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Measurements of Branching Fractions and *CP*-Violating Asymmetries in *B* Meson Decays to Charmless Two-Body States Containing a K^0

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We present measurements of branching fractions and *CP*-violating asymmetries in decays of B mesons to two-body final states containing a K^0. The results are based on a data sample of approximately 88 million $\Upsilon(4S) \to B\overline{B}$ decays collected with the *BABAR* detector at the PEP-II asymmetric-energy B Factory at SLAC. We measure $\mathcal{B}(B^+ \to K^0\pi^+) = (22.3 \pm 1.7 \pm 1.1) \times 10^{-6}$, $\mathcal{B}(B^0 \to K^0\pi^0) = (11.4 \pm 1.7 \pm 0.8) \times 10^{-6}$, $\mathcal{B}(B^+ \to \overline{K}^0K^+) < 2.5 \times 10^{-6}$, and $\mathcal{B}(B^0 \to K^0\overline{K}^0) < 1.8 \times 10^{-6}$, where the first uncertainty is statistical and the second is systematic, and the upper limits are at the 90% confidence level. In addition, the following *CP*-violating asymmetries have been measured: $\mathcal{A}_{CP}(B^+ \to K^0\pi^+) = -0.05 \pm 0.08 \pm 0.01$ and $\mathcal{A}_{CP}(B^0 \to K^0\pi^0) = 0.03 \pm 0.36 \pm 0.11$.

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The decays of B mesons into charmless hadronic final states provide important information for the study of *CP* violation. In particular, the study of the two-body decays $B \to \pi\pi$, $B \to K\pi$, and $B \to KK$ provides crucial ingredients for measuring or constraining the values of the angles α and γ, defined by the ratios of various elements of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix [1]: $\alpha \equiv \arg\left[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*\right]$ and $\gamma \equiv \arg\left[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right]$. In this paper, we present measurements of the branching fractions for B meson decays to the charmless two-body final states $K^0\pi^+$, $\overline{K}^0K^+$, $K^0\pi^0$, and $K^0\overline{K}^0$ (unless explicitly stated otherwise, charge conjugate decay modes are assumed throughout this paper and branching fractions are averaged accordingly). For the $B^+ \to K^0\pi^+$ and $B^0 \to K^0\pi^0$ modes we also report measurements of the direct *CP* asymmetries in the decay rates:

$$\mathcal{A}_{CP} = \frac{\Gamma\left(\overline{B} \to \bar{f}\right) - \Gamma\left(B \to f\right)}{\Gamma\left(\overline{B} \to \bar{f}\right) + \Gamma\left(B \to f\right)}. \qquad (1)$$

Measurement of the rates and charge asymmetries for $B \to K\pi$ decays can be used to establish direct *CP* violation and to constrain the angle γ [2]. The decay $B^+ \to K^0\pi^+$ is dominated by the $b \to s$ penguin process and in the Standard Model (SM) is expected to have $\mathcal{A}_{CP}$ close to zero ($< 1\%$) [3]. Thus, observation of a sizable charge asymmetry could be an indication of non-SM contributions to the penguin loop [3, 4]. The $B \to K\overline{K}$ decays are characterized by penguin and W-exchange processes similar to those in $B^0 \to \pi^+\pi^-$ and can be used [5] to determine the angle α from the measurement of the time-dependent asymmetries in $B^0 \to \pi^+\pi^-$. Measurements of the branching fractions for these decay modes also provide important information [6] regarding rescattering processes.

The measurements presented in this paper are based on data collected with the *BABAR* detector [7] at the PEP-II asymmetric-energy e^+e^- collider [8] located at the Stanford Linear Accelerator Center. The sample consists of 87.9 ± 1.0 million $B\overline{B}$ pairs produced at the $\Upsilon(4S)$ resonance ("on-resonance"), which corresponds to an integrated luminosity of about $81\,\mathrm{fb}^{-1}$. An additional $9\,\mathrm{fb}^{-1}$ of data recorded at an e^+e^- center-of-mass (CM) energy approximately $40\,\mathrm{MeV}$ below the $\Upsilon(4S)$ resonance ("off-resonance") are used for background studies.

