Observation of Direct CP Violation in $B^0 \rightarrow K^+\pi^-$ Decays


(The BABAR Collaboration)

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We present an updated search for direct CP violation in the decay $B^0 \rightarrow K^+\pi^-$. Using 227 million $\Upsilon(4S) \rightarrow B\bar{B}$ decays collected with the BABAR detector at the PEP-II asymmetric-energy $e^+e^-$ collider at SLAC, we observe a total signal yield of $n_{K^-\pi^+} + n_{K^+\pi^-} = 1606 \pm 51$ decays and measure the asymmetry $(n_{K^-\pi^+} - n_{K^+\pi^-}) / (n_{K^-\pi^+} + n_{K^+\pi^-}) = -0.133 \pm 0.030$ (stat) $\pm 0.009$ (syst).
measurement establishes direct CP violation in the $B^0$-meson system at the level of 4.2 standard deviations.

PACS numbers: 13.25.Hw, 11.30.Er 12.15.Hh

CP violation has been established in processes involving $B^0, \overline{B}^0$ oscillations through measurements of the time dependence of neutral-$B$-meson decays to final states that include charmonium [1, 2]. Direct CP violation, a phenomenon that does not involve particle-antiparticle oscillations, has been observed in $K^0_L$ decays [2], where the effect is a few parts per million. In contrast, a large effect is expected in the $B$-meson system if CP violation arises from the Kobayashi-Maskawa quark-mixing mechanism [3, 4]. In this Letter we report the observation of direct CP violation in the decay $B^0 \rightarrow K^+\pi^-$ using a sample of 227 million $B\overline{B}$ pairs collected with the BABAR detector at the SLAC PEP-II $e^+e^-$ asymmetric-energy storage ring.

Direct CP violation is observable as an asymmetry in yields between a decay and its CP conjugate when at least two contributing amplitudes carry different weak and strong phases. In the standard model, the decay $B^0 \rightarrow K^+\pi^-$ occurs through two different mechanisms ("penguin" and "tree"), which carry different weak phases and, in general, different strong phases. The direct CP-violating asymmetry [5] is defined as

$$A_{K^\pi} = \frac{n_{K^\pi}^- - n_{K^\pi}^+}{n_{K^\pi}^- + n_{K^\pi}^+},$$

where $n_{K^\pi}^+$ and $n_{K^\pi}^-$ are the measured yields for the two final states. The charge of the kaon identifies the flavor of the decaying $B$ meson ($B^0 \rightarrow K^+\pi^-$, $\overline{B}^0 \rightarrow K^-\pi^+$, neglecting second-order weak transitions). The Belle collaboration recently reported a measurement of $A_{K^\pi} = -0.088 \pm 0.035 \pm 0.013$ [6], which agrees with our previous result [2], and with a less-precise measurement from the CLEO collaboration [7].

The BABAR detector is described in detail elsewhere [8]. The primary components used in this analysis are a charged-particle-tracking system consisting of a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) surrounded by a 1.5-T solenoidal magnet, an electromagnetic calorimeter (EMC) comprising 6580 CsI(Tl) crystals, and a detector of internally reflected Cherenkov light (DIRC), providing $K\pi$ separation over the range of laboratory momentum relevant for this analysis (Fig. 1).

We reconstruct two-body neutral-$B$ decays from pairs of oppositely-charged tracks located within the geometric acceptance of the DIRC and originating from a common decay point near the interaction region. We require that each track have an associated Cherenkov-angle ($\theta_c$) measured with at least five signal photons detected in the DIRC. The value of $\theta_c$ must agree within 4$\sigma$ with either the pion or kaon particle hypothesis. The last requirement efficiently removes events containing high-momentum protons. Electrons are explicitly removed based on energy-loss measurements in the SVT and DCH, and on a comparison of the track momentum and associated energy deposited in the EMC. We use the $\theta_c$ measurement to separate kaons and pions in a maximum-likelihood fit that determines signal and background yields corresponding to the four distinguishable final states ($\pi^+\pi^-$, $K^+\pi^-$, $K^-\pi^+$, $K^0K^-$).

