Observation of CP Violation in $B \to \eta' K^0$ Decays

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We present measurements of the time-dependent CP-violation parameters S and C in $B^0 \to \eta' K^0$ decays. The data sample corresponds to 384×10^6 $B\bar{B}$ pairs produced by e^+e^- annihilation at the $\Upsilon(4S)$. The results are $S = 0.58 \pm 0.10 \pm 0.03$ and $C = -0.16 \pm 0.07 \pm 0.03$. We observe mixing-induced CP violation with a significance of 5.5 standard deviations in this $b \to s$ penguin dominated mode.

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Measurements of time-dependent CP asymmetries in B^0 meson decays through Cabibbo-Kobayashi-Maskawa (CKM) favored $b \to c\bar{c}s$ amplitudes [1] have provided crucial tests of the mechanism of CP violation in the standard model (SM) [2]. Decays of B^0 mesons to charmless hadronic final states such as $\eta' K^0$ proceed mostly via a single loop (penguin) amplitude. In the SM the penguin amplitude has approximately the same weak phase as the $b \to c\bar{c}s$ transition, but it is sensitive to the possible presence of new heavy particles in the loop [3]. The measurement of CP asymmetries in $B^0 \to \eta' K^0$ thus provides an important test for such effects.

Within the SM, CKM-suppressed amplitudes and multiple particles in the loop introduce additional weak phases whose contribution may not be negligible [4–7]. The time-dependent CP-violation parameter S [defined in Eq. (1) below] measured in the decay $B^0 \to \eta' K^0$ is compared with the value of $\sin 2\beta$ from measurements of time-dependent CP violation in B decays to states containing charmonium and a neutral kaon. The deviation $\Delta S = S - \sin 2\beta$ has been estimated in several theoretical approaches: QCD factorization (QCDF) [6,8], QCDF with modeled rescattering [9], soft collinear effective theory [10], and SU(3) symmetry [4,5,11]. These models estimate $|\Delta S|$ to be of the order 0.01, and with uncertainties give bounds $|\Delta S| \lesssim 0.05$.

The time-dependent CP asymmetry in the decay $B^0 \to \eta' K^0_S$ has been measured previously by the *BABAR* [12] and Belle [13] Collaborations. In this Letter we update our previous measurements using an integrated luminosity of 349 fb^{-1}, corresponding to $(384 \pm 4) \times 10^6$ $B\bar{B}$ pairs, recorded at the $\Upsilon(4S)$ resonance (center-of-mass energy $\sqrt{s} = 10.58$ GeV). Belle has since updated their results [14]. Our data were collected with the *BABAR* detector [15] at the PEP-II asymmetric-energy e^+e^- collider. In addition to the $B^0 \to \eta' K^0_S$ decays used previously, we now also include the decay $B^0 \to \eta' K^0_L$.

Charged particles from e^+e^- interactions are detected, and their momenta measured, by a combination of five layers of double-sided silicon microstrip detectors and a 40-layer drift chamber, both operating in the 1.5 T magnetic field of a superconducting solenoid. Photons and electrons are identified with a CsI(Tl) electromagnetic calorimeter (EMC). Charged particle identification is provided by the average energy loss in the tracking devices and by an internally reflecting ring imaging Cherenkov detector covering the central region. The instrumented flux return (IFR) of the magnet allows the identification of muons and K^0_L mesons.

We reconstruct a B^0 decaying into the CP eigenstate $\eta' K^0_S$ or $\eta' K^0_L$ (B_{CP}). From the remaining particles in the event we also reconstruct the decay 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

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

where η is the CP eigenvalue of the final state (-1 for $\eta' K^0_S$, $+1$ for $\eta' K^0_L$). The upper (lower) sign denotes a decay accompanied by a $B^0(\bar{B}^0)$ 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 $\bar{B}^0$ or vice versa. The tagging algorithm has six mutually exclusive tagging categories and a measured analyzing power of $(30.4 \pm 0.3)\%$ [16]. A nonzero value of the parameter C would indicate direct CP violation.

We establish the event selection criteria with the aid of a detailed Monte Carlo (MC) simulation of the B production and decay sequences, and of the detector response [17]. These criteria are designed to retain signal events with high efficiency while removing most of the background.

