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B-meson Semileptonic Decays at *BABAR*

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We report on the measurements of B-meson semileptonic decays at *BABAR*. The studies include precision measurement of $|V_{cb}|$ by a combined HQE fit to hadronic mass and electron energy spectral moments in inclusive $B \to X_c \ell \nu$ decays, measurements of $|V_{ub}|$ in inclusive and exclusive $B \to X_u \ell \nu$ decays, and measurements of $B \to (\pi, \rho)\ell\nu$ decay rates.

1. Introduction

The Cabibbo-Kobayashi-Maskawa (CKM) matrix elements V_{cb} and V_{ub}, the couplings of the b quark to the c and u quarks, are fundamental parameters of the Standard Model. With the increasingly precise measurements of decay-time-dependent CP asymmetries in B-meson decays, in particular the angle β, improved measurements of V_{ub} and V_{cb} will allow for stringent experimental tests of the Standard Model mechanism of CP violation and searches for new physics processes.

B-meson semileptonic decays are especially suitable for measurement of the $|V_{cb}|$ and $|V_{ub}|$, because the leptonic current cleanly factorizes and thus theoretical uncertainties of relations between the semileptonic decay rates and values of CKM matrix elements are relatively small.

The analyses presented here are based on data recorded with the *BABAR* detector [1] at the PEP-II asymmetric-energy e^+e^- storage rings. Most of the analyses are based on a dataset of about 80 million $B\overline{B}$ events.

2. Measurement of $|V_{cb}|$ in inclusive $B \to X_c \ell \nu$ decays

To relate inclusive semileptonic B-meson decay rate to $|V_{cb}|$, the parton-level calculations must be corrected for effects of strong interactions. Heavy-Quark Expansions (HQEs) [2] have become a powerful tool for calculating perturbative and non-perturbative QCD corrections and their uncertainties. We have chosen the kinetic-mass scheme [3,4] for expansions in $1/m_b$ and $\alpha_s(m_b)$, the strong coupling constant. To order $\mathcal{O}(1/m_b^3)$ there are six parameters: the running kinetic masses of the b and c quarks, $m_b(\mu)$ and $m_c(\mu)$, and four non-perturbative parameters: $\mu_\pi^2(\mu)$, $\mu_G^2(\mu)$, $\rho_D^3(\mu)$, and $\rho_{LS}^3(\mu)$, the expectation values of the kinetic, chromomagnetic, Darwin, and spin-orbit operators, respectively. All these parameters depend on the scale μ separating short-distance from long-distance QCD effects.

We determine these HQE parameters from a fit to the moments of the hadronic-mass and electron-energy distributions in $B \to X_c \ell \nu$ decays, averaged over charged and neutral B mesons. The moments are measured as functions of a lower limit on the lepton energy E_{cut}.

The hadronic-mass distribution is measured in events tagged by the fully reconstructed hadronic decay of the second B meson [5]. The hadronic-mass moments are defined as $M_n^X(E_{cut}) = \langle m_X^n \rangle_{E_\ell > E_{cut}}$ with n = 1,2,3,4. The electron-energy distribution is measured in events tagged by a high-momentum electron from the second B meson [6]. We define the first energy moment as $M_1^\ell(E_{cut}) = \langle E_\ell \rangle_{E_\ell > E_{cut}}$ and higher order moments as $M_n^\ell(E_{cut}) = \langle (E_\ell - M_1^\ell(E_{cut}))^n \rangle_{E_\ell > E_{cut}}$ with n = 2,3. We fit also the partial branching ratio $M_0^\ell(E_{cut}) = \int_{E_{cut}}^{E_{max}} (d\mathcal{B}_{c\ell\nu}/dE_\ell)\, dE_\ell$.

The fit results (for the mass scale $\mu = 1$ GeV) are the following:

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$|V_{cb}|$=$(41.4 \pm 0.4 \pm 0.75)\,10^{-3}$;
$\mathcal{B}_{ce\nu}$=$(10.61 \pm 0.16 \pm 0.06)\%$;
m_b=$(4.61 \pm 0.05 \pm 0.04)$ GeV/c^2;
m_c=$(1.18 \pm 0.07 \pm 0.06)$ GeV/c^2;
μ_π^2=$0.45 \pm 0.04 \pm 0.04\,\mathrm{GeV}^2$;
μ_G^2=$0.27 \pm 0.06 \pm 0.04\,\mathrm{GeV}^3$;
ρ_D^3=$0.20 \pm 0.02 \pm 0.02\,\mathrm{GeV}^3$;
ρ_{LS}^3=$-0.09 \pm 0.04 \pm 0.07\,\mathrm{GeV}^3$; and
$m_b - m_c$=$(3.436 \pm 0.025 \pm 0.018 \pm 0.010)\,\mathrm{GeV}/c^2$.

