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Study of $B \rightarrow \pi \ell \nu$ and $B \rightarrow \rho \ell \nu$ decays and determination of $|V_{ub}|$

STUDY OF $B \to \pi \ell \nu$ AND $B \to \rho \ell \nu$ DECAYS AND ... PHYSICAL REVIEW D 72, 051102 (2005)

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‡Deceased
We present an analysis of exclusive charmless semileptonic $B$-meson decays based on $83 \times 10^6$ $B\overline{B}$ pairs recorded with the BABAR detector at the $Y(4S)$ resonance. Using isospin symmetry, we measure branching fractions $B(B^0 \rightarrow \pi^- \ell^+ \nu) = (1.38 \pm 0.10 \pm 0.16 \pm 0.08) \times 10^{-4}$ and $B(B^0 \rightarrow \rho^- \ell^+ \nu) = (2.14 \pm 0.21 \pm 0.48 \pm 0.28) \times 10^{-4}$, where the errors are statistical, experimental systematic, and due to form-factor shape uncertainties. We compare the measured distribution in $q^2$, the momentum-transfer squared, with theoretical predictions for the form factors from lattice QCD and light-cone sum rules, and extract the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{ub}| = (3.82 \pm 0.14 \pm 0.22 \pm 0.11^{+0.08}_{-0.52}) \times 10^{-3}$ from $B \rightarrow \pi \ell \nu$, where the fourth error reflects the uncertainty of the form-factor normalization.


The parameter $|V_{ub}|$ is one of the smallest and least known elements of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. A precise determination of $|V_{ub}|$ would significantly improve the constraints on the unitarity triangle and provide a stringent test of the standard model mechanism for $CP$ violation. In this paper, we present a determination of $|V_{ub}|$ from charmless semileptonic decays of $B$ mesons with exclusively reconstructed final states, $B \rightarrow h_\pi \ell \nu$, where the hadronic state $h_\pi$ represents a $\pi^\pm$, $\pi^0$, $\rho^\pm$, or $\rho^0$, and $\ell$ represents $e$ or $\mu$. Exclusive decays allow for kinematic constraints and more efficient background suppression compared to inclusive decays, but must rely on theoretical form-factor predictions. Using isospin symmetry, we measure the branching fractions $B(B^0 \rightarrow \pi^- \ell^+ \nu)$ [2] and $B(B^0 \rightarrow \rho^- \ell^+ \nu)$ as a function of $q^2 = (p_\ell + p_\nu)^2$, the momentum-transfer squared, and extract $|V_{ub}|$ using recent form-factor calculations based on light-cone sum rules (LCSR) [3,4] and unquenched lattice QCD (LQCD) [5,6].

This measurement is based on a sample of $83 \times 10^6$ $B\overline{B}$ pairs recorded with the BABAR detector [7] at the PEP-II asymmetric-energy $e^+e^-$ storage rings. The data correspond to an integrated luminosity of 75.6 fb$^{-1}$ collected at the $Y(4S)$ resonance and 8.9 fb$^{-1}$ recorded 40 MeV below it. Simulated $B\overline{B}$ events are used to estimate signal efficiencies and shapes of signal and background distributions. Charmless semileptonic decays are simulated as a mixture of three-body decays $B \rightarrow X_\pi \ell \nu$ ($X_\pi = \pi, \eta, \eta', \rho, \omega$) based on the ISGW II quark model [8]. Decays to nonresonant hadronic states $X_\pi$ with masses $m_{X_\pi} > 2m_\pi$ are simulated following a prescription of Ref. [9].

