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

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We present measurements of the branching fractions of the decays $B^+ \to \eta' K^+$ and $B^0 \to \eta' K^0$. For $B^0 \to \eta' K^0_S$ we also measure the time-dependent CP-violation parameters $S_{\eta' K^0_S}$ and $C_{\eta' K^0_S}$, and for $B^+ \to \eta' K^+$ the time-integrated charge asymmetry $\mathcal{A}_{\rm ch}$. The data sample corresponds to 88.9×10^6 $B\overline{B}$ pairs produced by e^+e^- annihilation at the $\Upsilon(4S)$. The results are $\mathcal{B}(B^+ \to \eta' K^+) = (76.9 \pm 3.5 \pm 4.4) \times 10^{-6}$, $\mathcal{B}(B^0 \to \eta' K^0) = (60.6 \pm 5.6 \pm 4.6) \times 10^{-6}$, $S_{\eta' K^0_S} = 0.02 \pm 0.34 \pm 0.03$, $C_{\eta' K^0_S} = 0.10 \pm 0.22 \pm 0.04$, and $\mathcal{A}_{\rm ch} = 0.037 \pm 0.045 \pm 0.011$.

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Nonconservation of CP in the neutral B meson system has been clearly established [1,2] in decays to charmonium such as $B^0 \to J/\psi K^0_S$. The CP effect arises from the interference between mixing and decay involving the CP-violating phase $\beta = \arg(-V_{cd}V^*_{cb}/V_{td}V^*_{tb})$ of the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix, and appears experimentally as an asymmetry in the time evolution of the $B^0\overline{B}^0$ meson pair. These decays occur via a CKM-favored (though color suppressed) $b \to c$ tree amplitude.

Here we report results of a similar analysis of the decay $B^0 \to \eta' K_S^0$, a CKM-suppressed process that is expected to be dominated by penguin $b \to s$ transitions, while the tree and electroweak contributions are expected to be small [3–5]. The observed branching fraction is 3–10 times larger than initially expected [3], which has motivated a variety of conjectures by way of explanation, including flavor singlet [4] and charm enhanced [6] terms. A recent next-to-leading order QCD factorization calculation [5] suggests that the decay rate is not significantly enhanced by these mechanisms, but is adequately predicted by constructive interference between the penguin diagrams in which the spectator quark is contained in the η' or in the kaon.

The results presented in this Letter are based on data collected in 1999–2002 with the *BABAR* detector [7] at the PEP-II asymmetric e^+e^- collider [8] located at the Stanford Linear Accelerator Center. An integrated luminosity of 81.9 fb^{-1}, corresponding to 88.9×10^6 $B\overline{B}$ pairs, was recorded at the $\Upsilon(4S)$ resonance (center-of-mass energy $\sqrt{s} = 10.58$ GeV).

Charged particles from the e^+e^- interactions are detected, and their momenta measured, by a combination of a vertex tracker (SVT) consisting of five layers of double-sided silicon microstrip detectors, and a 40-layer central drift chamber, both operating in the 1.5 T magnetic field of a superconducting solenoid. Photons and electrons are detected by a CsI(Tl) electromagnetic calorimeter. Charged particle identification (PID) is provided by the average energy loss (dE/dx) in the tracking devices, and by an internally reflecting ring imaging Cherenkov detector (DIRC) covering the central region.

From a $B^0\overline{B}^0$ meson pair produced in $\Upsilon(4S)$ decay we reconstruct one of the mesons in the final state $f = \eta' K_S^0$, a *CP* eigenstate with eigenvalue $\eta_f = -1$. For the time evolution measurement, we also identify the flavor (B^0 or $\overline{B}^0$) and reconstruct the decay vertex of the partner (B_{tag}). The asymmetric beam configuration in the laboratory frame provides a boost of $\beta\gamma = 0.56$ to the $\Upsilon(4S)$, which allows the determination of the proper decay time difference $\Delta t \equiv t_f - t_{\text{tag}}$ from the vertex separation of the two B meson candidates. The distribution of Δt is

$$F(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\{1 \mp \Delta w \pm (1-2w) \times [S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)]\}. \tag{1}$$

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 ($\overline{B}^0$) meson is tagged as a $\overline{B}^0$ (B^0). The tagging algorithm is described in [1], and has a measured analyzing power [efficiency times $(1-2w)^2$] of $(28.1 \pm 0.7)\%$.

