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Direct CP Violating Asymmetry in $B^0 \to K^+\pi^-$ Decays

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We present a measurement of the direct *CP* violating asymmetry in the decay $B^0 \to K^+\pi^-$ using a data sample of 227×10^6 $\Upsilon(4S) \to B\overline{B}$ 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 $(n_{K^-\pi^+} - n_{K^+\pi^-})/(n_{K^-\pi^+} + n_{K^+\pi^-}) = -0.133 \pm 0.030(\text{stat}) \pm 0.009(\text{syst})$. The probability of observing such an asymmetry in the absence of direct CP violation is 1.3×10^{-5}, corresponding to 4.2 standard deviations.

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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_L^0 decays [3], 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 [4,5].

The Belle Collaboration has reported evidence of direct CP violation in the decay $B^0 \rightarrow \pi^+\pi^-$ at the level of 3.2σ [6], though this is not confirmed by our measurement based on a significantly larger data set [7]. In this Letter we report a measurement of direct CP violation in the decay $B^0 \rightarrow K^+\pi^-$ [8] at the level of 4.2σ using a sample of 227×10^6 $B\overline{B}$ 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 [9] is defined as

$$\mathcal{A}_{K\pi} \equiv \frac{n_{K^-\pi^+} - n_{K^+\pi^-}}{n_{K^-\pi^+} + n_{K^+\pi^-}}, \quad (1)$$

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 $\mathcal{A}_{K\pi} = -0.088 \pm 0.035 \pm 0.013$ using a data sample of 152×10^6 $B\overline{B}$ pairs [10], which agrees with our previous result [11], and with a less-precise measurement from the CLEO Collaboration [12].

The *BABAR* detector is described in detail elsewhere [13]. 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-π 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 (θ_c) measured with at least five signal photons detected in the DIRC. The value of θ_c must agree within 4σ 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 based on a comparison of the track momentum and associated energy deposited in the EMC. We use the θ_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^+K^-).

Signal decays are identified using two kinematic variables: (1) the difference ΔE between the energy of the B candidate in the e^+e^- center-of-mass (c.m.) frame and $\sqrt{s}/2$, and (2) the beam-energy substituted mass $m_{\text{ES}} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$. Here, $\sqrt{s}$ is the total c.m. energy, and the B momentum $\mathbf{p_B}$ and the four-momentum of the e^+e^- initial state (E_i, $\mathbf{p_i}$) are defined in the laboratory frame. For signal decays, ΔE 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 ΔE peak position is shifted and parametrized as a function of the kaon momentum in the laboratory frame. The average shifts with respect to zero are -45 and -91 MeV, respectively. We require $5.20 < m_{\text{ES}} < 5.29$ GeV$/c$ and $|\Delta E| < 150$ MeV. The large sideband region in m_{ES} is used to determine background-shape parameters, while the wide range in ΔE 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 ΔE region. The dominant source of background is the process $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$), which produces a distinctive jetlike topology. In the c.m. frame we define the angle θ_S between the sphericity axis [14] of the B candidate and the sphericity axis of the remaining parti-

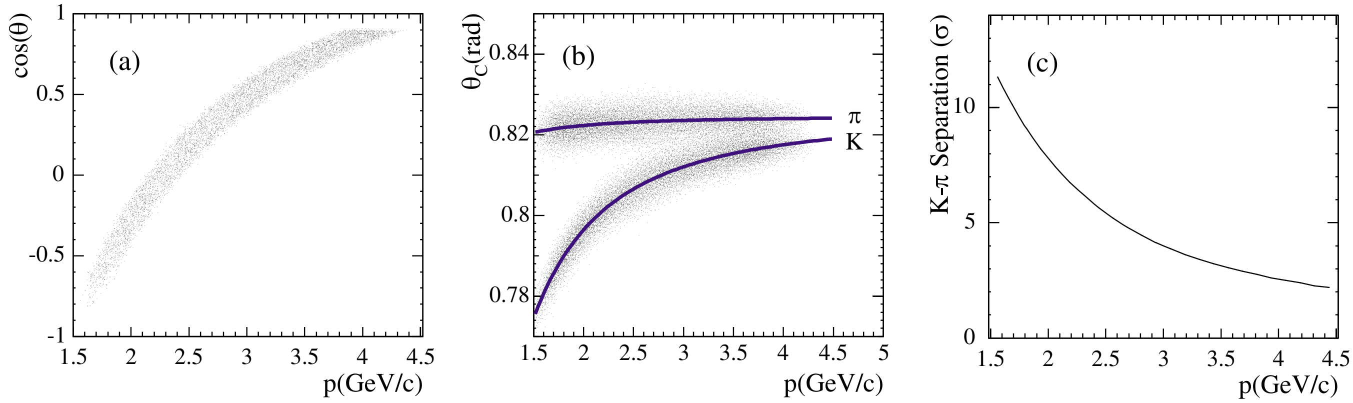

FIG. 1 (color online). (a) Cosine of the polar-angle (θ) as a function of laboratory momentum for kaons and pions in simulated $B^0 \to K^+\pi^-$ decays at *BABAR*. At a symmetric e^+e^- collider operating at the $\Upsilon(4S)$ resonance, particles from two-body B decays are nearly monoenergetic with $p \sim 2.6$ GeV$/c$. The boost at PEP-II results in an approximately uniform distribution of laboratory momenta between 1.5 and 4.5 GeV$/c$, and induces a correlation between momentum and polar angle. (b) The measured Cherenkov angle for pions (upper band) and kaons (lower band) from $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ decays reconstructed in data. The curves show the expected angle θ_c as a function of laboratory momentum, for the K and π mass hypothesis. (c) The average difference between the expected value of θ_c for kaons and pions, divided by the uncertainty, as a function of momentum.