We identify charmless semileptonic decays by a charged lepton with momentum $|p_\ell^*| > 1.3$ GeV [10], a $\pi$ or $\rho$ meson, and missing momentum $|p_{miss}| > 0.7$ GeV in the event. We identify $\rho$ mesons via the decays $\rho^+ \rightarrow \pi^+ \pi^0$ and $\rho^0 \rightarrow \pi^+ \pi^-$ with mass $0.65 < m_{\pi\pi} < 0.85$ GeV, rejecting candidates in which a charged track is identified as a kaon; both $\pi^+$ and $\rho$ candidates are rejected if a charged track is identified as a lepton. The charged lepton is combined with a $\pi^0$, $\rho^0$ or $\pi^\pm$, $\rho^\pm$ of opposite charge to form a "$Y$" candidate; $Y$ candidates are rejected if the lepton and an oppositely charged track from the signal hadron are consistent with a $J/\psi \rightarrow \ell^+\ell^-$ decay.

The neutrino four-momentum, $p_\nu = (E_{\text{miss}}, \vec{p}_{\text{miss}})$, is inferred from the difference between the net four-momentum of the colliding-beam particles, $p_{\text{beams}} = (E_{\text{beams}}, \vec{p}_{\text{beams}})$, and the sum of the four-momenta of all detected particles in the event. To reduce the effect of losses due to the detector acceptance, we require a total charge of the event of $|Q_{\text{tot}}| \leq 1$ and a polar angle of the missing momentum in the range $0.6 < \theta_{\text{miss}} < 2.9$ rad. In addition, the missing mass measured from the whole event should be compatible with zero. Because the missing-mass resolution varies linearly with the missing energy, we require $|m_{\text{miss}}^2/2E_{\text{miss}}| < 0.4$ GeV. We compute the angle between the $Y$ candidate and the $B$ meson, assuming zero missing mass, as $\cos\theta_{BY} = (2E_Y E_\gamma - M_B^2 - M_Y^2)/(2|\vec{p}_\pi^*| |\vec{p}_Y|)$. Here $M_B$, $M_Y$, $E_\gamma$, $E_Y$, $\vec{p}_\pi^*$, $\vec{p}_Y$ refer to the masses, energies, and momenta of the $B$ and $Y$. Signal candidates are required to satisfy $|\cos\theta_{BY}| < 1.1$, allowing for detector resolution and photon radiation.

We restrict the momenta of leptons and hadrons in $Y$ candidates to enhance the signal over backgrounds. For $B \rightarrow \pi \ell \nu$, we require $|\vec{p}_\gamma| + |\vec{p}_{\text{miss}}| > 2.6$ GeV; for $B \rightarrow \rho \ell \nu$, $1.5|\vec{p}_\gamma| + |\vec{p}_{\text{miss}}| > 4.2$ GeV and $|\vec{p}_\gamma| > 1.8$ GeV. These criteria keep 99.8% (75%) of true $B \rightarrow \pi(\rho)\ell\nu$ decays and reduce the $B \rightarrow X_\pi \ell \nu$ background by about 10% (80%) after all other selection criteria. To suppress backgrounds from $e^+e^- \rightarrow q\overline{q}$ ($q = u, d, s, c$) and QED processes, we require at least five charged tracks in each event or, to increase the efficiency for $B^+ \rightarrow \pi^0\ell^+\nu$, four tracks and at least two photons. We also require $L_2 = \Sigma_i |\vec{p}_i| \cos^2\theta_i < 1.5$ GeV. Here the sum is over all tracks in the event excluding the $Y$ candidate, and $\vec{p}_i$ and $\theta_i$ refer to the momenta and the angles measured with respect to the thrust axis of the $Y$. This requirement removes over 95% of $q\overline{q}$ and 80% of $B \rightarrow X_\pi \ell \nu$ background and retains about 50% of the signal in all modes.

