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Measurements of Branching Fractions and Time-Dependent CP-Violating Asymmetries in $B \to \eta' K$ Decays

The *BABAR* Collaboration

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Abstract

We present measurements of the $B \to \eta' K$ branching fractions; for $B^+ \to \eta' K^+$ we measure also the time-integrated charge asymmetry $\mathcal{A}_{ch}$, and for $B^0 \to \eta' K^0_S$ the time dependent CP-violation parameters S and C. The data sample corresponds to 232 million $B\overline{B}$ pairs produced by e^+e^- annihilation at the $\Upsilon(4S)$. The results are $\mathcal{B}(B^+ \to \eta' K^+) = (68.9 \pm 2.0 \pm 3.2) \times 10^{-6}$, $\mathcal{B}(B^0 \to \eta' K^0) = (67.4 \pm 3.3 \pm 3.2) \times 10^{-6}$, $\mathcal{A}_{ch} = 0.033 \pm 0.028 \pm 0.005$, $S = 0.30 \pm 0.14 \pm 0.02$, and $C = -0.21 \pm 0.10 \pm 0.02$, where the first error quoted is statistical and the second systematic.

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Measurements of time-dependent CP asymmetries in B^0 meson decays through a Cabibbo-Kobayashi-Maskawa (CKM) favored $b \to c\bar{c}s$ amplitude [1] have provided a crucial test of the mechanism of CP violation in the Standard Model (SM) [2]. Such decays to a charmonium state plus a K^0 meson are dominated by a single weak phase. Decays of B^0 mesons to charmless hadronic final states, such as ϕK^0, $K^+K^-K^0$, $\eta' K^0$, $\pi^0 K^0$ and $f_0(980)K^0$, proceed mostly via a single penguin (loop) amplitude with the same weak phase [3], but CKM-suppressed amplitudes and multiple particles in the loop introduce other weak phases whose contribution is not negligible [4, 5, 6, 7, 8].

For the decay $B^0 \to \eta' K^0$, these additional contributions are expected to be small, so the time-dependent asymmetry measurement for this decay provides an approximate measurement of sin2β. Theoretical bounds for the small deviation ΔS between the time-dependent CP-violating parameter measured in this decay and in the charmonium K^0 decays have been calculated with an SU(3) analysis [4, 5]. Such bounds have been improved by measurements of B^0 decays to a pair of neutral light pseudoscalar mesons [9, 10]. From these and other measurements, improved model-independent bounds have been derived [6], with the conclusion that ΔS is expected to be less than 0.10 (with a theoretical uncertainty less than $\sim$0.03). Specific model calculations conclude that ΔS is even smaller [7]. A significantly larger ΔS could arise from non-SM amplitudes [8].

The time-dependent CP-violating asymmetry in the decay $B^0 \to \eta' K^0$ has been measured previously by the *BABAR* [11] and Belle [12] experiments. In this Letter we update our previous measurements with an improved analysis and a data sample four times larger . We also measure the $B^0 \to \eta' K^0$ and $B^+ \to \eta' K^+$ branching fractions [13], and for $B^+ \to \eta' K^+$ the time-integrated charge asymmetry $\mathcal{A}_{ch} = (\Gamma^- - \Gamma^+)/(\Gamma^- + \Gamma^+)$ where $\Gamma^\pm = \Gamma(B^\pm \to \eta' K^\pm)$. In the SM $\mathcal{A}_{ch}$ is expected to be small; a non-zero value would signal direct CP violation in this channel.

The data were collected with the *BABAR* detector [14] at the PEP-II asymmetric e^+e^- collider [15]. An integrated luminosity of 211 fb^{-1}, corresponding to 232 million $B\overline{B}$ pairs, was recorded at the $\Upsilon(4S)$ resonance (center-of-mass energy $\sqrt{s} = 10.58$ GeV). Charged particles are detected and their momenta measured by the combination of a silicon vertex tracker (SVT), consisting of five layers of double-sided detectors, and a 40-layer central drift chamber, both operating in the 1.5 T magnetic field of a solenoid. Charged-particle identification (PID) is provided by the average energy loss in the tracking devices and by an internally reflecting ring-imaging Cherenkov detector (DIRC) covering the central region. Photons and electrons are detected by a CsI(Tl) electromagnetic calorimeter.