cles 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 68 030 events and is composed of two-body B decays (signal) and combinations of real kaons and pions produced in $q\bar{q}$ events (background). We use an unbinned, extended maximum-likelihood fit to extract yields, the signal asymmetry ($\mathcal{A}_{K\pi}$), and the background asymmetry ($\mathcal{A}^{\rm b}_{K\pi}$). The fit uses $m_{\rm ES}$, ΔE, θ_c, and the Fisher discriminant $\mathcal{F}$ described in Ref. [11] 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 $\mathcal{P}_i$ over the signal and background hypotheses i. The total likelihood for the sample is

$$\mathcal{L} = \exp\left(-\sum_i n_i\right)\prod_j\left[\sum_i n_i\mathcal{P}_i(\vec{x}_j; \vec{\alpha}_i)\right]. \qquad (2)$$

The probabilities $\mathcal{P}_i$ are evaluated as the product of the probability density functions (PDFs) with parameters $\vec{\alpha}_i$, for each of the independent variables $\vec{x}_j = \{m_{\rm ES}, \Delta E, \mathcal{F}, \theta_c^+, \theta_c^-\}$, where θ_c^+ and θ_c^- are the Cherenkov angles for the positively and negatively charged tracks, respectively. We have verified that there are no significant correlations between the $\vec{x}_j$. For both signal and background, the $K^\pm\pi^\mp$ yields are parametrized as $n_{K^\pm\pi^\mp} = n_{K\pi}(1 \mp \mathcal{A}_{K\pi})/2$, and we fit directly for the total yield $n_{K\pi}$ and the asymmetry $\mathcal{A}_{K\pi}$.

The θ_c PDFs are obtained from a sample of approximately 430 000 $D^{*+} \to D^0\pi^+(D^0 \to K^-\pi^+)$ decays reconstructed in data, where $K^\mp/\pi^\pm$ tracks are identified through the charge correlation with the $\pi^\pm$ from the $D^{*\pm}$ 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 (θ_c^K) and pions (θ_c^π). Figure 1(c) shows the average K-π separation, defined as $|\theta_c^K - \theta_c^\pi|/\sigma_{\theta_c}$, where σ_{θ_c} is the average uncertainty for kaon and pion tracks for a given momentum. The PDFs are constructed separately for K^+, K^-, π^+, and π^- tracks as a function of momentum and polar- angle using the measured and expected values of θ_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 $m_{\rm ES}$ and ΔE, as well as the background PDF parameters for $m_{\rm ES}$, ΔE, 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 θ_c PDFs are fixed to the values obtained from the D^* study. The analysis was performed with the value of $\mathcal{A}_{K\pi}$ 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 [11]. The direct CP violating asymmetry is

$$\mathcal{A}_{K\pi} = -0.133 \pm 0.030({\rm stat}) \pm 0.009({\rm syst}), \qquad (3)$$

and the background asymmetry is $\mathcal{A}^{\rm b}_{K\pi} = 0.001 \pm 0.008$. This result is consistent with, and supersedes, our previous measurement [11]. The correlations of $\mathcal{A}_{K\pi}$ with $\mathcal{A}^{\rm b}_{K\pi}$ and $n_{K\pi}$ are -8% and $+2\%$, respectively.

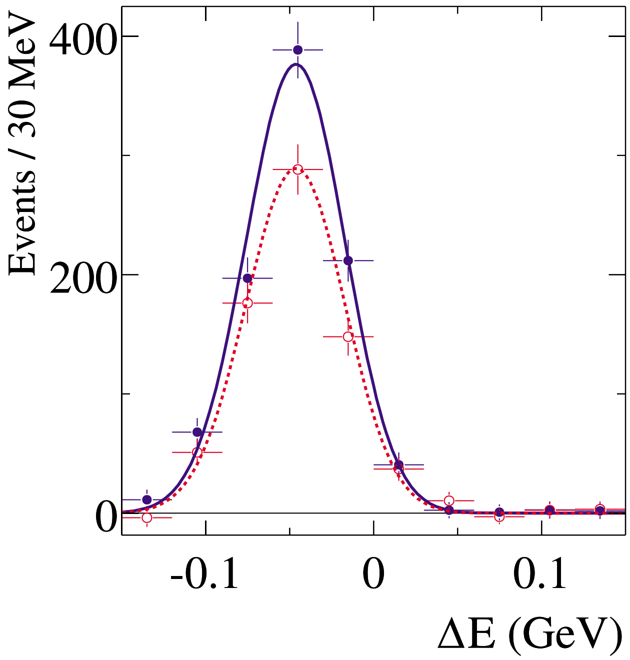

FIG. 2 (color online). Distributions of ΔE in data (points with error bars) and the PDFs (curves) used in the maximum-likelihood fit for $K^+\pi^-$ (solid circles and solid curve) and $K^-\pi^+$ (open circles and dashed curve). The data are weighted using the background-subtraction technique of Ref. [15] (see text).