We discriminate against the remaining background using the variables $\Delta E = (p_B \cdot p_{\text{beams}} - s/2)/\sqrt{s}$ and...
Because of the overlap of the backgrounds, we use a combined fit to the $B \to \pi \ell \nu$ and $B \to \rho \ell \nu$ decay modes. The total signal selection efficiencies for the sum of electrons and muons are 3.5% and 2.4% for $\pi^- \ell^+ \nu$ and $\pi^0 \ell^- \nu$, and 0.53% and 1.1% for $\rho^- \ell^+ \nu$ and $\rho^0 \ell^- \nu$ [11]. We use a low-statistics background sample of $B^0 \to D^{*-} \ell^+ \nu$ decays with $0 < q^2 < 25$ GeV$^2$, three for the signal yields in the three $q^2$ intervals for $B \to \rho \ell \nu$ decays, plus one scale parameter, shared among all $q^2$ intervals and signal modes, to fit the overall normalization of the $B \to X_c \ell \nu$ background. We classify signal candidates as “combinatoric signal” if the reconstructed lepton comes from the isospin-conjugate decay or the hadron is incorrectly selected. The fit uses common parameters for combinatoric signal and signal. The normalization of the simulated non-$B\overline{B}$ background is scaled separately for events with $e^\pm$ and $\mu^\pm$ to match the off-resonance data. We smooth the distributions for this low-statistics background to reduce single-bin statistical fluctuations.

Figures 1 and 2 show projections of the fitted $\Delta E$ vs. $m_{ES}$ distributions for each $q^2$ interval for $B \to \pi \ell \nu$ and $B \to \rho \ell \nu$, respectively. Integrated over the whole $q^2$ range, we observe 396 $\pi^- \ell^+ \nu$, 137 $\pi^0 \ell^+ \nu$, 95 $\rho^- \ell^+ \nu$, and 98 $\rho^0 \ell^- \nu$ decays. The resulting partial and total branching fractions are given in Table I. The fitted normalization of

\[
m_{ES} = \sqrt{(s/2 + \vec{p}_B \cdot \vec{p}_{beam})^2/E^2_{beam} - \vec{p}_B^2},\]

where $\Delta s$ is the mass of the $Y(4S)$. Only candidates with $|\Delta E| < 0.9$ GeV and $m_{ES} > 5.095$ GeV are retained. The total signal selection efficiencies for the sum of electrons and muons are 3.5% and 2.4% for $\pi^- \ell^+ \nu$ and $\pi^0 \ell^- \nu$, and 0.53% and 1.1% for $\rho^- \ell^+ \nu$ and $\rho^0 \ell^- \nu$ [11].
and obtain consistent results. The errors are statistical.

...and that...
TABLE II. Relative systematic uncertainties of the partial and total branching fractions $\mathcal{B}(B^0 \to \pi^- \ell^+ \nu)$ ($\Delta \mathcal{B}_\pi$) and $\mathcal{B}(B^0 \to \rho^- \ell^+ \nu)$ ($\Delta \mathcal{B}_\rho$) in the various $q^2$ bins. The total uncertainty in each column is the sum in quadrature of the listed contributions.

<table>
<thead>
<tr>
<th>$q^2$ range (GeV$^2$)</th>
<th>$\delta \Delta \mathcal{B}<em>\pi / \Delta \mathcal{B}</em>\pi$ (%)</th>
<th>$\delta \Delta \mathcal{B}<em>\rho / \Delta \mathcal{B}</em>\rho$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–5</td>
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<tr>
<td>90–100</td>
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</table>

The overall uncertainty of the number of produced $B$ mesons is 1.1%. We take into account the uncertainties of the ratio of $B$ lifetimes, $\tau_B / \tau_{B^0} = 1.081 \pm 0.015$ [16], the charged-to-neutral $B$ production ratio $f_{+}/f_{00} = 1.044 \pm 0.050$ [16], and the potential effect of isospin breaking due to $\rho^0\omega$ mixing [20]. We assign an uncertainty of 20% to the radiative corrections based on PHOTOS [21].

The impact of the uncertainties of the $B \to \pi \ell \nu$ form-factor shape on the measured branching fractions is negligible, whereas for the different $B \to \rho \ell \nu$ form-factor calculations we see variations of up to 6% in $\mathcal{B}(B^0 \to \pi^- \ell^+ \nu)$ and 13% in $\mathcal{B}(B^0 \to \rho^- \ell^+ \nu)$. We take the full spread between calculations as the uncertainty of the $q^2$ dependence of the form factors.