From a candidate $B\overline{B}$ pair we reconstruct a B^0 decaying into the flavor eigenstate $f = \eta' K^0_S$ (B_{CP}). We also reconstruct the vertex of the other B meson ($B_{\rm tag}$) and identify its flavor. The difference $\Delta t \equiv t_{CP} - t_{\rm tag}$ of the proper decay times t_{CP} and $t_{\rm tag}$ of the CP and tag B mesons, respectively, is obtained from the measured distance between the B_{CP} and $B_{\rm tag}$ decay vertices and from the boost ($\beta\gamma = 0.56$) of the e^+e^- system. The Δt distribution is given by:

$$F(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}[1 \mp \Delta w \pm (1-2w)\left(S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)\right)]. \quad (1)$$

The upper (lower) sign denotes a decay accompanied by a B^0 ($\overline{B}^0$) tag, τ is the mean

B^0 lifetime, Δm_d is the mixing frequency, and the mistag parameters w and Δw are the average and difference, respectively, of the probabilities that a true B^0 is incorrectly tagged as a $\overline{B}^0$ or vice versa. The tagging algorithm [16] has seven mutually exclusive tagging categories of differing response purities (including one for untagged events that we retain for yield determinations). The measured analyzing power, defined as efficiency times $(1-2w)^2$ summed over all categories, is $(30.5\pm0.6)\%$, as determined from a large sample of B-decays to fully reconstructed flavor eigenstates ($B_{\rm flav}$). The parameter C measures direct CP violation. If $C=0$, then $S=\sin2\beta+\Delta S$.

Monte Carlo (MC) simulations [17] of the signal decay modes, $B\overline{B}$ backgrounds, and detector response are used to tailor the event selection criteria. We reconstruct B meson candidates by combining a K^+ or a K^0_S with an η' meson. We reconstruct η' mesons through the decays $\eta'\to\rho^0\gamma$ ($\eta'_{\rho\gamma}$) and $\eta'\to\eta\pi^+\pi^-$ with $\eta\to\gamma\gamma$ ($\eta'_{\eta(\gamma\gamma)\pi\pi}$) or $\eta\to\pi^+\pi^-\pi^0$ ($\eta'_{\eta(3\pi)\pi\pi}$). For the K^+ track we require an associated DIRC Cherenkov angle between -5 and $+2$ standard deviations (σ) from the expected value for a kaon. We select $K^0_S\to\pi^+\pi^-$ decays by requiring the $\pi^+\pi^-$ invariant mass to be within 12 MeV of the nominal K^0 mass and by requiring a flight length with significance $>3\sigma$. We select $K^0_S\to\pi^0\pi^0$ decays by requiring that the $\pi^0\pi^0$ invariant mass be within 30 MeV of the nominal K^0 mass. Daughter pions from η' decays are required to have PID information inconsistent with proton, electron and kaon hypotheses. The photon energy E_γ must be greater than 30 MeV for π^0 candidates, 50 (100) MeV for η candidates for the $\eta'_{\eta(\gamma\gamma)\pi\pi}K^0$ ($\eta'_{\eta(\gamma\gamma)\pi\pi}K^+$) samples, and greater than 100 MeV for $\eta'_{\rho\gamma}$ candidates. We make the following requirements on the invariant mass (in MeV): $490<m_{\gamma\gamma}<600$ for $\eta\to\gamma\gamma$, $120<m_{\gamma\gamma}<150$ for π^0 ($100<m_{\gamma\gamma}<155$ in $K^0_S\to\pi^0\pi^0$), $510<m_{\pi\pi}<1000$ for ρ^0, $520<m_{\pi\pi\pi}<570$ for $\eta\to\pi^+\pi^-\pi^0$, $945<m_{\eta'}<970$ for $\eta'_{\eta(\gamma\gamma)\pi\pi}$, and $930<m_{\eta'}<980$ for $\eta'_{\rho\gamma}$.

A B meson candidate is characterized kinematically by the energy-substituted mass $m_{\rm ES}\equiv\sqrt{(\frac{1}{2}s+\mathbf{p}_0\cdot\mathbf{p}_B)^2/E_0^2-\mathbf{p}_B^2}$ and the energy difference $\Delta E\equiv E_B^*-\frac{1}{2}\sqrt{s}$, where $(E_0,\mathbf{p}_0)$ and $(E_B,\mathbf{p}_B)$ are four-momenta of the $\Upsilon(4S)$ and the B candidate, respectively, and the asterisk denotes the $\Upsilon(4S)$ rest frame. We require $|\Delta E|\leq0.2$ GeV and $5.25\leq m_{\rm ES}\leq 5.29$ GeV.