The parameter C_f measures direct *CP* violation. If $C_f = 0$, then $S_f = \sin 2\beta_{\text{eff}}$, with β_{eff} equal to β combined with any weak phase difference arising from multiple amplitudes in the decay. Assuming the tree amplitudes are negligible, a deviation from the value found in charmonium channels can be considered an effect of phases coming from new physics [9]. Direct *CP* violation can also be detected as an asymmetry $\mathcal{A}_{\text{ch}} = (\Gamma^- - \Gamma^+)/(\Gamma^- + \Gamma^+)$ in the rates $\Gamma^\pm = \Gamma(B^\pm \to \eta' K^\pm)$.

We reconstruct a B meson candidate by combining a K^+ [10] or K_S^0 with an $\eta' \to \eta\pi^+\pi^-$ ($\eta'_{\eta\pi\pi}$) or $\eta' \to \rho^0\gamma$ ($\eta'_{\rho\gamma}$). The $K_S^0 \to \pi^+\pi^-$, η', $\eta \to \gamma\gamma$, and $\rho^0 \to \pi^+\pi^-$ candidates are selected with requirements on the relevant invariant masses similar to those of our previous analysis [11]. Distributions from the data and from Monte Carlo (MC) simulations [12] guide the choice of these selection criteria. For those quantities taken subsequently as observables for fitting we retain sidebands adequate to characterize the background as well as the signal. For charged B decays, the K^+ candidate must have an associated DIRC Cherenkov angle between $-5\,\sigma$ and $+2\,\sigma$ of the value expected for a kaon. This requirement rejects 91% of pions.

The B-meson candidate is characterized by the energy substituted mass $m_{\text{ES}} = \sqrt{(\frac{1}{2}s + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - |\mathbf{p}_B|^2}$ and energy difference $\Delta E = E_B^* - \frac{1}{2}\sqrt{s}$, where the subscripts 0 and B refer to the initial $\Upsilon(4S)$ and the B candidate, respectively, and the asterisk denotes the $\Upsilon(4S)$ rest frame. The resolutions on these quantities measured for signal events are 29 MeV for ΔE and 2.9 MeV/c^2 for m_{ES}. We require $|\Delta E| \le 0.2$ GeV and $5.2 \le m_{\text{ES}} \le 5.29$ GeV/c^2.

Backgrounds arise primarily from combinatorics among continuum events. To reject these we make use of the angle θ_T between the thrust axis of the B candidate in the $\Upsilon(4S)$ frame and that of the rest of the charged tracks and neutral clusters in the event. The distribution of $\cos\theta_T$ is sharply peaked near ± 1 for combinations drawn from jetlike $q\bar{q}$ pairs, and nearly uniform for the isotropic B meson decays; we require $|\cos\theta_T| < 0.9$.

We obtain the yields and decay time evolution from extended unbinned maximum likelihood fits, with input observables Δt, ΔE, m_{ES}, $m_{\eta'}$, and a Fisher discriminant $\mathcal{F}$. The Fisher discriminant [13] combines four variables: the angles with respect to the beam axis of the B momentum and B thrust axis [in the $\Upsilon(4S)$ frame], and the zeroth and second angular moments of the energy flow (excluding the B candidate) about the B thrust axis.

We use MC simulation to estimate backgrounds from other B decays, including final states with and without charm. These contributions are negligible for the $\eta'_{\eta\pi\pi}$ modes. For $\eta'_{\rho\gamma}$ we include in the fit a $B\overline{B}$ component (which we find to be small).

Since we measure the correlations among the observables to be small in the (background-dominated) data samples entering the fit, we take the probability density function (PDF) for each event to be a product of the PDFs for the separate observables. The efficiencies and mistag rates w for each of four tagging categories are measured with a large sample ($B_{\rm flav}$) of decays to fully reconstructed flavor eigenstates [1]. The signatures of the four tagging categories are essentially lepton, K^+ from D^*, K^+, and a flavor-correlated inclusive class. For each event hypothesis j (signal, $B\overline{B}$ background, continuum background) and tagging category k, we define the PDF (to be evaluated with the observable set for event i) as

$$\mathcal{P}^{i}_{j,k} = \mathcal{P}_j(m_{\rm ES})\mathcal{P}_j(\Delta {\rm E})\mathcal{P}_j(\mathcal{F})\mathcal{P}_j(m_{\eta'})\mathcal{P}_j(\Delta t;\, \sigma_{\Delta t},\, k). \tag{2}$$

The likelihood function for each decay chain is then

$$\mathcal{L} = \prod_k \exp\Big(-\sum_j Y_{j,k}\Big)\prod_i^{N_k}\Big[\sum_j Y_{j,k}\mathcal{P}^i_{j,k}\Big], \tag{3}$$

where $Y_{j,k}$ is the yield of events of hypothesis j found by the fitter in category k, and N_k is the number of category k events in the sample.