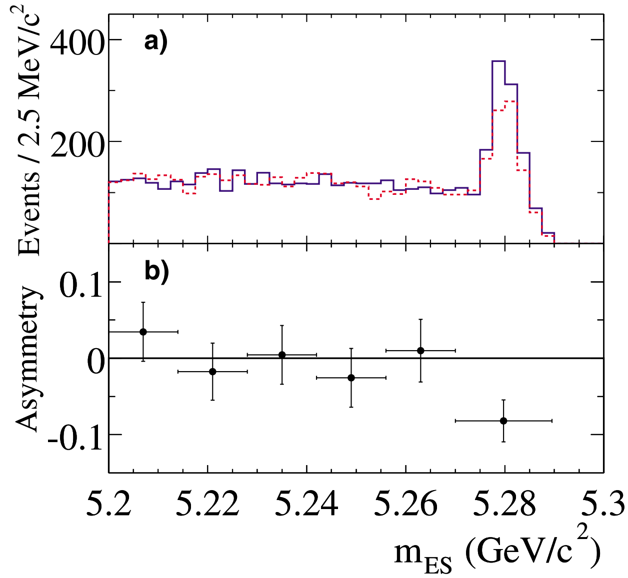

FIG. 3 (color online). (a) Distribution of m_{ES} enhanced in $K^+\pi^-$ (solid histogram) and $K^-\pi^+$ (dashed histogram). (b) Asymmetry $\mathcal{A}_{K\pi}$ calculated for ranges of m_{ES}. The asymmetry in the highest m_{ES} bin is somewhat diluted by the presence of background.

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 $\mathcal{A}^{\mathrm{b}}_{K\pi}$ as a conservative systematic error on $\mathcal{A}_{K\pi}$. 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 sensitivity 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 π^+/π^- are consistent with zero within the small error of the measurements (0.002). Doubly Cabibbo-suppressed D^0 decays ($D^0 \to K^+\pi^-$) would produce a bias in the θ_C PDFs derived from the D^* sample, but are a negligible effect given the current size of the data set.

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 θ_c 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 ΔE for signal $K^+\pi^-$ and $K^-\pi^+$ decays. The subtraction is performed using the technique described in Ref. [15], 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 $B^0 \to \pi^+\pi^-$ decays due to imperfect parametrizations of the θ_c 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 ΔE, $\mathcal{F}$, and θ_c. The efficiency of the selection is approximately 80% for signal $K\pi$ decays, while the contamination from $B^0 \to \pi^+\pi^-$ is less than 2%. Figure 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 pseudoexperiments, where the variables $\vec{x}_j$ for each event are generated randomly from the PDFs, and confirm that

TABLE I. The signal yield $n_{K\pi}$, and signal ($\mathcal{A}_{K\pi}$) and background ($\mathcal{A}^{b}_{K\pi}$) asymmetries measured in different data-taking periods. The number of $B\overline{B}$ pairs $N_{B\overline{B}}$ (in millions) for each data set is also given.

Sample	$N_{B\overline{B}}$	$n_{K\pi}$	$\mathcal{A}_{K\pi}$	$\mathcal{A}^{b}_{K\pi}$
1999–2001	21.1	142 ± 15	−0.240 ± 0.102	0.006 ± 0.026
2002	66.4	479 ± 27	−0.102 ± 0.055	−0.008 ± 0.015
2003	34.1	241 ± 19	−0.109 ± 0.079	0.007 ± 0.021
2004	104.9	743 ± 33	−0.142 ± 0.044	0.004 ± 0.012

the value of $\mathcal{A}_{K\pi}$ is intrinsically unbiased. To check for a potential effect from K-π misidentification, we fit the subsample of events (less than half) where both tracks have laboratory momentum less than 3.5 GeV/c. The K-π separation for all tracks in this sample is greater than 3σ, 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 two-body sample using B-flavor identification and decay-time information as described in Ref. [11]. From this fit, we simultaneously determine the B lifetime $\tau_B = 1.60 \pm 0.04$ ps, B^0-$\overline{B}^0$ mixing frequency $\Delta m_d = 0.523 \pm 0.028\ \mathrm{ps}^{-1}$, and $\mathcal{A}_{K\pi} = -0.126 \pm 0.029$, where the errors are statistical only. $\mathcal{A}_{K\pi}$ is consistent with the nominal fit, and the values of τ_B and Δm_d are consistent with the world averages [16], demonstrating that the signal events have the expected time evolution. Finally, we divide the full sample into the approximate period in which the data were recorded (Table I). We find $\mathcal{A}_{K\pi} < 0$ and a background asymmetry consistent with zero in each data set.

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

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