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Measurement of Branching Fractions and Search for CP -Violating Charge Asymmetries in Charmless Two-Body B Decays into Pions and Kaons

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We present measurements, based on a sample of approximately 23×10^6 $B\bar{B}$ pairs, of the branching fractions and a search for CP -violating charge asymmetries in charmless hadronic decays of B mesons into two-body final states of kaons and pions. We find the branching fractions $\mathcal{B}(B^0 \rightarrow \pi^+ \pi^-) = (4.1 \pm 1.0 \pm 0.7) \times 10^{-6}$, $\mathcal{B}(B^0 \rightarrow K^+ \pi^-) = (16.7 \pm 1.6 \pm 1.3) \times 10^{-6}$, $\mathcal{B}(B^+ \rightarrow K^+ \pi^0) = (10.8^{+2.1}_{-1.9} \pm 1.0) \times 10^{-6}$, $\mathcal{B}(B^+ \rightarrow K^0 \pi^+) = (18.2^{+3.3}_{-3.0} \pm 2.0) \times 10^{-6}$, $\mathcal{B}(B^0 \rightarrow K^0 \pi^0) = (8.2^{+3.1}_{-2.7} \pm 1.2) \times 10^{-6}$. We also report 90% confidence level upper limits for B meson decays to the $\pi^+ \pi^0$,

K^+K^- , and \bar{K}^0K^+ final states. In addition, charge asymmetries have been found to be consistent with zero, where the statistical precision is in the range of ± 0.10 to ± 0.18 , depending on the decay mode.

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The study of B meson decays into charmless hadronic final states plays an important role in the understanding of CP violation, which, in the standard model, is a consequence of the phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. Recently, the *BABAR* and Belle Collaborations published measurements [2,3] of the angle β of the CKM unitarity triangle from the study of B decays into final states containing charmonium. Measurements of the rates and charge asymmetries for B decays into the charmless final states $\pi\pi$ and $K\pi$ can be used to constrain the angles α and γ [4] of the unitarity triangle.

In this Letter we present new measurements of the branching fractions for B meson decays to the charmless hadronic final states $\pi^+\pi^-$, $K^+\pi^-$, $K^+\pi^0$, $K^0\pi^+$, and $K^0\pi^0$ [5]. In addition, we search for charge asymmetries in the modes $B^0 \rightarrow K^+\pi^-$, $B^+ \rightarrow K^+\pi^0$, and $B^+ \rightarrow K^0\pi^+$. Measurements [6,7] of these decays were first reported by the CLEO Collaboration.

The data sample used in these analyses was collected with the *BABAR* detector [8] at the PEP-II e^+e^- collider at the Stanford Linear Accelerator Center. It corresponds to an integrated luminosity of 20.6 fb^{-1} taken on the $Y(4S)$ resonance (“on-resonance”), amounting to $(22.57 \pm 0.36) \times 10^6 B\bar{B}$ pairs, and 2.61 fb^{-1} taken at a center-of-mass (CM) energy 40 MeV below the $Y(4S)$ resonance (“off-resonance”), which are used for continuum background studies. The collider is operated with asymmetric beam energies, producing a boost ($\beta\gamma = 0.56$) of the $Y(4S)$ along the collision axis (z). The boost increases the momentum range of two-body B decay products from a narrow distribution centered near $2.6 \text{ GeV}/c$ to a broad distribution extending from 1.7 to $4.3 \text{ GeV}/c$.

The *BABAR* detector is a spectrometer of charged and neutral particles and is described in detail in Ref. [8]. Charged particle (track) momenta are measured in a tracking system consisting of a 5-layer, double-sided, silicon vertex detector and a 40-layer drift chamber (DCH) filled with a gas mixture of helium (80%) and isobutane (20%), both operating within a 1.5 T superconducting solenoidal magnet. Photons are detected in an electromagnetic calorimeter (EMC) consisting of 6580 CsI(Tl) crystals. Charged hadron identification is based on the Cherenkov angle θ_c measured by a unique, internally reflecting Cherenkov ring imaging detector (DIRC).

Hadronic events are selected based on track multiplicity and event topology. Backgrounds from nonhadronic events are reduced by requiring the ratio of Fox-Wolfram moments H_2/H_0 [9] to be less than 0.95 and the sphericity [10] of the event to be greater than 0.01.