To reject the dominant background from continuum $e^+e^-\to q\bar{q}$ events ($q=u,d,s,c$), we use the angle θ_T between the thrust axis of the B candidate and that of the rest of the tracks and neutral clusters in the event, calculated in the $\Upsilon(4S)$ rest frame. The distribution of $\cos\theta_T$ is sharply peaked near ±1 for combinations drawn from jet-like $q\bar{q}$ pairs and is nearly uniform for the isotropic B decays; we require $|\cos\theta_T|<0.9$. From Monte Carlo simulations of $B^0\overline{B}^0$ and B^+B^- events, we find evidence for a small (1–2%) $B\overline{B}$ background contribution for the channels with $\eta'\to\rho^0\gamma$, so we have added a $B\overline{B}$ component to the fit described below for those channels.

We use an unbinned, multivariate maximum-likelihood fit to extract signal yields and CP-violation parameters. We indicate with j the species of event: signal, $q\bar{q}$ combinatorial background, or $B\overline{B}$ background. We use four discriminating variables: $m_{\rm ES}$, ΔE, Δt, and a Fisher discriminant $\mathcal{F}$ [18]. The Fisher discriminant combines four variables: the angles with respect to the beam axis of the B momentum and B thrust axis in the $\Upsilon(4S)$ rest frame, and the zeroth and second angular moments of the energy flow, excluding the B candidate, about the B thrust axis [19].

For each species j and tagging category c, we define a total probability density function (PDF) for event i as

$$\mathcal{P}_{j,c}^{i} \equiv \mathcal{P}_j({m_{\rm ES}}^i) \cdot \mathcal{P}_j(\Delta E^i) \cdot \mathcal{P}_j(\mathcal{F}^i) \cdot \mathcal{P}_j(\Delta t^i, \sigma_{\Delta t}^i; c)\,, \tag{2}$$

where $\sigma_{\Delta t}^i$ is the error on Δt for event i. With n_j defined to be the number of events of the species j and $f_{j,c}$ the fraction of events of species j for each category c, we write the extended likelihood function for all events belonging to category c as

$$\mathcal{L}_c = \exp\Big(-\sum_j n_{j,c}\Big)\prod_i^{N_c}(n_{\rm sig} f_{{\rm sig},c}\mathcal{P}_{{\rm sig},c}^i + n_{q\bar{q}} f_{q\bar{q},c}\mathcal{P}_{q\bar{q}}^i + n_{B\bar{B}} f_{B\bar{B},c}\mathcal{P}_{B\bar{B}}^i), \tag{3}$$

where $n_{j,c}$ is the yield of events of species j found by the fitter in category c and N_c the number of events of category c in the sample. We fix both $f_{{\rm sig},c}$ and $f_{B\bar{B},c}$ to $f_{B_{\rm flav},c}$, the values measured with the large $B_{\rm flav}$ sample [20]. The total likelihood function $\mathcal{L}_d$ for decay mode d is given as the product over the seven tagging categories. Finally, when combining decay modes we form the grand likelihood $\mathcal{L} = \prod \mathcal{L}_d$.

The PDF $\mathcal{P}_{\rm sig}(\Delta t,\, \sigma_{\Delta t}; c)$, for each category c, is the convolution of $F(\Delta t;\, c)$ (Eq. 1) with the signal resolution function (sum of three Gaussians) determined from the $B_{\rm flav}$ sample. The other PDF forms are: the sum of two Gaussians for $\mathcal{P}_{\rm sig}(m_{\rm ES})$ and $\mathcal{P}_{\rm sig}(\Delta E)$; the sum of three Gaussians for $\mathcal{P}_{q\bar{q}}\,(\Delta t; c)$; a conjunction of two Gaussians with different widths below and above the peak for $\mathcal{P}_j(\mathcal{F})$ (a small "tail" Gaussian is added for $\mathcal{P}_{q\bar{q}}\,(\mathcal{F})$); a linear dependence for $\mathcal{P}_{q\bar{q}}\,(\Delta E)$; and for $\mathcal{P}_{q\bar{q}}\,(m_{\rm ES})$ the function $x\sqrt{1-x^2}\exp\left[-\xi(1-x^2)\right]$, with $x \equiv 2m_{\rm ES}/\sqrt{s}$.

For the signal and $B\overline{B}$ background components we determine the PDF parameters from simulation. For the $q\bar{q}$ background we use $(m_{\rm ES}, \Delta E)$ sideband data to obtain initial values and ultimately leave them free to vary in the final fit.

