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Measurements of Branching Fractions and *CP*-violating Asymmetries in $B^0 \rightarrow \pi^+\pi^-$, $K^+\pi^-$, K^+K^- Decays

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We present measurements of branching fractions and CP-violating asymmetries for neutral B meson decays to two-body final states of charged pions and kaons based on a sample of about 88 million $\Upsilon(4S) \to B\overline{B}$ decays. From a time-independent fit we measure the charge-averaged branching fractions $\mathcal{B}(B^0 \to \pi^+\pi^-) = (4.7 \pm 0.6 \pm 0.2) \times 10^{-6}$, $\mathcal{B}(B^0 \to K^+\pi^-) = (17.9 \pm 0.9 \pm 0.7) \times 10^{-6}$, and the direct CP-violating charge asymmetry $\mathcal{A}_{K\pi} = -0.102 \pm 0.050 \pm 0.016\ [-0.188, -0.016]$, where the ranges in square brackets indicate the 90% confidence intervals. From a time-dependent fit we measure the $B^0 \to \pi^+\pi^-$ CP-violating parameters $S_{\pi\pi} = 0.02 \pm 0.34 \pm 0.05\ [-0.54, +0.58]$ and $C_{\pi\pi} = -0.30 \pm 0.25 \pm 0.04\ [-0.72, +0.12]$.

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Recent measurements of the *CP*-violating asymmetry parameter $\sin 2\beta$ reported by the *BABAR* [1] and Belle [2] Collaborations established *CP* violation in neutral B decays. These results are consistent with the Standard Model (SM) expectation based on indirect constraints on the magnitudes of the elements of the Cabibbo-Kobayashi-Maskawa [3] quark-mixing matrix. However, a full test of the *CP* violation mechanism in the SM, through a single complex phase in the CKM matrix, will require additional direct constraints on the angles (α, β, and γ) of the Unitarity Triangle [4].

The time-dependent *CP*-violating asymmetry in the decay $B^0 \to \pi^+\pi^-$ is related to the angle α, and ratios of branching fractions for various $\pi\pi$ and $K\pi$ decay modes are sensitive to the angle γ. In this Letter we present results for branching fractions and *CP*-violating asymmetries in $B^0 \to \pi^+\pi^-$, $K^+\pi^-$, and K^+K^- decays [5] using a sample of 87.9 ± 1.0 million $B\overline{B}$ pairs. A detailed description of the *BABAR* detector is presented in Ref. [6], and more details on the analysis technique are given in Refs. [7], which describe our previous measurements of these quantities. Other measurements of the branching fractions and the charge asymmetry in $B^0 \to K^+\pi^-$ have been performed by the CLEO and Belle Collaborations [8]. More recently, the Belle Collaboration reported a measurement of the time-dependent *CP* asymmetry in $B^0 \to \pi^+\pi^-$ [9].

We reconstruct a sample of neutral B mesons ($B_{\rm rec}$) decaying to the $h^+h'^-$ final state, where h and h' refer to π or K. Signal yields are determined with a maximum likelihood fit including kinematic, topological, and particle identification information. For the $K^{\mp}\pi^{\pm}$ components, the yield is parameterized as $N_{K^{\mp}\pi^{\pm}} = N_{K\pi}\left(1 \pm \mathcal{A}_{K\pi}\right)/2$, where $N_{K\pi}$ is the total yield and $\mathcal{A}_{K\pi} \equiv (N_{K^-\pi^+} - N_{K^+\pi^-})/(N_{K^-\pi^+} + N_{K^+\pi^-})$ is the *CP*-violating charge asymmetry. The asymmetry arises from interference between the $b \to s$ penguin and $b \to u$ tree amplitudes, and is predicted [10, 11] to be less than 20% in the Standard Model. However, a larger asymmetry could be induced by new particles, such as charged Higgs bosons or supersymmetric particles, contributing to the penguin amplitude.