Signal decays are identified using two kinematic variables: (1) the difference $\Delta E$ between the energy of the $B$ candidate in the $e^+e^-$ center-of-mass (CM) frame and $\sqrt{s}/2$ and (2) the beam-energy substituted mass $m_{ES} = \sqrt{(s/2 + p_B \cdot p_B)^2/E_f^2 - p_B^2}$. Here, $\sqrt{s}$ is the total CM energy, and the $B$ momentum $p_B$ and the four-momentum of the initial state ($E_i, p_i$) are defined in the laboratory frame. For signal decays, $\Delta E$ and $m_{ES}$ are distributed according to Gaussian distributions with resolutions of 27 MeV and 2.6 MeV/$c^2$, respectively. The distribution of $m_{ES}$ peaks near the $B$ mass for all four particle combinations. To simplify the likelihood definition, we reconstruct the kinematics of the $B$ candidate using the pion mass for both tracks. With this choice, $B^0 \rightarrow \pi^+\pi^-$ decays peak near $\Delta E = 0$. For $B$ decays with one or two kaons in the final state, the $\Delta E$ peak position is shifted and parameterized as a function of the kaon momentum in the laboratory frame. The average shifts with respect to zero are $-45$ MeV and $-91$ MeV, respectively. We require $5.20 < m_{ES} < 5.29$ GeV/$c^2$ and $|\Delta E| < 150$ MeV. The large sideband region in $m_{ES}$ is used to determine background-shape parameters, while the wide range in $\Delta E$ allows us to separate $B$ decays to all four final states in the same fit.

We have studied potential backgrounds from higher-multiplicity $B$ decays and find them to be negligible in the selected $\Delta E$ region. The dominant source of background is the process $e^+e^- \rightarrow q\overline{q}$ ($q = u, d, s, c$), which produces a distinctive jet-like topology. In the CM frame we define the angle $\theta_S$ between the sphericity axis [10] of the $B$ candidate and the sphericity axis of the remaining particles in the event. For background events, $|\cos \theta_S|$ peaks sharply near unity, while it is nearly flat for signal decays. We require $|\cos \theta_S| < 0.8$, which removes approximately 80% of this background.

The selected sample contains 68030 events and is composed of two-body $B$ decays (signal) and combinations of real kaons and pions produced in $q\overline{q}$ events (background). We use an unbinned, extended maximum-likelihood fit to extract yields, the signal asymmetry ($A_{K^\pi}$), and the background asymmetry ($A_{K^\pi}^B$). The fit uses $m_{ES}$, $\Delta E$, $\theta_c$, and the Fisher discriminant $F$ described in Ref. [9] to
distinguish signal and background components for each of the four $\pi^+\pi^-$, $K^+\pi^-$, $K^-\pi^+$, and $K^+K^-$ combinations. The likelihood for event $j$ is obtained by summing the product of the event yield $n_i$ and probability $P_i$ over the signal and background hypotheses $i$. The total likelihood for the sample is

$$L = \exp \left( -\sum_i n_i \prod_j \left[ \sum_i n_i P_i(\vec{x}_j; \vec{a}_i) \right] \right).$$

The probabilities $P_i$ are evaluated as the product of the probability density functions (PDFs) with parameters $\vec{a}_i$, for each of the independent variables $x_j = \{m_{ES}, \Delta E, \mathcal{F}, \theta^+_c, \theta^-_c\}$, where $\theta^+_c$ and $\theta^-_c$ are the Cherenkov angles for the positively- and negatively-charged tracks, respectively. We have verified that there are no significant correlations between the $x_j$. For both signal and background, the $K^+\pi^\pm$ yields are parameterized as $n_{K^+\pi^\pm} = n_{K\pi} \left( 1 + A_{K\pi} \right)/2$, and we fit directly for the total yield $n_{K\pi}$ and the asymmetry $A_{K\pi}$.

The $\theta_c$ PDFs are obtained from a sample of approximately 430,000 $D^{*+} \to D^0\pi^+ (D^0 \to K^-\pi^+) \to K^-\pi^+$ decays reconstructed in data, where $K^\mp/\pi^\mp$ tracks are identified through the charge correlation with the $\pi^\pm$ from the $D^{\mp}$ decay. Figure 1(b) shows the measured values of the Cherenkov angle as a function of laboratory momentum for tracks from the $D^{*+}$ sample, and the expected values for kaons ($\theta_c^K$) and pions ($\theta_c^\pi$). Figure 1(c) shows the average $K^-\pi$ separation, defined as $|\theta_c^K - \theta_c^\pi|/\sigma_{\theta_c}$, where $\sigma_{\theta_c}$ is the average uncertainty for kaon and pion tracks for a given momentum. The PDFs are constructed separately for $K^+$, $K^-$, $\pi^+$, and $\pi^-$ tracks as a function of momentum and polar angle using the measured and expected values of $\theta_c$, and its uncertainty. We use the same PDFs for signal and background events.