The *BABAR* detector is described in detail in Ref. [7]. Charged-particle (track) momenta are measured in a tracking system consisting of a five-layer, double-sided silicon vertex detector and a 40-layer drift chamber (DCH), which operate in a solenoidal magnetic field of $1.5\,rmT$. Particles are identified as pions or kaons based on the Cherenkov angle measured with a detector of internally reflected Cherenkov light (DIRC). The direction and energy of photons are determined from the energy deposits in a segmented CsI(Tl) electromagnetic calorimeter (EMC).

Hadronic events are selected on the basis of charged-particle multiplicity and event topology. We reconstruct B-meson candidates decaying to K^0X, where X refers to π^+, π^0, K^- or $\overline{K}^0$. The K^0 and π^0 candidates are reconstructed in the modes $K^0 \to K_S^0 \to \pi^+\pi^-$ and $\pi^0 \to \gamma\gamma$, respectively. The following selection criteria are applied to the candidate B-decay products.

Charged tracks are required to be within the tracking fiducial volume and to have at least 12 DCH hits and a minimum transverse momentum of $0.1\,\mathrm{GeV}/c$. Tracks that are not K_S^0 decay products are also required to originate from the interaction point, to be associated with at least six Cherenkov photons in the DIRC and to have a Cherenkov angle within $4\,\sigma$ of the expected value for a pion or kaon.

Candidate K_S^0 mesons are reconstructed from pairs of oppositely charged tracks that form a vertex with $\pi^+\pi^-$ invariant mass within $3.5\,\sigma$ of the nominal K_S^0 mass and measured proper decaytime greater than five times its uncertainty.

Candidate π^0 mesons are formed from pairs of photons having invariant mass within $3\,\sigma$ of the nominal π^0 mass, where the resolution is about $8\,\mathrm{MeV}/c^2$ for the candidates of interest. Photon candidates are required to not be matched to a track, to have an energy of at least $30\,\mathrm{MeV}$, and to have the lateral shower shape expected for a photon. The π^0 candidates are then kinematically fit with their mass constrained to the nominal π^0 mass.

The B-meson candidate is characterized by two nearly independent kinematic variables, the energy-substituted mass $m_{\mathrm{ES}} = \sqrt{\left(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B\right)^2/E_i^2 - p_B^2}$ and the energy difference $\Delta E = E_B^* - \sqrt{s}/2$, where the subscripts i and B refer to the initial e^+e^- system and the B candidate, respectively, the asterisk denotes the $\Upsilon(4S)$ rest frame, and $\sqrt{s}$ is the total CM energy. The pion mass is assigned to all charged particles in calculating E_B^*. For $B^0 \to K^0\overline{K}^0$ and $B^0 \to K^0\pi^0$ candidates, we require $|\Delta E| < 0.11\,\mathrm{GeV}$ and $|\Delta E| < 0.15\,\mathrm{GeV}$, respectively. For $B^+ \to K^0h^+$ candidates, where h refers to π or K, we require $-0.115 < \Delta E < 0.075\,\mathrm{GeV}$. The interval is asymmetric in order to select both $B^+ \to K^0\pi^+$ and $B^+ \to \overline{K}^0K^+$ decays with nearly 100% efficiency. The ΔE distribution is peaked near zero for the modes with no charged kaons and shifted on average $-45\,\mathrm{MeV}$ for $B^+ \to \overline{K}^0K^+$ decays due to the pion mass being used for the charged B daughter in the calculation. The distribution of m_{ES} peaks near the B mass for all modes, and we require $5.20 < m_{\mathrm{ES}} < 5.29\,\mathrm{GeV}/c^2$.

Simulated events [9], off-resonance data, and events in on-resonance m_{ES} and ΔE sideband regions are used to study backgrounds. The contribution from other B-meson decays is found to be negligible. The primary background is from random combinations of tracks and neutral clusters produced in the $e^+e^- \to q\overline{q}$ events, where $q = u$, d, s, or c. In the CM frame, this background is characterized by its jet structure, in contrast to the more uniformly distributed decays of the B mesons produced in the $\Upsilon(4S)$ decays. We exploit this topological difference to suppress such background. We require that the angle θ_S^* between the sphericity axes of the B candidate and of the remaining particles in the event, in the CM frame, satisfies $|\cos\theta_S^*| < 0.8$. We also construct a Fisher discriminant $\mathcal{F}$ given by an optimized linear combination of $\sum_i p_i^*$ and $\sum_i p_i^* \cos^2\theta_i^*$ [10], where p_i^* is the momentum of particle i and θ_i^* is the angle between its momentum and the B-candidate thrust axis, both calculated in the CM frame. The shapes of $\mathcal{F}$ for signal and background events are included as probability density functions (PDFs) in the fits described below.