All tracks (except K_S^0 decay products) are required to have a polar angle within the tracking fiducial region

$0.41 < \theta < 2.54$ rad and a Cherenkov measurement from the DIRC with a minimum of six photons above background, where the average is approximately 30 for both pions and kaons. The efficiency of requiring a θ_c measurement is 91% per track, and 97% of such tracks satisfy the minimum photon requirement. We reject tracks with a θ_c within 3σ of the expected value for a proton. Electrons are rejected based on specific ionization (dE/dx) in the DCH system, shower shape in the EMC, and the ratio of shower energy to track momentum.

Candidate K_S^0 mesons are reconstructed from pairs of oppositely charged tracks that form a well-measured vertex and have an invariant mass within 3.5σ of the nominal K_S^0 mass [11]. The measured proper decay time of the K_S^0 candidate is required to exceed 5 times its error.

Candidate π^0 mesons are formed from pairs of photons with an invariant mass within 3σ of the nominal π^0 mass. Photons are defined as showers in the EMC that have the expected lateral shape, are not matched to a track, and have a minimum energy of 30 MeV. The π^0 candidates are then kinematically fitted with their mass constrained to the nominal π^0 mass.

B meson candidates are reconstructed in four topologies: $h^+h'^-$, $h^+\pi^0$, $K_S^0h^+$, and $K_S^0\pi^0$, where the symbols h and h' refer to π or K . The kinematic constraints provided by the $Y(4S)$ initial state and relatively precise knowledge of the beam energies are exploited to efficiently identify B candidates. We define a beam-energy substituted mass $m_{ES} = \sqrt{E_b^2 - \mathbf{p}_B^2}$, where $E_b = (s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)/E_i$, \sqrt{s} and E_i are the total energies of the e^+e^- system in the CM and lab frames, respectively, and \mathbf{p}_i and \mathbf{p}_B are the momentum vectors in the lab frame of the e^+e^- system and the B candidate, respectively. To improve the resolution in modes containing π^0 mesons, the B candidate is kinematically fitted with the energy constrained to the CM beam energy. For all modes, the m_{ES} resolution is dominated by the beam energy spread and is approximately $2.5 \text{ MeV}/c^2$. Candidates are selected in the range $5.2 < m_{ES} < 5.3 \text{ GeV}/c^2$.

We define an additional kinematic parameter ΔE as the difference between the energy of the B candidate and half the energy of the e^+e^- system, computed in the CM system, where the pion mass is assumed for all charged decay products of the B . The ΔE distribution is peaked near zero for modes with no charged kaons and shifted on average -45 MeV (-91 MeV) for modes with one (two) kaons, where the exact separation depends on the laboratory kaon momentum. For modes with no π^0 mesons the ΔE resolution is about 26 MeV ; with π^0 mesons the resolution is about 42 MeV and asymmetric due to underestimation of the π^0 energy in the EMC. Candidates are accepted in the following ΔE ranges (given in GeV): $[-0.15, 0.15]$

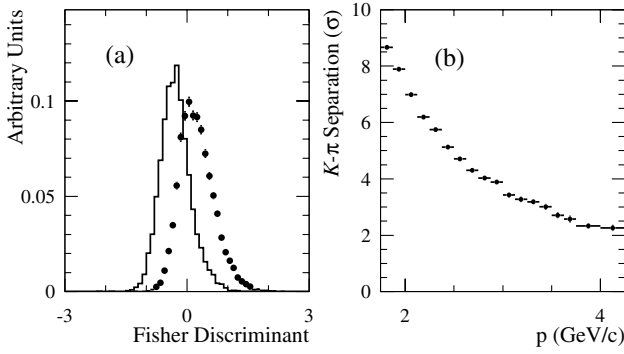


FIG. 1. (a) The distributions of the Fisher discriminant for Monte Carlo simulated $B^0 \rightarrow h^+ h'^-$ decays (histogram) and background events (points) in the m_{ES} sideband region $5.20 < m_{ES} < 5.27 \text{ GeV}/c^2$; (b) the K - π separation, in units of standard deviations, as a function of momentum, derived from the Cherenkov angle measurements of kaon and pion tracks in a $D^{*+} \rightarrow D^0 \pi^+$ control sample, as described in the text.

$(h^+ h'^-)$, $[-0.2, 0.15]$ ($h^+ \pi^0$), $[-0.115, 0.075]$ ($K_S^0 h^+$), and $[-0.2, 0.2]$ ($K_S^0 \pi^0$).

Detailed Monte Carlo simulation [12], off-resonance data, and events in on-resonance m_{ES} and ΔE sideband regions are used to study backgrounds. The contribution due to other B -meson decays, both from $b \rightarrow c$ and charmless decays, is found to be negligible. The largest background source is random combinations of tracks and neutrals produced in the $e^+ e^- \rightarrow q\bar{q}$ continuum (where $q = u, d, s$, or c). In the CM frame this background typically exhibits a two-jet structure in contrast to the spherically symmetric nature of $Y(4S) \rightarrow B\bar{B}$ events.