A total of 21 parameters are varied in the fit. Signal and background yields and $K\pi$ asymmetries are determined simultaneously with the parameters of the signal PDFs for $m_{ES}$ and $\Delta E$, as well as the background PDF parameters for $m_{ES}$, $\Delta E$, and $\mathcal{F}$. The parameters describing the signal $\mathcal{F}$ distribution are fixed to the values obtained from a large sample of simulated events, and the parameters of the $\theta_c$ PDFs are fixed to the values obtained from the $D^*$ study. The analysis was performed with the value of $A_{K\pi}$ hidden until the event selection and PDF definitions were finalized.

The fitted signal yields are $n_{K\pi} = 1606 \pm 51$, $n_{\pi\pi} = 467 \pm 33$, and $n_{KK} = 3 \pm 12$, which are all consistent with our previously published measurements of the flavor-averaged branching fractions in these decay modes [9]. The direct $CP$-violating asymmetry is

$$A_{K\pi} = -0.133 \pm 0.030 \text{ (stat)} \pm 0.009 \text{ (syst)},$$

and the background asymmetry is $A_{K\pi}^b = 0.001 \pm 0.008$. This result is consistent with, and supersedes, our previous measurement [9]. The correlations of $A_{K\pi}$ with $A_{K\pi}^b$ and $n_{K\pi}$ are $-8\%$ and $+2\%$, respectively. Correlations with the remaining free parameters are all $1\%$ or less.

The dominant source of systematic error is the potential difference between kaons and pions in the dependence of track reconstruction and particle identification on the charge of the particle. To estimate this systematic uncertainty, we use the statistical uncertainty (0.008) on the measurement of $A_{K\pi}^b$ as a conservative systematic error on $A_{K\pi}$. This background is due to combinations of real kaons and pions in the same momentum and polar-angle range as the signal tracks, and should have similar sensi-
tivity to a potential bias. We have also investigated potential differences in efficiencies for track reconstruction, and for the requirement of a minimum number of signal photons detected in the DIRC. Using the large sample of kaons and pions from the \( D^* \) study, we confirm that the efficiency asymmetries between \( K^+ / K^- \) and \( \pi^+ / \pi^- \) are consistent with zero within the small error of the measurements (0.002).

We confirm that we are sensitive to a nonzero value of \( \mathcal{A}_{K\pi} \) by performing fits on samples of Monte-Carlo-simulated signal events, and background events generated directly from the PDF shapes. With a generated asymmetry of \(-10\%\), the average fitted value in the ensemble of events is \( \mathcal{A}_{K\pi} = -0.102 \pm 0.002 \). Although the result is consistent with the generated value, we take the sum in quadrature of the error and the difference with respect to the generated value as a systematic uncertainty (0.003). The systematic errors from uncertainties in the distribution of \( \mathcal{F} \) for signal events (0.001) and from the parameters describing the \( \theta \), PDFs (0.001) are negligible. The total systematic error (0.009) is calculated as the sum in quadrature of the individual uncertainties.

Figure 2 shows background-subtracted distributions of \( \Delta E \) for signal \( K^+ \pi^- \) and \( K^- \pi^+ \) decays. The subtraction is performed using the technique described in Ref. [13], where each event is given a statistical weight that depends on the PDFs and covariance matrix from a fit excluding the variable being plotted. The resulting distribution is normalized to the signal yield and its shape can be compared with the PDF we use in the full fit. We see no evidence of an enhancement near \( \Delta E = 0 \), which could arise from significant contamination of \( B^0 \rightarrow \pi^+ \pi^- \) decays due to imperfect parameterizations of the \( \theta \) PDFs.