The first error is experimental and the second is an HQE uncertainty. Beyond the statistical, systematic and HQE uncertainties that are included in the fit, the uncertainties from various perturbative and higher-order non-perturbative corrections introduce an additional 1.5% [4] error on $|V_{cb}|$, included in the stated HQE error. The fit results are fully compatible with independent estimates of $\mu_G^2 = (0.35 \pm 0.07)\,\mathrm{GeV}^2$, based on the $B^* - B$ mass splitting [4], and of $\rho_{LS}^3 = (-0.15 \pm 0.10)\,\mathrm{GeV}^3$, from heavy-quark sum rules [7].

3. Measurement of $|V_{ub}|$ in $B \to X_u \ell \nu$ decays

The $|V_{ub}|$ can be extracted with small theoretical uncertainty from the total inclusive charmless semileptonic decay rate, but measurement of the total $B \to X_u \ell \nu$ branching ratio is a difficult experimental task due to high background from CKM-favored $B \to X_c \ell \nu$ decays. The $|V_{ub}|$ can be extracted from the differential decay rates integrated over phase space regions, where dominant $B \to X_c \ell \nu$ decays are kinematically suppressed, for example with lepton energy above $B \to X_c \ell \nu$ decay endpoint, or with the hadronic mass below charm threshold. But theoretical estimations of the corresponding partial decay rates have larger uncertainties due to non-perturbative effects, which include Fermi motion of the b quark in B meson, described in terms of shape functions (SF), weak annihilation, subleading shape functions, etc. The SF properties can be extracted from $B \to X_s \gamma$ and $B \to X_c \ell \nu$ decays.

The exclusive charmless semileptonic decays can be extracted with higher signal to background ratio, but the decay rates depend not only on $|V_{ub}|$ but also on form factors. The statistics of exclusive decay modes is lower than of inclusive decays. Comparison of V_{ub} measurements in inclusive and exclusive decays is an important test of the accuracy of theoretical description of heavy quarks weak decays.

3.1. q^2–E_e analysis with neutrino reconstruction [8]

We select hadronic events containing identified electron with $2.1\,\mathrm{GeV} < E_e < 2.8\,\mathrm{GeV}$. For each event we form a missing 4-momentum $p_{miss} = p_{e^+e^-} - p_{vis}$, where p_{miss} is the 4-momentum of the initial state. We require $0.0 < (E_{miss} - p_{miss}) < 0.8\,\mathrm{GeV}$; where E_{miss} is a missing energy in the event; $|\mathbf{p}_{miss}| < 2.4\,\mathrm{GeV}/c$.

Since the measured $|\mathbf{p}_{miss}|$ differs from the true neutrino momentum due to additional particles that escape detection, a bias correction derived from simulation is applied. Because the resolution in $\mathbf{p}_{miss}$ is higher than that for E_{miss}, the neutrino 4-momentum is set to $(|\mathbf{p}_\nu|, \mathbf{p}_\nu)$. The quality of neutrino reconstruction was evaluated using control sample of $\overline{B} \to D^0 e \overline{\nu}(X)$ with X system typically no more than a pion or photon from a $D^* \to D^0 X$ transition.

For a given E_e and $q^2 = (p_e + p_\nu)^2$ the maximum allowed hadronic mass squared can be calculated. We require $s_h^{max} < 3.5\,\mathrm{GeV}^2 \approx m_{D^0}^2$ to reject $B \to X_c e \nu$ events. The total number of selected events is 5130±150 while the estimated $B\overline{B}$ background is 3176 ± 35 events. Using observed event yields and detection efficiency from MC simulation we get the following partial branching ratio: $\Delta\mathcal{B}(2.0, 3.5) = (3.54 \pm 0.33 \pm 0.34) \times 10^{-4}$, where the uncertainties are statistical and systematic, respectively.