We exploit this topology difference by making use of two event-shape quantities. The first variable is the angle θ_S [10] between the sphericity axes of the B candidate and of the remaining tracks and photons in the event, computed in the CM frame. We require $|\cos\theta_S| < 0.9$, which rejects 66% of the background that remains at this stage of the analysis.

The second quantity is a Fisher discriminant \mathcal{F} constructed from the scalar sum of the CM momenta of all tracks and photons (excluding the B candidate decay products) flowing into nine concentric cones centered on the

thrust axis of the B candidate. Each cone subtends an angle of 10° and is folded to combine the forward and backward intervals. Monte Carlo samples are used to obtain the values of the coefficients, which are chosen to maximize the statistical separation between signal and background events. The distributions of \mathcal{F} for Monte Carlo simulated $B^0 \rightarrow h^+ h'^-$ decays and background events in the m_{ES} sideband region $5.20 < m_{ES} < 5.27 \text{ GeV}/c^2$ are displayed in Fig. 1(a).

The final reconstruction efficiencies range from 31% to 45%, depending on the mode. Table I shows the overall detection efficiencies, which include the branching fractions of $K^0 \rightarrow K_S^0 \rightarrow \pi^+ \pi^-$ and $\pi^0 \rightarrow \gamma\gamma$ [11].

Signal yields are determined from an unbinned maximum likelihood fit that uses m_{ES} , ΔE , \mathcal{F} , and θ_c (where applicable). Separate fits are performed for each of the four topologies, where the likelihood for a given candidate j is obtained by summing the product of event yield n_i and probability \mathcal{P}_i over all possible signal and background hypotheses i . The n_i are determined by maximizing the extended likelihood function \mathcal{L} :

$$\mathcal{L} = \exp\left(-\sum_{i=1}^M n_i\right) \prod_{j=1}^N \left[\sum_{i=1}^M n_i \mathcal{P}_i(\vec{x}_j; \vec{\alpha}_i) \right]. \quad (1)$$

The probabilities $\mathcal{P}_i(\vec{x}_j; \vec{\alpha}_i)$ are evaluated as the product of probability density functions (PDFs) for each of the independent variables \vec{x}_j , given the set of parameters $\vec{\alpha}_i$. Monte Carlo simulation is used to validate the assumption that the fit variables are uncorrelated. The exponential factor in the likelihood accounts for Poisson fluctuations in the total number of observed events N . For the $K^\pm \pi^\mp$, $\pi^\pm \pi^0$, $K^\pm \pi^0$, $K_S^0 \pi^\pm$, and $K_S^0 K^\pm$ terms, the yields are rewritten in terms of the sum $n_f + n_{\bar{f}}$ and the asymmetry $\mathcal{A} = (n_{\bar{f}} - n_f)/(n_{\bar{f}} + n_f)$, where n_f ($n_{\bar{f}}$) is the fitted number of events in the mode $B \rightarrow f$ ($\bar{B} \rightarrow \bar{f}$). The numbers of events, N , entering the maximum likelihood fit for each topology are 16 032 ($h^+ h'^-$), 16 452 ($h^+ \pi^0$), 3623 ($K_S^0 h^+$), and 1503 ($K_S^0 \pi^0$).

The parameters for background m_{ES} and ΔE PDFs are determined from events in on-resonance ΔE sideband regions. The signal m_{ES} and ΔE PDF parameters

TABLE I. Summary of results for detection efficiencies (ε), fitted signal yields (N_S), statistical significances (S), measured branching fractions (\mathcal{B}), and charge asymmetries. The efficiencies include the branching fractions for $K^0 \rightarrow K_S^0 \rightarrow \pi^+ \pi^-$ and $\pi^0 \rightarrow \gamma\gamma$. Equal branching fractions for $Y(4S) \rightarrow B^0 \bar{B}^0$ and $B^+ B^-$ are assumed. The 90% confidence level (C.L.) intervals for the charge asymmetries include the systematic uncertainties, which have been added in quadrature with the statistical errors.