We extract $|V_{ub}|$ (see Table III) from the partial branching fractions $\Delta \mathcal{B}$ using the relation $|V_{ub}| = \sqrt{\Delta \mathcal{B}}/(\tau_B \Delta \zeta)$, where $\tau_B = (1.536 \pm 0.014)$ ps [16] is the $B^0$ lifetime and $\Delta \zeta$ denotes the predicted form-factor normalization in each $q^2$ interval. For $q^2 < 15$ GeV$^2$ we derive $|V_{ub}|$ using LCSR calculations; for $q^2 > 15$ GeV$^2$ we use unquenched LQCD. To extract $|V_{ub}|$ from this measurement over the whole $q^2$ range, we extrapolate the LQCD results to low $q^2$ using the fits of the BK parametrization in Ref. [5] and the LCSR results to high $q^2$ using the parametrization given in Ref. [3]. We adopt the uncertainties of the form-factor normalization estimated in Refs. [3–6].

In conclusion, we have measured the exclusive branching fractions $\mathcal{B}(B^0 \to \pi^- \ell^+ \nu)$ and $\mathcal{B}(B^0 \to \rho^- \ell^+ \nu)$ as a function of $q^2$, and have extracted $|V_{ub}|$ using recent form-factor calculations. We measure the total branching fractions.
\[ \mathcal{B}(B^0 \to \pi^- \ell^+ \nu) = (1.38 \pm 0.10 \pm 0.16 \pm 0.08) \times 10^{-4}, \]
\[ \mathcal{B}(B^0 \to \rho^- \ell^+ \nu) = (2.14 \pm 0.21 \pm 0.48 \pm 0.28) \times 10^{-4}, \]

where the errors are statistical (data and simulation), experimental systematic, and uncertainties of the form-factor shapes. As a consistency check, we have also measured the branching fractions for the charged and neutral \( \pi \ell \nu \) samples separately, \( \mathcal{B}(B^0 \to \pi^- \ell^+ \nu) = (1.41 \pm 0.17 \pm 0.08 \pm 0.08) \times 10^{-4}, \) \( \mathcal{B}(B^+ \to \pi^0 \ell^+ \nu) = (0.70 \pm 0.10 \pm 0.08 \pm 0.04) \times 10^{-4}. \) The ratio \( \Gamma(B^0 \to \pi^- \ell^+ \nu)/\Gamma(B^+ \to \pi^0 \ell^+ \nu) = 2.21 \pm 0.41 \) is consistent with the assumed isospin relation within the quoted statistical uncertainty.

For \( B \to \pi \ell \nu \), the \( q^2 \) distribution agrees well with calculations based on LCSR [3] and unquenched LQCD [5,6], but the data disfavor ISGW II [8]. Instead of averaging results based on different calculations, we choose the measured form-factor shape and normalization of LQCD2 and quote

\[ |V_{ub}| = (3.82 \pm 0.14 \pm 0.22 \pm 0.11^{+0.88}_{-0.52}) \times 10^{-3}, \]

where the additional fourth error reflects the uncertainty of the form-factor normalization. The results are consistent with previous measurements [22,23], but have higher statistical accuracy, are less dependent on theoretical form-factor predictions, and benefit from recent advances in theoretical calculations [3–6].

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[2] Charge-conjugate modes are included implicitly.
[10] All variables denoted with a star (e.g. \( \rho^* \)) are given in the \( Y(4S) \) rest frame; all others are given in the laboratory frame.
[11] These efficiencies and signal yields depend upon \( q^2 \)-dependent form factors which, unless otherwise stated, are fit to the data for \( B \to \pi \ell \nu \) and calculated using LCSR [4] for \( B \to \rho \ell \nu \).