The signal PDF factor $\mathcal{P}_{\rm sig}(\Delta t;\, \sigma_{\Delta t},\, k)$ is equal to the convolution of $F(\Delta t;\, k)$ [Eq. (1)], with the signal resolution function, determined from the $B_{\rm flav}$ sample; $\sigma_{\Delta t}$ is the error on Δt for a given event. We determine the remaining PDFs from simulation for the signal and $B\overline{B}$ background components, and from $(m_{\rm ES}, \Delta E)$ sideband data for continuum background. Each of the functions $\mathcal{P}_{\rm sig}(m_{\rm ES})$, $\mathcal{P}_{\rm sig}(\Delta {\rm E})$, $\mathcal{P}_j(\mathcal{F})$, $\mathcal{P}_{\rm bkg}(\Delta t; k)$, and the peaking component of $\mathcal{P}_j(m_{\eta'})$ is parametrized as a Gaussian function, with or without a second or third Gaussian or asymmetric width as required to describe the distribution. Slowly varying distributions (combinatoric background under mass or energy peaks) are represented by linear or quadratic dependences, or for $m_{\rm ES}$, by the function $x\sqrt{1-x^2}\exp[-\xi(1-x^2)]$, with $x \equiv 2m_{\rm ES}/\sqrt{s}$ and parameter ξ. Large control samples of B decays to charmed final states of similar topology are used to verify the simulated resolutions in ΔE and $m_{\rm ES}$.

We compute the branching fractions and $\mathcal{A}_{\rm ch}$ from fits made without Δt or flavor tagging. Seven parameters of the background PDF are free in the fit, along with signal and continuum background yields, for $\eta'_{\rho\gamma}K$ the $B\overline{B}$ background yield, and for charged modes the signal and background $\mathcal{A}_{\rm ch}$. We compute the branching fractions from the fitted signal yields, reconstruction efficiencies, daughter branching fractions, and the number of produced B mesons, assuming equal production rates of charged and neutral pairs. To determine the reconstruction efficiency, including any yield bias of the likelihood fit, we apply the method to simulated samples constructed to contain the signal and continuum background populations expected for data.

Table I shows for each decay chain the branching fraction we measure, together with the quantities entering into its computation. The purity estimate is given by the ratio of the signal yield to the effective background plus signal, defined as the square of the error on the yield. In Fig. 1 we show projections onto $m_{\rm ES}$ and ΔE of a subset of the data for which the signal likelihood (computed without the variable plotted) exceeds a mode-dependent threshold that optimizes the sensitivity.

For the time evolution we combine the two decay chains in a single fit with 28 free parameters: S_f, C_f, signal fractions (two), $\eta'_{\rho\gamma}K$ $B\overline{B}$ background yield (one), common background $\mathcal{F}$ PDF parameters (three), and separate background Δt, $m_{\rm ES}$, ΔE, $m_{\eta'}$ PDF parameters (20). The last four columns of Table I give the tagged subsample yields with their purity, along with S_f and C_f. The S_f and C_f values for $B^+ \to \eta' K^+$ are included as a control; they are consistent with zero, as expected. We show in Fig. 2 the Δt projections and asymmetry of the combined neutral modes for events selected as for Fig. 1.

Most of the systematic errors on yields, which arise from PDF uncertainties (1%–2%, depending on the decay mode), have already been incorporated into the overall statistical error, because their background parameters are free in the fit. We verify that the likelihood of each fit is consistent with the distribution found in simulation.

The uncertainty in our knowledge of the efficiency is found from auxiliary studies to be 0.8% per charged track, 2.5% per photon, and 4% per K^0_S. Our estimate of the B production systematic error is 1.1%. The estimate of systematic bias from the fitter itself (0%–4%) comes from fits of simulated samples with varying background

TABLE I. Signal yield, purity P, detection efficiency ϵ, daughter branching fraction product that was forced to 100% in our signal mode simulation, measured branching fraction, background ($\mathcal{A}^{qq}_{\rm ch}$) and signal ($\mathcal{A}_{\rm ch}$) charge asymmetries, tagged subsample yield $Y_{\rm tag}$ and purity $P_{\rm tag}$, S_f, and C_f for each decay chain, and the combined result for each mode, with statistical error.