In order to extract the *CP* asymmetry parameters in $B^0 \to \pi^+\pi^-$ decay, we examine each event in the $B_{\rm rec}$ sample to determine whether the second B meson ($B_{\rm tag}$) decayed as a B^0 or $\overline{B}^0$ (flavor tag) and reconstruct the difference Δt between the proper decay times of the $B_{\rm rec}$ and $B_{\rm tag}$ decays. The decay rate distribution $f_+\,(f_-)$ when $h^+h'^- = \pi^+\pi^-$ and $B_{\rm tag} = B^0\,(\overline{B}^0)$ is given by

$$f_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}[1 \pm S_{\pi\pi}\sin(\Delta m_d \Delta t) \mp C_{\pi\pi}\cos(\Delta m_d \Delta t)], \qquad (1)$$

where τ is the mean B^0 lifetime and Δm_d is the mixing frequency due to the eigenstate mass difference. The parameters $S_{\pi\pi}$ and $C_{\pi\pi}$ are defined as

$$S_{\pi\pi} \equiv \frac{2\,\mathcal{I}m\lambda}{1+|\lambda|^2} \quad \text{and} \quad C_{\pi\pi} \equiv \frac{1-|\lambda|^2}{1+|\lambda|^2}, \qquad (2)$$

and vanish in the absence of *CP* violation. If the decay proceeds purely through the $b \to u$ tree amplitude, the complex parameter λ is given by

$$\lambda(B \to \pi^+\pi^-) = \left(\frac{V^*_{\rm tb}V_{\rm td}}{V_{\rm tb}V^*_{\rm td}}\right)\left(\frac{V^*_{\rm ud}V_{\rm ub}}{V_{\rm ud}V^*_{\rm ub}}\right). \qquad (3)$$

In this case $C_{\pi\pi} = 0$ and $S_{\pi\pi} = \sin 2\alpha$, where $\alpha \equiv \arg\left[-V_{\rm td}V^*_{\rm tb}/V_{\rm ud}V^*_{\rm ub}\right]$. In general, the $b \to d$ penguin amplitude modifies both the magnitude and phase of λ, so that $C_{\pi\pi} \neq 0$ and $S_{\pi\pi} = \sqrt{1-C^2_{\pi\pi}}\sin 2\alpha_{\rm eff}$, where $\alpha_{\rm eff}$ depends on the magnitudes and relative strong and weak phases of the tree and penguin amplitudes. Several approaches have been proposed to obtain information on α in the presence of penguins [10, 12].

The event selection and $B_{\rm rec}$ reconstruction used in this analysis are similar to those used in Ref. [7]. Hadronic events are selected based on charged particle multiplicity and event topology. Candidate $B_{\rm rec}$ decays are reconstructed from pairs of oppositely-charged tracks forming a good quality vertex, where the $B_{\rm rec}$ four-momentum is calculated with the pion mass assumed for both tracks.

Signal decays are identified kinematically using two variables, the difference ΔE between the center-of-mass (CM) energy of the $B_{\rm rec}$ candidate and $\sqrt{s}/2$, and the beam-energy substituted mass $m_{\rm ES} = \sqrt{(s/2 + \mathbf{p}_i\cdot\mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$, where $\sqrt{s}$ is the total CM energy, and the $B_{\rm rec}$ momentum $\mathbf{p_B}$ and the four-momentum of the initial state $(E_i, \mathbf{p_i})$ are defined in the laboratory frame. For signal decays ΔE and $m_{\rm ES}$ are Gaussian distributed with resolutions of 26 MeV and 2.6 MeV/c^2, respectively. For $\pi^+\pi^-$ decays ΔE peaks near zero, while for decays with one or two kaons the ΔE peak position is parameterized as a function of the kaon momenta in the laboratory frame, with an average shift of -45 MeV and -91 MeV, respectively. The distribution of $m_{\rm ES}$ peaks near the B mass. We require $5.20 < m_{\rm ES} < 5.29\,{\rm GeV}/c^2$ and $|\Delta E| < 0.15\,{\rm GeV}$.

Identification of $h^+h'^-$ tracks as pions or kaons is accomplished with the Cherenkov angle measurement θ_c from a detector of internally reflected Cherenkov light. We construct charge-dependent double-Gaussian probability density functions (PDFs) from the difference between measured and expected values of θ_c for the pion or kaon hypothesis, normalized by the error σ_{θ_c}. The PDF parameters are measured in a sample of $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ decays, reconstructed in data. The typical separation between pions and kaons varies from $8\sigma_{\theta_c}$ at 2 GeV/c to $2.5\sigma_{\theta_c}$ at 4 GeV/c.

We have studied potential backgrounds from other B decays and find them to be negligible. Backgrounds from

TABLE I: Average tagging efficiency ϵ, average mistag fraction w, mistag fraction difference $\Delta w = w(B^0) - w(\overline{B}^0)$, and effective tagging efficiency Q for signal events in each tagging category. The quantities are measured in the $B_{\rm flav}$ sample.