As a further consistency check on the fit result, in Fig. 3(a) we show distributions of \( m_{ES} \) for samples enhanced in signal \( K \pi \) decays using probability ratios based on the PDFs for \( \Delta E \), \( \mathcal{F} \), and \( \theta \). The efficiency of the selection is approximately 80% for signal \( K \pi \) decays, while the contamination from \( B^0 \rightarrow \pi^+ \pi^- \) is less than 2%. Fig. 3(b) shows the resulting distribution of \( \mathcal{A}_{K\pi} \) as a function of \( m_{ES} \).

A number of consistency checks are performed to validate the result. We generate and fit a large set of pseudo-experiments, where the variables \( x_j \) for each event are generated randomly from the PDFs, and confirm that the value of \( \mathcal{A}_{K\pi} \) is intrinsically unbiased. To check for a potential effect from \( K^- \pi^+ \) misidentification, we fit the subsample of events (less than half) where both tracks have laboratory momentum less than 3.5 GeV/c. The \( K^- \pi^+ \) separation for all tracks in this sample is greater than 3\( \sigma \), and we find \( \mathcal{A}_{K\pi} = -0.151 \pm 0.047 \). We perform a \( B^0 - \overline{B}^0 \) mixing analysis on the full sample using \( B \)-flavor identification and decay-time information as described in Ref. [13]. From this fit, we simultaneously determine the \( B \) lifetime \( \tau_B = 1.60 \pm 0.04 \) ps, \( B^0 - \overline{B}^0 \) mixing frequency \( \Delta m_d = 0.523 \pm 0.028 \) ps\(^{-1} \), and \( \mathcal{A}_{K\pi} = -0.126 \pm 0.029 \), where the errors are statistical only. The values of \( \tau_B \) and \( \Delta m_d \) are consistent with the world averages [14], and \( \mathcal{A}_{K\pi} \) is consistent with the nominal fit. Finally, we divide the full sample into the approximate period in which the
organizations that support for the substantial dedicated effort from the computing conditions provided by our PEP-II colleagues, and Alexander von Humboldt Foundation.

ico), A. P. Sloan Foundation, Research Corporation, and individuals have received support from CONACyT (Mexico), A. P. Sloan Foundation, Research Corporation, and Alexander von Humboldt Foundation.

The statistical significance of the measurement ($4.3\sigma$) is computed by taking the square root of the change in $2\ln \mathcal{L}$ when $A_{K\pi}$ is fixed to zero. If we include the systematic error by summing in quadrature with the statistical uncertainty, the significance is $4.2\sigma$, and the probability of obtaining a negative asymmetry of this magnitude or larger in the absence of CP violation is $1.3 \times 10^{-5}$. We conclude that the measurement of $A_{K\pi} = -0.133 \pm 0.030 \text{ (stat)} \pm 0.009 \text{ (syst)}$ reported here establishes direct CP violation in the $B^0$-meson system.

The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from CONACyT (Mexico), A. P. Sloan Foundation, Research Corporation, and Alexander von Humboldt Foundation.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$N_{B\Xi}$</th>
<th>$n_{K\pi}$</th>
<th>$A_{K\pi}$</th>
<th>$A_{K\pi}^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999-2001</td>
<td>21.1</td>
<td>142 $\pm$ 15</td>
<td>$-0.240 \pm 0.102$</td>
<td>0.006 $\pm 0.026$</td>
</tr>
<tr>
<td>2002</td>
<td>66.4</td>
<td>479 $\pm$ 27</td>
<td>$-0.102 \pm 0.055$</td>
<td>$-0.008 \pm 0.015$</td>
</tr>
<tr>
<td>2003</td>
<td>34.1</td>
<td>241 $\pm$ 19</td>
<td>$-0.109 \pm 0.079$</td>
<td>0.007 $\pm 0.021$</td>
</tr>
<tr>
<td>2004</td>
<td>104.9</td>
<td>743 $\pm$ 33</td>
<td>$-0.142 \pm 0.044$</td>
<td>0.004 $\pm 0.012$</td>
</tr>
</tbody>
</table>

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§ Deceased

[6] Unless otherwise stated, charge conjugate modes are included implicitly.
[7] A nonzero value of $A_{K\pi}$ could arise purely from CP violation in mixing, but this effect is known to be small. See for example BABAR Collaboration, B. Aubert et al., Phys. Rev. Lett. 92, 181801 (2004).