Mode	Yield	P (%)	ϵ (%)	$\prod \mathcal{B}_i$ (%)	$\mathcal{B}$ (10^{-6})	$\mathcal{A}^{qq}_{\rm ch}$ (%)	$\mathcal{A}_{\rm ch}$ (%)	$Y_{\rm tag}$	$P_{\rm tag}$ (%)	S_f	C_f
$\eta'_{\eta\pi\pi}K^+$	268 ± 19	78	25	17.4	71 ± 5	0.6 ± 1.6	-0.1 ± 6.8	183	92	0.08 ± 0.20	-0.16 ± 0.15
$\eta'_{\rho\gamma}K^+$	514 ± 31	55	24	29.5	82 ± 5	-0.9 ± 0.5	6.3 ± 5.9	355	63	-0.07 ± 0.16	-0.14 ± 0.11
$\eta' K^+$					76.9 ± 3.5	-0.8 ± 0.4	3.7 ± 4.5			-0.01 ± 0.13	-0.15 ± 0.09
$\eta'_{\eta\pi\pi}K^0$	48 ± 8	75	22	6.0	42 ± 7			31.6	75	0.75 ± 0.51	-0.21 ± 0.35
$\eta'_{\rho\gamma}K^0$	155 ± 17	59	23	10.1	76 ± 8			77.6	61	-0.41 ± 0.42	0.24 ± 0.27
$\eta' K^0$					60.6 ± 5.6					0.02 ± 0.34	0.10 ± 0.22

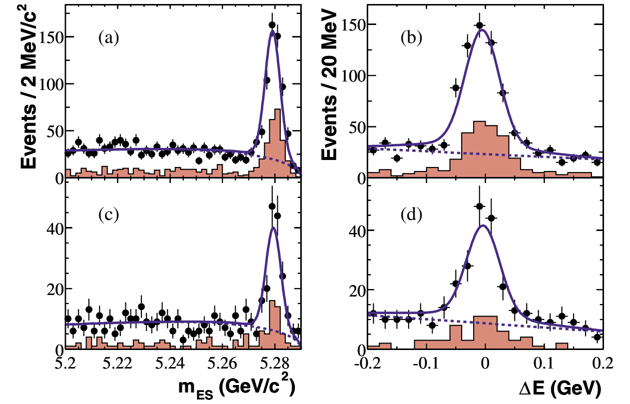

FIG. 1 (color online). The B candidate $m_{\rm ES}$ and ΔE projections for $B^+ \to \eta' K^+$ (a),(b) and $B^0 \to \eta' K_S^0$ (c),(d). The points with errors represent the data, the solid curves represent the full fit functions, and the dashed curves represent the background functions; the shaded histogram represents the $\eta'_{\eta\pi\pi}K$ subset.

populations. Published data [14] provide the B daughter product branching fraction uncertainties (3.4%). Selection efficiency uncertainties are 1% for $\cos\theta_T$ and 0.5% for PID. As can be seen in Table I, the branching fractions we find for $B^0 \to \eta' K^0$ are rather different (3 standard deviations) as measured with $\eta' \to \eta\pi\pi$ or $\eta' \to \rho\gamma$. Having exhausted other explanations, we attribute this difference to a statistical fluctuation, and include both components in the final measurement.

Using several large inclusive kaon and B-decay samples, we find a systematic uncertainty for $\mathcal{A}_{\rm ch}$ of 1.1% due to the dependence of reconstruction efficiency on the charge of the high momentum $K^\pm$.

We find systematic uncertainties for $S_{\eta' K_S^0}$ and $C_{\eta' K_S^0}$ by varying within their errors the fit parameters controlling the PDF shapes. We use the $B_{\rm flav}$ sample to determine the errors associated with the signal Δt resolutions, tagging efficiencies, and mistag rates, and published measurements [14] for τ_B and Δm_d. All of these sum to 0.013 (0.014) for $S_{\eta' K_S^0}$ ($C_{\eta' K_S^0}$). The contributions from the $m_{\rm ES}$, ΔE, $m_{\eta'}$, and $\mathcal{F}$ PDFs are 0.025 (0.014), for $S_{\eta' K_S^0}$ ($C_{\eta' K_S^0}$). We take systematic uncertainties due to SVT alignment (0.01), beam spot (0.01), boost, and z scale (negligible) from previous determinations of these effects [1]. We estimate an uncertainty in $C_{\eta' K_S^0}$ of 0.025 from the effect on some tagside B decays of the interference between the CKM-suppressed $\bar{b} \to \bar{u}c\bar{d}$ amplitude with that of the favored $b \to c\bar{u}d$ [15].