Category	ϵ (%)	w (%)	Δw (%)	Q (%)
Lepton	9.1 ± 0.2	3.3 ± 0.7	-1.6 ± 1.3	8.0 ± 0.3
Kaon I	16.6 ± 0.2	9.5 ± 0.7	-2.8 ± 1.3	10.7 ± 0.4
Kaon II	19.8 ± 0.3	20.6 ± 0.8	-5.3 ± 1.3	6.7 ± 0.4
Inclusive	20.1 ± 0.3	31.7 ± 0.9	-2.6 ± 1.4	2.7 ± 0.3
Untagged	34.4 ± 0.5			
Total Q				28.4 ± 0.7

the process $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) are suppressed by their topology. In the CM frame we define the angle θ_S between the sphericity axis of the B candidate and the sphericity axis of the remaining particles in the event, and require $|\cos\theta_S| < 0.8$, which removes 83% of this background. For these particles we also define a Fisher discriminant $\mathcal{F} = 0.53 - 0.60 \times \sum_i p_i^* + 1.27 \times \sum_i p_i^* \, |\cos(\theta_i^*)|^2$ where p_i^* is the momentum of particle i and θ_i^* is the angle between its momentum and the $B_{\rm rec}$ thrust axis in the CM frame. The shapes of $\mathcal{F}$ for signal and background events are included as PDFs in the maximum likelihood fit.

We use a multivariate technique [13] to determine the flavor of the $B_{\rm tag}$ meson. Separate neural networks are trained to identify primary leptons, kaons, soft pions from D^* decays, and high-momentum charged particles from B decays. Events are assigned to one of five mutually exclusive tagging categories based on the estimated mistag probability and the source of the tagging information (Table I). The quality of tagging is expressed in terms of the effective efficiency $Q = \sum_k \epsilon_k (1 - 2w_k)^2$, where ϵ_k and w_k are the efficiencies and mistag probabilities, respectively, for events tagged in category k. Table I summarizes the tagging performance measured in a data sample $B_{\rm flav}$ of fully reconstructed neutral B decays to $D^{(*)-}(\pi^+, \rho^+, a_1^+)$. The assumption of equal tagging efficiencies and mistag probabilities for signal $\pi^+\pi^-$, $K^+\pi^-$, and K^+K^- decays is validated in a detailed Monte Carlo simulation. The background hypothesis have separate tagging efficiencies.

The time difference Δt is obtained from the known boost of the e^+e^- system and the measured distance between the z positions of the $B_{\rm rec}$ and $B_{\rm tag}$ decay vertices. A detailed description of the algorithm is given in Ref. [14]. We require $|\Delta t| < 20\,\rm ps$ and $\sigma_{\Delta t} < 2.5\,\rm ps$, where $\sigma_{\Delta t}$ is the error on Δt. The resolution function for signal candidates is a sum of three Gaussians, identical to the one described in Ref. [13], with parameters determined from a fit to the $B_{\rm flav}$ sample (including events in all five tagging categories). The background Δt distribution is modeled as the sum of an exponential convolved with a Gaussian, with two additional Gaussians to account for tails. Common parameters are used to describe the background shape for all tagging categories. We find that 96% of background events are described by an effective lifetime of approximately 0.7 ps.

We use an unbinned extended maximum likelihood fit to extract yields and *CP* parameters from the $B_{\rm rec}$ sample. The likelihood for candidate j tagged in category k is obtained by summing the product of event yield N_i, tagging efficiency $\epsilon_{i,k}$, and probability $\mathcal{P}_{i,k}$ over the eight possible signal and background hypotheses i (referring to $\pi^+\pi^-$, $K^+\pi^-$, $K^-\pi^+$, and K^+K^- decays). The extended likelihood function for category k is

$$\mathcal{L}_k = \exp\left(-\sum_i N_i \epsilon_{i,k}\right) \prod_j \left[\sum_i N_i \epsilon_{i,k} \mathcal{P}_{i,k}(\vec{x}_j; \vec{\alpha}_i)\right]. \tag{4}$$

The probabilities $\mathcal{P}_{i,k}$ are evaluated as the product of PDFs for each of the independent variables $\vec{x}_j = \{m_{\rm ES}, \Delta E, \mathcal{F}, \theta_c^+, \theta_c^-, \Delta t\}$, where θ_c^+ and θ_c^- are the Cherenkov angles for the positively and negatively charged tracks. We use separate PDF parameters for θ_c^+ and θ_c^- to account for possible systematic differences. The total likelihood $\mathcal{L}$ is the product of likelihoods for each tagging category, and the free parameters are determined by maximizing the quantity $\ln\mathcal{L}$. The fitted sample contains 26070 events.