We compute the branching fractions and charge asymmetry from fits made without Δt or flavor tagging, applied to candidates with $\eta^\prime_{\eta(\gamma\gamma)\pi\pi}$ and $\eta^\prime_{\rho\gamma}$ combined with K^+ or $K_S^0 \to \pi^+\pi^-$. The free parameters in the fit are: the signal and $q\bar{q}$ background yields, the peak position and lower and upper width parameters of $\mathcal{P}_j(\mathcal{F})$ for signal and $q\bar{q}$ background, the tail fraction for $\mathcal{P}_{q\bar{q}}\,(\mathcal{F})$, the slope of $\mathcal{P}_{q\bar{q}}\,(\Delta E)$ and ξ, the width of the core Gaussian of $\mathcal{P}_{\rm sig}(\Delta E)$, the mean of the core Gaussian of $\mathcal{P}_{\rm sig}(m_{\rm ES})$, n_{BB} for $B \to \eta^\prime_{\rho\gamma} K$, and for charged modes the signal and background $\mathcal{A}_{ch}$.

Table 1 lists the quantities used to determine the branching fraction. Equal production rates of B^+B^- and $B^0\overline{B}^0$ pairs have been assumed. To study biases from the likelihood fit, we apply the method to simulated samples constructed to contain the signal and background populations expected for data. The resulting yield biases, from unmodeled correlations in the signal PDF, are about 4% for the measurements with $\eta^\prime \to \rho^0\gamma$, and negligible for those with $\eta^\prime_{\eta(\gamma\gamma)\pi\pi}$. The purity estimate in Table 1 is given by the ratio of the signal yield to the effective background plus signal, the latter being defined as the square of the error on the yield.

Table 1: Signal yield, purity $P(\%)$, reconstruction efficiency $\epsilon(\%)$, daughter branching fraction product, measured branching fraction ($\mathcal{B}$) in units of 10^{-6}, and $\mathcal{A}_{ch}$.

Mode	Yield	P	ϵ	$\prod \mathcal{B}_i$	$\mathcal{B}$	$\mathcal{A}_{ch}$ (10^{-2})
$\eta'_{\eta(\gamma\gamma)\pi\pi}K^+$	609 ± 28	78	23	0.175	66 ± 3	-0.1 ± 4.4
$\eta'_{\rho\gamma}K^+$	1347 ± 57	41	26	0.295	72 ± 3	5.5 ± 3.6
$\eta' K^+$	combined				69 ± 2	3.3 ± 2.8
$\eta'_{\eta(\gamma\gamma)\pi\pi}K^0_{\pi^+\pi^-}$	198 ± 16	77	23	0.060	61 ± 5	
$\eta'_{\rho\gamma}K^0_{\pi^+\pi^-}$	457 ± 30	51	26	0.102	73 ± 5	
$\eta' K^0$	combined				68 ± 3	

In Fig. 1 we show projections onto $m_{\rm ES}$ and ΔE for a subset of the data for which the signal likelihood (computed without the variable plotted) exceeds a mode-dependent threshold that optimizes the sensitivity.

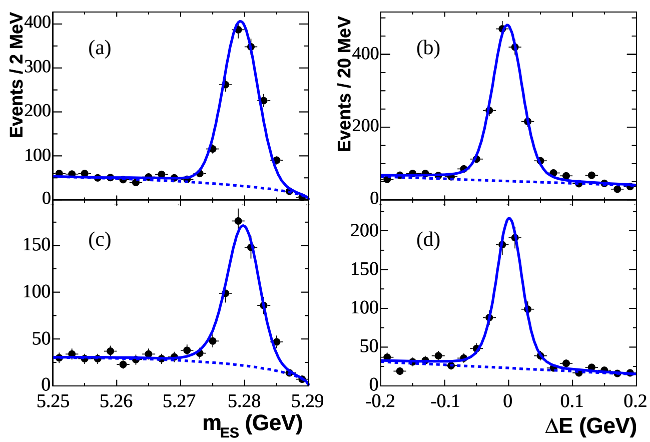

Figure 1: The B candidate $m_{\rm ES}$ and ΔE projections for $\eta' K^+$ (a, b) and $\eta' K^0_S$ (c, d). Points with error bars represent the data, the solid line the fit function, and the dashed line its background component.

For the time-dependent analysis, we require $|\Delta t| < 20\ ps$ and $\sigma_{\Delta t} < 2.5\ ps$. We improve the sample size by combining the five decay chains listed in Table 2 in a single fit with 98 free parameters: S, C, signal yields (5), $\eta'_{\rho\gamma}K^0$ $B\overline{B}$ background yields (2), continuum background yields (5) and fractions (30), background Δt, $m_{\rm ES}$, ΔE, $\mathcal{F}$ PDF parameters (54). The parameters τ and Δm_d are fixed to world-average values [21].

Table 2 gives the yields, S and C, and Fig. 2 the Δt projections and asymmetry of the combined neutral modes for events selected as for Fig. 1.