We have reconstructed about 800 events of $B^+ \to \eta' K^+$ and 200 of $B^0 \to \eta' K_S^0$ with which we have measured the branching fractions, the time-integrated charge asymmetry $\mathcal{A}_{\rm ch}$, and the time-dependent asymmetry parameters $S_{\eta' K_S^0}$ and $C_{\eta' K_S^0}$. We find $S_{\eta' K_S^0} = 0.02 \pm 0.34 \pm 0.03$ and $C_{\eta' K_S^0} = 0.10 \pm 0.22 \pm 0.04$. These are in agreement with a previous measurement by the Belle Collaboration [16]. A nonzero value of $C_{\eta' K_S^0}$ would indicate direct CP nonconservation in the $B^0 \to \eta' K_S^0$ decay. With $C_{\eta' K_S^0} = 0$, and provided the decay is dominated by amplitudes with a single weak phase, $S_{\eta' K_S^0}$ is equal to $\sin 2\beta$. Our result for $S_{\eta' K_S^0}$ is about 2 standard deviations smaller than the value obtained with $B^0 \to J/\psi K_S^0$ [1,2], and consistent with zero.

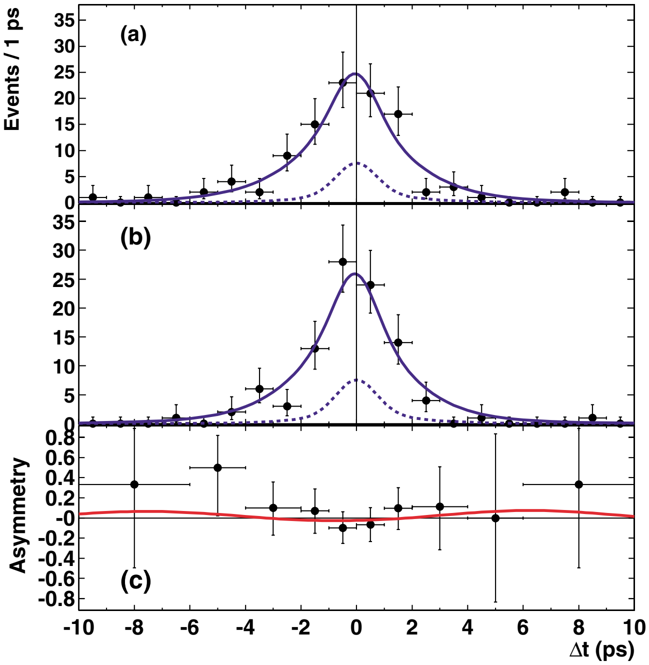

FIG. 2 (color online). Projections onto Δt for $B^0 \to \eta' K_S^0$ data (points with errors), the fit function (solid line), and background function (dashed line), for (a) B^0 and (b) $\overline{B}^0$ tagged events, and (c) the asymmetry between B^0 and $\overline{B}^0$ tags.

The measured branching fractions are $\mathcal{B}(B^+ \to \eta' K^+) = (76.9 \pm 3.5 \pm 4.4) \times 10^{-6}$ and $\mathcal{B}(B^0 \to \eta' K^0) = (60.6 \pm 5.6 \pm 4.6) \times 10^{-6}$, and we find $\mathcal{A}_{\rm ch} = 0.037 \pm 0.045 \pm 0.011$. The null result for $\mathcal{A}_{\rm ch}$ represents a limit on direct CP nonconservation in $B^+ \to \eta' K^+$; the 90% C.L. limit range is $[-0.04, 0.11]$, and is consistent with predictions [5]. These values supersede our previous measurements [11], and are more than a factor of 2 more precise than previous results [11,17]. The branching fractions depend on $R_{+/0} \equiv \mathcal{B}(\Upsilon(4S) \to B^+B^-)/\mathcal{B}(\Upsilon(4S) \to B^0\overline{B}^0)$, which we have assumed to be unity. To compare the decay rates we form their ratio, making use of measurements [18] of $r_{+/0} \equiv R_{+/0} \times \tau(B^+)/\tau(B^0) = 1.14 \pm 0.06$ (our average); we find

$$\frac{\Gamma(B^+ \to \eta' K^+)}{\Gamma(B^0 \to \eta' K^0)} = 1.12 \pm 0.13 \pm 0.06 \pm 0.06,$$

where the last error is from $r_{+/0}$.

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