Signal yields are determined from a fit excluding tagging or Δt information. There are 16 free parameters, including signal and background yields (6 parameters); $K\pi$ asymmetries (2); and parameters for the background shapes in $m_{\rm ES}$ (1), ΔE (2), and $\mathcal{F}$ (5). Table II summarizes signal yields, total efficiencies, charge-averaged branching fractions, and $\mathcal{A}_{K\pi}$. In the efficiency calculation we neglect possible effects due to final state radiation from the $B_{\rm rec}$ decay products. The significance of $\mathcal{A}_{K\pi}$ is 2.0, where significance is defined as the square root of the change in $-2\log\mathcal{L}$ when $\mathcal{A}_{K\pi}$ is fixed to zero. These results are consistent with our previous measurements [7], and with measurements from other experiments [8]. For the decay $B^0 \to K^+K^-$ we measure a yield of only 1 ± 8 events and so compute a Bayesian 90% confidence level (C.L.) upper limit on the branching fraction. Ref. [7] gives a detailed description of the method used.

The dominant sources of systematic error on the branching fraction measurements are from possible fit bias (determined in large samples of Monte Carlo simulated events), uncertainty in track and θ_c reconstruction efficiencies, and imperfect knowledge of the PDF shapes. The calculation of selection efficiencies using Monte Carlo simulated decays has been checked against control samples in data and residual uncertainties are included in the systematic error on branching fractions. For $\mathcal{A}_{K\pi}$ the systematic error is dominated by the θ_c PDF shape and possible charge bias in track reconstruction. The total

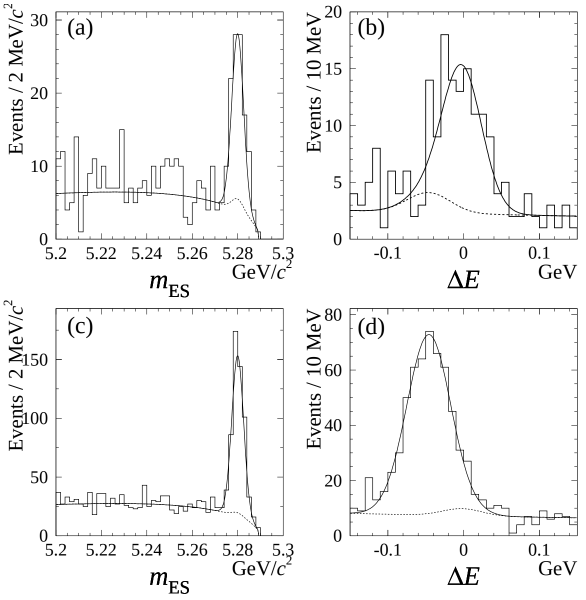

FIG. 1: Distributions of $m_{\rm ES}$ and ΔE for events enhanced in signal (a), (b) $\pi^+\pi^-$ and (c), (d) $K^\mp\pi^\pm$ decays. Solid curves represent projections of the maximum likelihood fit, dashed curves represent $q\bar{q}$ and $\pi\pi \leftrightarrow K\pi$ cross-feed background.

systematic error is computed as the sum in quadrature of the individual uncertainties.

Figure 1 shows distributions of $m_{\rm ES}$ and ΔE after selecting on probability ratios to enhance the signal purity. The solid curve in each plot represents the fit projection after correcting for the efficiency of the additional selection (52% for $\pi\pi$, 79% for $K\pi$).

The parameters $S_{\pi\pi}$ and $C_{\pi\pi}$ are determined from a second fit including tagging and Δt information, where the $B_{\rm flav}$ sample is included to determine the signal parameters describing tagging information and the Δt resolution function. The Δt PDF for signal $\pi^+\pi^-$ decays is given by Eq. 1, modified to include w_k and Δw_k for each tagging category and convolved with the signal resolution function. We also take into account possible differences in reconstruction and tagging efficiencies between B^0 and $\overline{B}^0$ mesons. The Δt PDF for signal $K^+\pi^-$ events takes into account B^0–$\overline{B}^0$ mixing based on the charge of the kaon and the flavor of $B_{\rm tag}$.