Signal yields and charge asymmetries are determined from unbinned extended maximum likelihood fits. The extended likelihood for a sample of N K^0X candidates is

$$\mathcal{L} = \exp\left(-\sum_i n_i\right) \prod_{j=1}^{N} \left[\sum_i N_i \mathcal{P}_i(\vec{x}_j;\vec{\alpha}_i)\right], \qquad (2)$$

where $\mathcal{P}_i(\vec{x}_j;\vec{\alpha}_i)$ is the probability for a signal or background category i, given by a product of PDFs for the measured variables $\vec{x}_j$ of candidate j. The parameters $\vec{\alpha}_i$ determine the expected distributions of measured variables in each category and n_i are the yields determined from the fit. We perform separate fits for each of the three samples of B candidates: $B^0 \to K^0\pi^0$, $B^0 \to K^0\overline{K}^0$, and $B^+ \to K^0h^+$ ($h^+ = \pi^+$ or K^+). For the two neutral B samples there are two categories, signal and background, and the yield in each category is obtained by maximizing the likelihood. For these fits the probability coefficients N_i are the yields (i.e., $N_i = n_i$). The charged B decays, $B^+ \to K^0h^+$, are fit simultaneously with two signal categories, $B^+ \to K^0\pi^+$ and $B^+ \to \overline{K}^0K^+$, and two corresponding background categories. In addition, the probability coefficient for each category i is given by $N_i = n_i\,(1 - q_j\mathcal{A}_i)$, where n_i is the *total* yield, summed over charge states, $\mathcal{A}_i$ is the charge asymmetry, and q_j is the measured charge of the given B candidate. The total yields and charge asymmetries are determined by maximizing $\mathcal{L}$.

The independent input variables to the fit $\vec{x}_j$ for a given event j are m_{ES}, ΔE, and $\mathcal{F}$. For the fit to the $B^+ \to K^0h^+$ sample we include the normalized Cherenkov residuals $(\theta_c - \theta_c^\pi)/\sigma_{\theta_c}$ and $\left(\theta_c - \theta_c^K\right)/\sigma_{\theta_c}$, where θ_c is the measured Cherenkov angle of the primary daughter h^+, σ_{θ_c} is its error and θ_c^π (θ_c^K) is the expected Cherenkov angle for a pion (kaon). The quantities σ_{θ_c}, θ_c^π, and θ_c^K are measured separately for negatively and positively charged pions and kaons from a control sample of $D^0 \to K^-\pi^+$ originating from D^{*+} decays.

The parameterizations of the PDFs are determined from a combination of data and simulated events. The signal m_{ES} PDFs for $B^+ \to K^0h^+$ and $B^0 \to K^0\overline{K}^0$ are derived from fully reconstructed $B^+ \to \overline{D}^0\pi^+$ decays and are Gaussian. For $B^0 \to K^0\pi^0$, simulated signal events are employed and the m_{ES} PDF is modeled as a Gaussian distribution with a low-side power-law tail. We use an empirical threshold function [11] to describe the background m_{ES} PDFs. The single shape parameter of this function is a free parameter in the $B^+ \to K^0h^+$ and $B^0 \to K^0\pi^0$ fits, where the event sample is sufficiently large. For the $B^0 \to K^0\overline{K}^0$ fit this shape parameter is determined from on-resonance events in ΔE sidebands.

The $\mathcal{F}$ distribution for signal is modeled as a Gaussian function with an asymmetric width [12], where the parameters are determined from simulated events. For background, it is modeled as a sum of two Gaussian functions with parameters determined from on-resonance events in m_{ES} sidebands.