Mode	ε (%)	N_S	S (σ)	$\mathcal{B}(10^{-6})$	\mathcal{A}	\mathcal{A} 90% C.L.
$\pi^+ \pi^-$	45	$41 \pm 10 \pm 7$	4.7	$4.1 \pm 1.0 \pm 0.7$		
$K^+ \pi^-$	45	$169 \pm 17 \pm 13$	15.8	$16.7 \pm 1.6 \pm 1.3$	$-0.19 \pm 0.10 \pm 0.03$	$[-0.35, -0.03]$
$K^+ K^-$	43	$8.2^{+7.8}_{-6.4} \pm 3.5$	1.3	< 2.5 90% C.L. ($0.85^{+0.81}_{-0.66} \pm 0.37$)		
$\pi^+ \pi^0$	32	$37 \pm 14 \pm 6$	3.4	< 9.6 90% C.L. ($5.1^{+2.0}_{-1.8} \pm 0.8$)		
$K^+ \pi^0$	31	$75 \pm 14 \pm 7$	8.0	$10.8^{+2.1}_{-1.9} \pm 1.0$	$0.00 \pm 0.18 \pm 0.04$	$[-0.30, +0.30]$
$K^0 \pi^+$	14	$59^{+11}_{-10} \pm 6$	9.8	$18.2^{+3.3}_{-3.0} \pm 2.0$	$-0.21 \pm 0.18 \pm 0.03$	$[-0.51, +0.09]$
$\bar{K}^0 K^+$	14	$-4.1^{+4.5}_{-3.8} \pm 2.3$...	< 2.4 90% C.L. ($-1.3^{+1.4}_{-1.0} \pm 0.7$)		
$K^0 \pi^0$	10	$17.9^{+6.8}_{-5.8} \pm 1.9$	4.5	$8.2^{+3.1}_{-2.7} \pm 1.2$		

are determined from fully reconstructed $B^+ \rightarrow \bar{D}^0 \pi^+$ and $B^+ \rightarrow \bar{D}^0 \rho^+$ ($\rho^+ \rightarrow \pi^+ \pi^0$) decays. Events in on-resonance m_{ES} sideband regions and Monte Carlo simulated signal decays are used to parametrize the Fisher discriminant PDFs for background and signal, respectively [see Fig. 1(a)]. Alternative parametrizations obtained from off-resonance data and Monte Carlo simulation are used as cross-checks and for determination of systematic uncertainties. The θ_c PDFs are derived from kaon and pion tracks in the momentum range of interest from approximately 42 000 $D^{*+} \rightarrow D^0 \pi^+$ ($D^0 \rightarrow K^- \pi^+$) decays. This control sample is used to parametrize the θ_c resolution σ_{θ_c} as a function of track polar angle. The resulting K - π separation, defined as $|\theta_c^K - \theta_c^\pi|/\sigma_{\theta_c}$, where θ_c^K (θ_c^π) is the expected Cherenkov angle for a kaon (pion), is shown as a function of momentum in Fig. 1(b).

The results of the fit are summarized in Table I, where the statistical error for each mode corresponds to a 68% confidence interval and is given by the change in signal yield n_i that corresponds to a $-2 \ln \mathcal{L}$ increase of one unit. Signal significance is defined as the square root of the change in $-2 \ln \mathcal{L}$ with the corresponding signal yield fixed to zero. For the three modes that have statistical significance less than 4σ we report Bayesian 90% confidence level upper limits. In addition, for the purpose of combining with measurements from other experiments, we report the branching fractions corresponding to the fitted signal yields. The upper limit on the signal yield for mode i is given by the value of n_i^0 for which $\int_0^{n_i^0} \mathcal{L}_{\max} dn_i / \int_0^\infty \mathcal{L}_{\max} dn_i = 0.90$, where \mathcal{L}_{\max} is the likelihood as a function of n_i , maximized with respect to the remaining fit parameters. Branching fraction upper limits are calculated by increasing the signal yield upper limit and reducing the efficiency by their respective systematic errors.

Figure 2 shows the distributions in m_{ES} and ΔE for events passing the selection criteria, as well as requirements on likelihood ratios, which are used to increase the relative fraction of signal events of a given type. These likelihood ratios are defined for a given topology as $\mathcal{R}_{\text{sig}} = \sum_s n_s \mathcal{P}_s / \sum_i n_i \mathcal{P}_i$ and $\mathcal{R}_k = n_k \mathcal{P}_k / \sum_s n_s \mathcal{P}_s$, where \sum_s denotes the sum over the probabilities for signal hypotheses only, \sum_i denotes the sum over all the probabilities (signal and background), and \mathcal{P}_k denotes the probability for signal hypothesis k . These probabilities are constructed from all the PDFs except that describing the displayed variable. The likelihood fit projections, scaled by the relative efficiencies for the likelihood ratio requirements, are overlaid on each distribution.