The major systematic uncertainties affecting the branching fraction measurements reflect the imperfect knowledge of the η' branching fractions (3.4%) [21], and of the reconstruction efficiency (0.8% per charged track, 1.5% per photon, and 2.1% per K^0_S) estimated from

Table 2: Results with statistical errors for the $B^0 \to \eta' K_S^0$ time-dependent fits.

Mode	Signal yield	S	C
$\eta'_{\eta(\gamma\gamma)\pi\pi} K^0_{\pi^+\pi^-}$	188 ± 15	0.01 ± 0.28	-0.18 ± 0.18
$\eta'_{\rho\gamma} K^0_{\pi^+\pi^-}$	430 ± 26	0.44 ± 0.19	-0.30 ± 0.13
$\eta'_{\eta(3\pi)\pi\pi} K^0_{\pi^+\pi^-}$	54 ± 8	0.79 ± 0.47	0.11 ± 0.35
$\eta'_{\eta(\gamma\gamma)\pi\pi} K^0_{\pi^0\pi^0}$	44 ± 9	-0.04 ± 0.57	-0.65 ± 0.42
$\eta'_{\rho\gamma} K^0_{\pi^0\pi^0}$	94 ± 23	-0.45 ± 0.68	0.41 ± 0.40
Combined fit	804 ± 40	0.30 ± 0.14	-0.21 ± 0.10

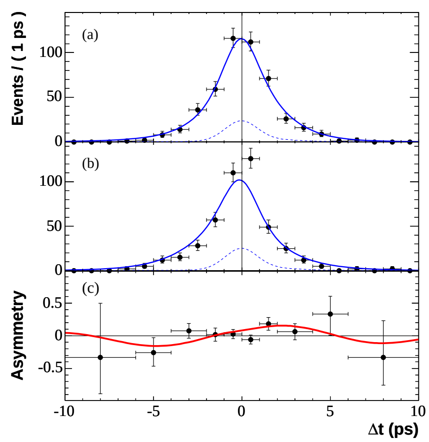

Figure 2: Projections onto Δt for $\eta' K_S^0$ of the data (points with error bars), fit function (solid line), and background function (dashed line), for (a) B^0 and (b) $\overline{B}^0$ tagged events, and (c) the asymmetry between B^0 and $\overline{B}^0$ tags.

auxiliary studies. We take one-half of the measured yield bias (0–2%) as a systematic error. Bias and systematic uncertainties for $\mathcal{A}_{ch}$ have been estimated from the values obtained for the background component in the fit to the data. We apply a correction of +0.016 and assign a systematic error of 0.005.

For the time-dependent measurements, we find approximately equal (0.01) systematic uncertainties from several sources: variation of the signal PDF shape parameters within their errors, SVT alignment, position and size of the beam spot, $B\overline{B}$ background, modeling of the signal Δt distribution, and interference between the CKM-suppressed $\bar{b} \to \bar{u}c\bar{d}$ amplitude and the favored $b \to c\bar{u}d$ amplitude for some tag-side B decays [22]. The $B_{\rm flav}$ sample is used to determine the errors associated with the signal Δt resolutions, tagging efficiencies, and mistag rates, and published measurements [21] for τ_B and Δm_d. Summing all systematic errors in quadrature, we obtain 0.02 for S and C.

In conclusion, we have used samples of about 2000 $\eta' K^+$ and 800 $\eta' K_S^0$ events to measure the branching fractions, the time-integrated charge asymmetry and the time-dependent asymmetry parameters S and C. The measured branching fractions are $\mathcal{B}(B^+ \to \eta' K^+) =$

$(68.9 \pm 2.0 \pm 3.2) \times 10^{-6}$ and $\mathcal{B}(B^0 \to \eta' K^0) = (67.4 \pm 3.3 \pm 3.2) \times 10^{-6}$, and the charge asymmetry is $\mathcal{A}_{ch} = 0.033 \pm 0.028 \pm 0.005$. These precise branching fraction measurements challenge the theoretical understanding of these decays [23]. The measured charge asymmetry is consistent with zero, with 90% CL interval $[-0.012, 0.078]$, and constrains the amount of possible direct *CP* violation in $B^+ \to \eta' K^+$ decays.

The measured time-dependent *CP* violation parameters in $B^0 \to \eta' K^0_S$ are $S = 0.30 \pm 0.14 \pm 0.02$ and $C = -0.21 \pm 0.10 \pm 0.02$. Our result for S differs from that measured by *BABAR* in $B^0 \to J/\psi K^0_S$ [16] by 3.0 standard deviations; it also represents an improvement by a factor 2.4 (1.9) in precision over the published results of *BABAR* [11] (Belle [12]). All these measurements supersede our previous published results [11].

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