The signal ΔE PDFs are derived from simulated events and are parameterized as a sum of two Gaussian functions for the modes $B^+ \to K^0h^+$ and $B^0 \to K^0\overline{K}^0$, and as a Gaussian distribution with a low-side power-law tail for $B^0 \to K^0\pi^0$. The ΔE distribution for background is modeled as a second-order polynomial whose parameters are determined from on-resonance events in m_{ES} sidebands. The normalized Cherenkov-angle residuals are modeled as a sum of two Gaussian functions.

The results of the maximum likelihood fits are summarized in Table I. The $K^0\overline{K}^0$ final state is an equal admixture of $K_S^0K_S^0$ and $K_L^0K_L^0$. We therefore assume a 50% probability for the $K^0\overline{K}^0$ to decay as $K_S^0K_S^0$ in computing the $B^0 \to K^0\overline{K}^0$ branching fraction. We also use the current world averages [13] for $\mathcal{B}(K_S^0 \to \pi^+\pi^-)$ and $\mathcal{B}(\pi^0 \to \gamma\gamma)$ in computing the branching fractions given

TABLE I: Summary of results for numbers of selected K^0X candidates N, total detection efficiencies ε, fitted signal yields N_S, statistical significances S, charge-averaged branching fractions $\mathcal{B}$, charge asymmetries $\mathcal{A}_{CP}$, and 90% confidence-level (C.L.) allowed asymmetry intervals. The efficiencies include the branching fractions for intermediate states ($K^0 \to K^0_S \to \pi^+\pi^-$ and $\pi^0 \to \gamma\gamma$). Branching fractions are calculated assuming equal rates for $\Upsilon(4S) \to B^0\overline{B}^0$ and B^+B^-. Upper limits for the $\overline{K}^0K^+$ and $K^0\overline{K}^0$ branching fractions correspond to the 90% C.L. and the central values are given in parentheses.

Mode	N	ε (%)	N_S	$S(\sigma)$	$\mathcal{B}(10^{-6})$	$\mathcal{A}_{CP}$	$\mathcal{A}_{CP}$ (90% C.L.)
$K^0\pi^+$	8047	13.0 ± 0.3	$255 \pm 20^{+11}_{-9}$	22	$22.3 \pm 1.7 \pm 1.1$	$-0.05 \pm 0.08 \pm 0.01$	$[-0.18, 0.08]$
$\overline{K}^0K^+$		12.8 ± 0.3	$12.4 \pm 8.4^{+1.6}_{-2.0}$	1.7	$< 2.5\,(1.1 \pm 0.75^{+0.14}_{-0.18})$		
$K^0\pi^0$	2668	8.6 ± 0.5	$86 \pm 13 \pm 3$	12	$11.4 \pm 1.7 \pm 0.8$	$0.03 \pm 0.36 \pm 0.11$	$[-0.59, 0.65]$
$K^0\overline{K}^0$	754	8.7 ± 0.3	$4.3^{+5.2}_{-4.1} \pm 1.1$	1.0	$< 1.8\,(0.6^{+0.7}_{-0.5} \pm 0.1)$		

in Table I.

Figure 1 shows distributions of $m_{\rm ES}$ and ΔE for $B^+ \to K^0\pi^+$ and $B^0 \to K^0\pi^0$ candidates after selecting on probability ratios to enhance the signal purity. The solid curves represent the fit projections after having corrected for the efficiency of the additional selection. The efficiencies for these $m_{\rm ES}$ (ΔE) selection criteria are 70% (93%) and 65% (98%) for the $K^0\pi^+$ and $K^0\pi^0$ states, respectively, as determined from simulated signal events.

Signal significance is defined as the square root of the difference between $-2\ln\mathcal{L}$ for the best fit and for the null-signal hypothesis. The upper limit on the signal yield for a given mode i is defined as the value of $n_i^{\rm ul}$ for which $\int_0^{n_i^{\rm ul}} \mathcal{L}_{\rm max} dn_i / \int_0^{\infty} \mathcal{L}_{\rm max} dn_i = 0.9$, where $\mathcal{L}_{\rm max}$ is the likelihood as a function of n_i, maximized with respect to the remaining fit parameters. Branching fraction upper limits are then calculated by increasing the signal yield upper limit and reducing the efficiency by their respective systematic uncertainties.