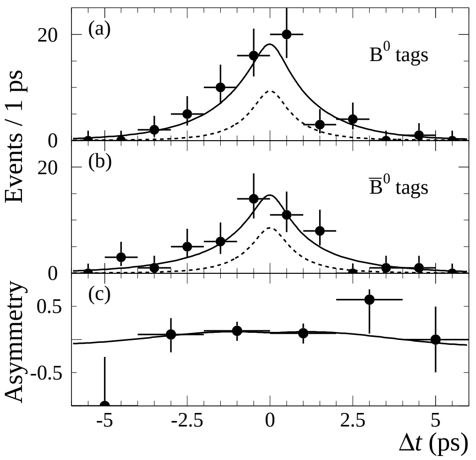

FIG. 2: Distributions of Δt for events enhanced in signal $\pi\pi$ decays with $B_{\rm tag}$ tagged as (a) B^0 (N_{B^0}) or (b) $\overline{B}^0$ ($N_{\overline{B}^0}$), and (c) the asymmetry $[N_{B^0} - N_{\overline{B}^0}]\,/\,[N_{B^0} + N_{\overline{B}^0}]$ as a function of Δt. Solid curves represent projections of the maximum likelihood fit, dashed curves represent the sum of $q\bar{q}$ and $K\pi$ background events.

A total of 76 parameters are varied in the fit, including the values of $S_{\pi\pi}$ and $C_{\pi\pi}$ (2); signal and background yields (5); $K\pi$ charge asymmetries (2); signal and background tagging efficiencies (16) and efficiency asymmetries (16); signal mistag fraction and mistag fraction differences (8); signal resolution function (9); and parameters for the background shapes in $m_{\rm ES}$ (5), ΔE (2), $\mathcal{F}$ (5), and Δt (6). We assume zero events from $B^0 \to K^+K^-$ decays and we fix τ_{B^0} and Δm_d to their world average values [15]. As a means of validating the analysis technique, we determine τ and Δm_d in the $B_{\rm rec}$ sample and find $\tau = (1.56 \pm 0.07)\,{\rm ps}$ and $\Delta m_d = (0.52 \pm 0.05)\,{\rm ps}^{-1}$.

The combined fit to the $B_{\rm rec}$ and $B_{\rm flav}$ samples yields

$$\begin{aligned} S_{\pi\pi} &= \ 0.02 \pm 0.34\,({\rm stat}) \pm 0.05\,({\rm syst}) \ \ [-0.54, +0.58]\,, \\ C_{\pi\pi} &= \ -0.30 \pm 0.25\,({\rm stat}) \pm 0.04\,({\rm syst}) \ \ [-0.72, +0.12]\,, \end{aligned}$$

where the range in square brackets indicates the 90% C.L. interval taking into account the systematic errors. The correlation between $S_{\pi\pi}$ and $C_{\pi\pi}$ is -10%. The signal yields determined in this fit are within 3% of the yields obtained from the time-independent fit. Systematic uncertainties on $S_{\pi\pi}$ and $C_{\pi\pi}$ are dominated by imperfect knowledge of the PDF shapes and possible fit bias. We also evaluate multiplicative systematic errors (0.015), which are calculated at one standard deviation and summed in quadrature with the additive systematic uncertainties. Figure 2 shows distributions of Δt for events with $B_{\rm tag}$ tagged as B^0 or $\overline{B}^0$, and the asymmetry as a function of Δt for tagged events enhanced in signal $\pi\pi$ decays.

In summary, we have presented updated measurements of branching fractions and *CP*-violating asymmetries in $B^0 \to \pi^+\pi^-$, $K^+\pi^-$, and K^+K^- decays. These results are consistent with, and supersede our previous measurements [7]. We do not observe large mixing-induced or direct *CP* violation in the time-dependent asymmetry of $B^0 \to \pi^+\pi^-$ decays, as reported in [9].

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TABLE II: Summary of results for total detection efficiencies, fitted signal yields N_S, charge-averaged branching fractions $\mathcal{B}$, and $\mathcal{A}_{K\pi}$. Branching fractions are calculated assuming equal rates for $\Upsilon(4S) \to B^0\overline{B}^0$ and B^+B^-. The upper limits for $N_{K^+K^-}$ and $\mathcal{B}(B^0 \to K^+K^-)$ correspond to the 90% C.L.

Mode	Efficiency (%)	N_S	$\mathcal{B}(10^{-6})$	$\mathcal{A}_{K\pi}$	$\mathcal{A}_{K\pi}$ 90% C.L.
$\pi^+\pi^-$	38.0 ± 0.8	$157 \pm 19 \pm 7$	$4.7 \pm 0.6 \pm 0.2$		
$K^+\pi^-$	37.5 ± 0.8	$589 \pm 30 \pm 17$	$17.9 \pm 0.9 \pm 0.7$	$-0.102 \pm 0.050 \pm 0.016$	$[-0.188, -0.016]$
K^+K^-	36.2 ± 0.8	$1 \pm 8\,(< 16)$	< 0.6		

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