Systematic uncertainties arise from imperfect knowledge of the PDF shapes, which affects both branching fraction and charge asymmetry measurements; uncertainties in the detection efficiencies; and potential charge bias in track reconstruction and particle identification.

The largest source of systematic error is due to uncertainty in the PDF shapes, except in $B^+ \rightarrow K^+ \pi^0$ where it is due to the 5% uncertainty on π^0 reconstruction efficiency. Systematic errors due to PDF shapes are estimated

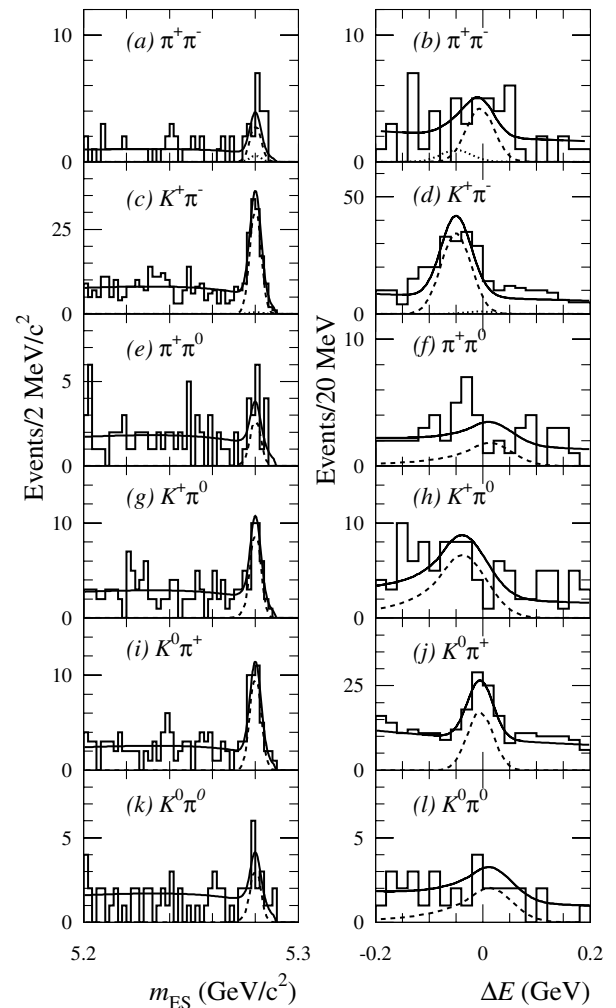


FIG. 2. The m_{ES} and ΔE distributions for the various modes, using likelihood ratio requirements described in the text. The solid curves represent the fit predictions for both signal and background; the dashed curve represents the given signal mode only and the dotted curve represents other modes of the same topology.

either by varying the parameters within 1 standard deviation, or by substituting alternative parameter sets obtained from off-resonance data, or $B^+ \rightarrow \bar{D}^0 \pi^+$ (ρ^+) decays in the on-resonance sample. Systematic errors in the signal yields due to PDF uncertainties depend on decay mode as shown in Table I.

The D^{*+} control sample of kaon and pion tracks is used to estimate systematic uncertainties in the asymmetries arising from possible charge biases in the θ_c quality requirements and from differences in θ_c reconstruction for different charge species. From these studies we conservatively assign a systematic uncertainty of ± 0.01 on \mathcal{A} for all modes. Charge asymmetries in the detector and track reconstruction chain are shown to be less than 0.005 with high statistics samples of charged tracks in multihadron events. We assign an overall systematic uncertainty of ± 0.01 on \mathcal{A} for possible charge-correlated biases in track reconstruction and particle identification. All measured background asymmetries are consistent with zero with

statistical uncertainties less than 0.03. The fitted signal yields and asymmetries for off-resonance data and on-resonance ΔE sidebands are also consistent with zero.

The overall systematic errors on the branching fractions and charge asymmetry measurements are computed by adding in quadrature the PDF systematic uncertainties and the systematic uncertainties on the efficiencies or because of possible charge biases, respectively.

In summary, we have measured branching fractions for the rare charmless decays $B^0 \rightarrow \pi^+ \pi^-$, $B^0 \rightarrow K^+ \pi^-$, $B^+ \rightarrow K^+ \pi^0$, $B^+ \rightarrow K^0 \pi^+$, and $B^0 \rightarrow K^0 \pi^0$, and set upper limits on $B^0 \rightarrow K^+ K^-$, $B^+ \rightarrow \pi^+ \pi^0$, and $B^+ \rightarrow \bar{K}^0 K^+$. We find no evidence for direct CP violation in the observed decays and set 90% confidence level intervals. These measurements are in good agreement with existing results [6,7,13].

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