For the $B^0 \to K^0\pi^0$ mode, which is a *CP* eigenstate, we measure the time-integrated *CP* asymmetry by determining whether the *other* B meson in the event decayed as a B^0 or $\overline{B}^0$ (flavor tag). The tagging algorithm is described in Ref. [14]. The measured asymmetry $\mathcal{A}_{\rm meas}$ is given by $\mathcal{A}_{CP}/(1+x_d^2)$, where $x_d = 0.755 \pm 0.015$ [13] is the B^0 mixing parameter. The dilution of the *CP* asymmetry by the factor $1/(1+x_d^2)$ is due to the effect of B^0-$\overline{B}^0$ mixing in the time evolution of the coherent B^0 $\overline{B}^0$ system.

Systematic uncertainties in the signal yields arise primarily from imperfect knowledge of the PDF shapes. Such systematic errors are evaluated either by varying the PDF parameters by their measured ($1\,\sigma$) uncertainties or by substituting alternative PDFs from independent control samples. The dominant systematic uncertainty of this type is that associated with the signal Fisher discriminant for both $B^+ \to K^0\pi^+$ (± 7.1 events) and $B^0 \to K^0\pi^0$ (± 1.4 events). Also contributing to the systematic uncertainties in the branching fraction measurements are the uncertainties in the K^0_S and π^0 efficiencies, which are about 3% and 5%, respectively. The systematic uncertainties in the charge asymmetries are evaluated by adding in quadrature the contributions from PDF variations and the upper limit on intrinsic charge bias in the detector (± 0.01). For the measurement of $\mathcal{A}_{CP}$ in the decay $B^0 \to K^0\pi^0$, there is an additional contribution of ± 0.07 due to uncertainties in the tagging efficiencies and mistag fractions.

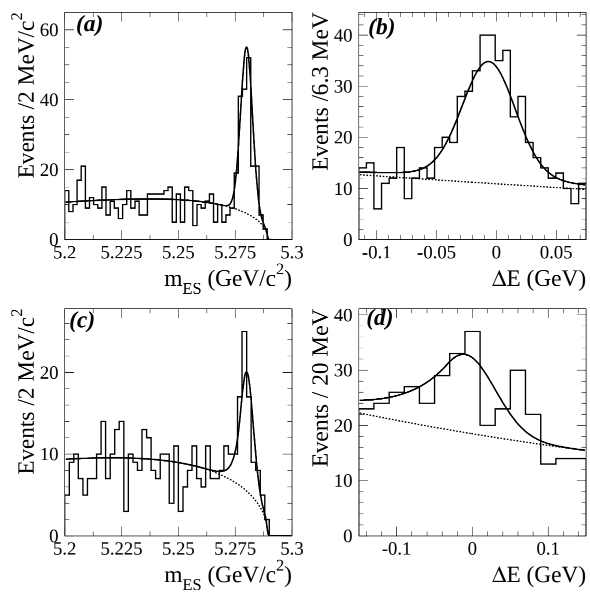

FIG. 1: Distributions of $m_{\rm ES}$ and ΔE for (a,b) $B^+ \to K^0\pi^+$ and (c,d) $B^0 \to K^0\pi^0$ candidates that satisfy an optimized requirement on the signal probability, based on all the variables except the one being plotted. The solid curves are projections of the fit, while the dashed curves show the background contribution.

In summary, we have measured the branching fractions and *CP*-violating charge asymmetries for $B^+ \to K^0\pi^+$ and $B^0 \to K^0\pi^0$. No evidence of direct *CP* violation has been observed. We have also searched for the decays $B^0 \to \overline{K}^0K^+$ and $B^0 \to K^0\overline{K}^0$ and set upper limits on their branching fractions at 2.5×10^{-6} and 1.8×10^{-6}, respectively, at the 90% C.L. The branching fraction measurements reported here are consistent with previous measurements of the same quantities [15–17], but have nearly twice the statistical precision. Our measured $B^+ \to K^0\pi^+$ charge asymmetry is of the same statistical precision and consistent with the value recently reported [18] by the Belle collaboration. All of the aforementioned results supersede our previous measurements [16], apart from the $B^0 \to K^0\pi^0$ charge asymmetry, which has not previously been measured.

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