy moments with $E_{\text{min}} > 2$ GeV). All fit results are preliminary.

3.1. 1S Fit

The inclusive spectral moments of $B \to X_c \ell \nu$ decays have been derived in the 1S scheme up to $O(1/m_b^3)$ \(^2\). The theoretical expressions for the truncated moments are given in terms of HQE parameters, and coefficients determined by theory, which are functions of $E_{\text{min}}$. The non-perturbative corrections are parametrized by $\Lambda$ ($O(m_b)$), $\lambda_1$ and $\lambda_2$ ($O(1/m_b^3)$), and $\tau_1$, $\tau_2$, $\tau_3$, $\tau_4$, $\rho_1$ and $\rho_2$ ($O(1/m_b^4)$). We find the following results for the fit parameters (Fig. 3),

$$|V_{cb}| = (41.49 \pm 0.52_{\text{fit}} \pm 0.20_{\text{th}}) \times 10^{-3},$$

$$m_b^{1S} = (4.729 \pm 0.048) \text{ GeV},$$

and

$$\lambda_1 = (-0.30 \pm 0.04) \text{ GeV}^2.$$

The first error is from the fit including experimental and theory errors, and the second error (on $|V_{cb}|$ only) is due to the uncertainty on the average $B$ lifetime ($\chi^2/\text{n.d.f.} = 5.7/17$). Using the partial branching fraction measurement at $E_{\text{min}} = 0.6$ GeV, we obtain for the full semileptonic branching ratio, $B(B \to X_c \ell \nu) = (10.62 \pm 0.25)\%$.

3.2. Kinetic fit

Spectral moments of $B \to X_c \ell \nu$ decays have been derived up to $O(1/m_b^3)$ in the kinetic scheme \(^8\). The theoretical expressions used in the fit contain improved calculations of the perturbative corrections to
the lepton energy moments and account for the $E_{\text{min}}$ dependence of the perturbative corrections to the hadronic mass moments. For the $B \to X_s \gamma$ moments, the (biased) OPE prediction and the bias correction have been calculated. All these expressions depend on the $b$- and $c$-quark masses $m_b(\mu)$ and $m_c(\mu)$, the non-perturbative parameters $\mu^2(\mu)$ and $\mu^2(\mu)$ ($O(1/m_b^2)$), $\rho_2(\mu)$ and $\rho_2(\mu)$ ($O(1/m_b^2)$), and $\alpha_s$. The CKM element $|V_{cb}|$ is a free parameter in the fit, related to the semileptonic width $\Gamma(B \to X_s \ell \nu)$. We find the following results for the fit parameters (Fig. 4),

$$|V_{cb}| = (41.93 \pm 0.65 \pm 0.48 \pm 0.63) \times 10^{-3},$$

$$B_{X_s \ell \nu} = (10.590 \pm 0.164 \pm 0.006)\%,$$

$$m_b = (4.564 \pm 0.076 \pm 0.003) \text{ GeV},$$

$$m_c = (1.105 \pm 0.116 \pm 0.005) \text{ GeV}$$

and

$$\rho^2 = (0.557 \pm 0.091 \pm 0.013) \text{ GeV}^2.$$

The first error is from the fit (experimental error, non-perturbative and bias corrections). The second error is obtained by varying $\alpha_s$ in the expressions for the moments. The last error is a 1.5% uncertainty from the theoretical expression for the semileptonic width ($\chi^2/n.\text{d.f.} = 17.8/24$).

![Fig. 4. The kinetic scheme fit repeated using lepton energy moments only, hadron mass moments only and photon energy moments only. The ellipses are $\Delta \chi^2 = 1$.](image)

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