We extract $|V_{ub}| = [\Delta\mathcal{B}/\Delta\zeta\tau_B]^{1/2}$ using $\tau_B = 1.604 \pm 0.023\,\mathrm{ps}$ [9]. The normalized partial decay rate $\Delta\zeta$ is taken from Ref. [10], in which the leading terms in the HQE of the $\overline{B} \to X_u e \overline{\nu}$ are computed at next-to-leading order, and power corrections are included at $\mathcal{O}(\alpha_{\mathcal{S}})$ for the leading SF and at tree level for subleading SFs. The values for HQE parameters $m_b = 4.61 \pm 0.08\,\mathrm{GeV}$ and $\mu_\pi^2 = 0.15 \pm 0.07\,\mathrm{GeV}^2$ with a correlation coefficient of -0.4 are based on fits to $\overline{B} \to X_c \ell \overline{\nu}$ described above translated from the kinetic to shape function scheme according to Ref. [11].

We find $|V_{ub}| = (3.95 \pm 0.26\ ^{+0.58}_{-0.42} \pm 0.25) \times 10^{-3}$ for electron energy in the B-meson rest frame above 2 GeV. The errors represent experimental, HQE parameters, and theoretical uncertainties, respectively. The latter includes estimates of the effects of subleading SFs, variations of matching scales, and weak annihilation [12]

3.1.1. Measurement of $B \to \pi(\rho)\ell\nu$ decay rates, untagged analysis [13]

Signal decays are identified by presence of an electron or muon with c.m.s. momentum $p_\ell > 1.3\,\mathrm{GeV}$, final state $\pi(\rho)$ meson, and $|\mathbf{p}_{miss}| > 1.3\,\mathrm{GeV}$. Charged leptons are then combined with tracks from $\pi(\rho)$ and charged tracks are fitted to a common vertex to form signal decay candidate.

The neutrino 4-momentum is inferred from the difference between total 4-momentum of the colliding-beam particles and the sum of 4-momenta of all detected particles in the event. Assuming, that neutrino is the only missing particle in the event we can fully reconstruct the signal event. As a discriminating variable we use $\cos(\theta_{BY})$, where θ_{BY} is an angle between momenta of the B meson and $\pi(\rho)\ell$ system (“Y”): $\cos^2(\theta_{BY}) = (2E_BE_Y - m_B^2 - m_Y^2)/(2p_Bp_Y)$. Allowing for detector resolution we required the signal candidates to have $|\cos(\theta_{BY})| < 1.1$ and a missing mass compatible with zero.

To extract signal yields we perform binned extended likelihood fit [14] to the $\Delta E = E_B^* - \sqrt{s}/2$ and $m_{ES} = E_B^* - \sqrt{s}/2$ distributions for the four selected samples simultaneously. We assumed the validity of isospin relations between $B^0 \to \pi^-(\rho^-)\ell^+\nu$ and $B^+ \to \pi^0(\rho^0)\ell^+\nu$ decay rates. Remaining are nine free parameters: five for signal yields for five q^2 intervals for $B \to \pi\ell\nu$ decays, three for the signal yields in three q^2 intervals for $B \to \rho\ell\nu$ decays, and one for common scale factor for the $b \to c\ell\nu$ background, shared among all signal modes and q^2 regions.

The extracted partial branching fractions are shown in Fig. 1. Our results on the total branching fractions are the following:
$\mathcal{B}_{\pi^-\ell^+\nu} = (1.38 \pm 0.10 \pm 0.16 \pm 0.08) \times 10^{-4}$,
$\mathcal{B}_{\rho^-\ell^+\nu} = (2.14 \pm 0.21 \pm 0.48 \pm 0.28) \times 10^{-4}$,
Using fitted partial decay rates, lattice QCD form factor calculations for $q^2 > 15\,\mathrm{GeV}^2$ [19,20], and the extrapolation of LQCD calculations to lower q^2 [15] we obtained the following result on $|V_{ub}|$: $|V_{ub}| = (3.82 \pm 0.14 \pm 0.22 \pm 0.11\ ^{+0.88}_{-0.52}) \times 10^{-3}$. Here the errors represent the statistical, systematic and form factor shape errors, respectively. Fourth error on $|V_{ub}|$ reflects the form factor normalization uncertainty.

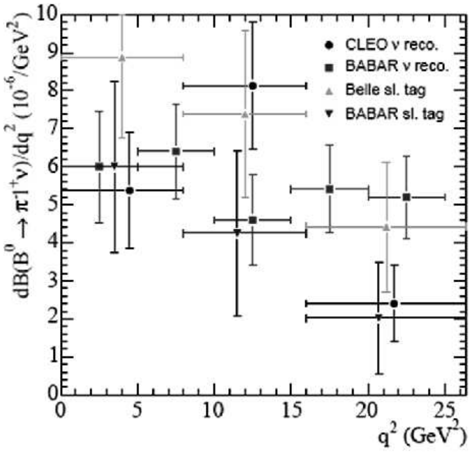

Figure 1. Measurements of $d\mathcal{B}(B \to \pi^-\ell^+\nu)/dq^2$ by *BABAR* [13,18], CLEO [16], and Belle [17].

3.2. Measurement of $B \to \pi\ell\nu$ decay rates using semileptonic tag from recoil B-meson [18]

This analysis is based on a data sample corresponding to integrated luminosity of 211 fb^{-1} for B^+B^- and 81 fb^{-1} for $B^0\overline{B}^0$ events. The candidate $B\overline{B}$ events are required to have semileptonic $B \to D^{(*)}\ell\nu$ decay on one side. The D mesons are reconstructed in several $K\pi, K2\pi, K3\pi$ modes, the D^* decay in $D\pi$ modes. The signal events contain two neutrinos, one from each B-decay. As discriminating kinematic variables we use $\cos(\theta_{BY})$ and $\cos(\theta_{B\pi\ell})$ in the $\Upsilon(4S)$ frame, where the angles θ_{BY} and $\theta_{B\pi\ell}$ are between the momenta of $D^{(*)}\pi$ (“Y”) system and B meson, and between $\pi\ell$ system and B meson, respectively. For signal events these variables should be within $[-1, 1]$ interval and widely distributed for background. Additional discriminating variable is an angle between B momentum and the $(p_Y, p_{\pi\ell})$ plane: $\cos^2(\varphi_B) = (\cos^2(\theta_Y) + \cos^2(\theta_{\pi\ell}) + 2\cos(\theta_Y)\cos(\theta_{\pi\ell})\cos(\gamma))/\sin^2(\gamma)$, where γ is an angle between Y and $\pi\ell$ momenta.

We extract $B^0 \to \pi^-\ell^+\nu$ signal yield from fit to the $\cos^2(\varphi_B)$ distributions in three bins in $q^2 = (p_\ell + p_\nu)$. From the signal yields and detection efficiencies evaluated using simulation corrected for known data-MC differences we obtain the following preliminary results on total branching fractions:
$\mathcal{B}(B^0 \to \pi^-\ell^+\nu) = (1.03 \pm 0.25 \pm 0.13) \times 10^{-4}$,
$\mathcal{B}(B^+ \to \pi^0\ell^+\nu) = (1.80 \pm 0.37 \pm 0.23) \times 10^{-4}$.
The partial branching fractions of the $B^0 \to \pi^-\ell^+\nu$ decay in three q^2 intervals: $q^2 < 8$, $8 < q^2 < 16$, and $q^2 > 16\,\mathrm{GeV}^2$ are shown in Fig. 1. Using measured partial branching ratios and theoretical calculation of the decay form factor [20] we extracted the following $|V_{ub}|$ value:
$|V_{ub}| = (3.3 \pm 0.4 \pm 0.2\,{}^{+0.8}_{-0.4}) \times 10^{-3}$ (preliminary). Here the first error is statistical, the second is systematic, and the third is an uncertainty of form factor calculation.

4. Summary

The semileptonic $B \to X_c\ell\nu$ and $B \to X_u\ell\nu$ decays were measured by *BABAR* in several independent inclusive and exclusive analyses, using both tagged and untagged techniques. Precision data on $|V_{cb}|$ and non-perturbative HQE parameters was obtained. The measurements of $|V_{ub}|$ in different approaches give consistent results. The measurements of the exclusive charmless semileptonic modes become sensitive to decay form factor q^2 dependence, which permits comparison with different theoretical predictions. Further improvement of accuracy of these measurements will permit to test consistency of different theoretical approaches for extraction of $|V_{ub}|$ from the decay data. We plan to extend most of the analyses described here to larger data samples and to extend the scope of observables under consideration according to recent theoretical studies.

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