The B-daughter candidates are reconstructed through their decays $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$ ($\eta_{\gamma\gamma}$), $\eta \to \pi^+\pi^-\pi^0$ ($\eta_{3\pi}$), $\eta' \to \eta_{\gamma\gamma}\pi^+\pi^-$ ($\eta'_{\eta(\gamma\gamma)\pi\pi}$), $\eta' \to \eta_{3\pi}\pi^+\pi^-$ ($\eta'_{\eta(3\pi)\pi\pi}$), $\eta' \to \rho^0\gamma$ ($\eta'_{\rho\gamma}$), where $\rho^0 \to \pi^+\pi^-$, $K^0_S \to \pi^+\pi^-$ ($K^0_{\pi^+\pi^-}$) or $\pi^0\pi^0$ ($K^0_{\pi^0\pi^0}$). Only the $\eta'_{\eta(\gamma\gamma)\pi\pi}$ mode is used for the $\eta' K^0_L$ sample. The requirements on the invariant masses of these particle combinations are the same as in our previous analysis [12]. The list of all decay modes used in the current analysis can be seen in Table I. Signal K^0_L candidates are reconstructed from clusters of energy deposited in the EMC or from hits in the IFR not associated with any charged track in the event [18]. From the cluster centroid and the B_0 decay vertex we determine the direction (but not the magnitude) of the K^0_L momentum $\mathbf{p}_{K^0_L}$.

For $\eta' K^0_S$ decays we reconstruct the B-meson candidate by combining the four-momenta of the K^0_S and η' with a vertex constraint. We also constrain the η, η', and π^0 masses to world-average values [19]. From the kinematics

TABLE I. Results of the fits. Subscripts for η' decay modes denote $\eta'_{\eta(\gamma\gamma)\pi\pi}$ (1), $\eta'_{\rho\gamma}$ (2), and $\eta'_{\eta(3\pi)\pi\pi}$ (3).

Mode	# events	Signal yield	S	C
$\eta'_1 K^0_{\pi^+\pi^-}$	664	224 ± 16	0.61 ± 0.23	-0.26 ± 0.14
$\eta'_2 K^0_{\pi^+\pi^-}$	11 943	566 ± 30	0.56 ± 0.14	-0.24 ± 0.10
$\eta'_3 K^0_{\pi^+\pi^-}$	177	73 ± 9	0.89 ± 0.35	0.14 ± 0.25
$\eta'_1 K^0_{\pi^0\pi^0}$	490	52 ± 9	0.84 ± 0.42	-0.26 ± 0.36
$\eta'_2 K^0_{\pi^0\pi^0}$	13 915	133 ± 24	0.56 ± 0.41	0.15 ± 0.27
$\eta' K^0_S$			0.62 ± 0.11	-0.18 ± 0.07
$\eta'_1 K^0_L$	4199	204 ± 24	0.32 ± 0.28	0.08 ± 0.23
$\eta' K^0$			0.58 ± 0.10	-0.16 ± 0.07

of $\Upsilon(4S)$ decays we determine 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 the laboratory four-momenta of the $\Upsilon(4S)$ and the B candidate, respectively, and the asterisk denotes the $\Upsilon(4S)$ rest frame. The resolution is 3 MeV in $m_{\rm ES}$ and 20–50 MeV in ΔE, depending on the decay mode.

For $\eta' K^0_L$ candidates we obtain ΔE and $\mathbf{p}_{K^0_L}$ from a fit with the B^0 and K^0_L masses constrained to world-average values [19]. To make a match with the measured K^0_L direction we construct the missing momentum $\mathbf{p}_{\rm miss}$ from $\mathbf{p}_0$ and all charged tracks and neutral clusters other than the K^0_L candidate. We then project $\mathbf{p}_{\rm miss}$ onto $\mathbf{p}_{K^0_L}$, and require the component perpendicular to the beam line, $p^{\rm proj}_{\rm miss\perp}$, to satisfy $p^{\rm proj}_{\rm miss\perp} - p_{K^0_L\perp} > -0.5$ GeV. This value was chosen to minimize the yield uncertainty in the presence of background.

For $\eta' K^0_S$ we require $5.25 < m_{\rm ES} < 5.29$ GeV and $|\Delta E| < 0.2$ GeV, for $\eta' K^0_L$ we require $-0.01 < \Delta E < 0.04$ GeV, and for all decays $|\Delta t| < 20$ ps, and, for the error on Δt, $\sigma_{\Delta t} < 2.5$ ps.

Background events arise primarily from random combinations of particles in continuum $e^+e^- \to q\bar{q}$ events ($q = u, d, s, c$). We reduce these with requirements on 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 calorimeter clusters in the event. In the fit we discriminate further against $q\bar{q}$ background with a Fisher discriminant $\mathcal{F}$ that combines several variables that characterize the production dynamics and energy flow in the event [20]. For the $\eta'_\rho\gamma$ decays we require $|\cos\theta^\rho_{\rm dec}| < 0.9$ to reduce the combinatorial background. Here $\theta^\rho_{\rm dec}$ is the angle between the momenta of the ρ^0 daughter π^- and of the η', measured in the ρ^0 rest frame.

For $B^0 \to \eta' K^0_L$ candidates we require that the cosine of the polar angle of the total missing momentum in the laboratory system be less than 0.95, to reject very forward $q\bar{q}$ jets. The purity of the K^0_L candidates reconstructed in the EMC is further improved by a requirement on the output of a neural network (NN) that takes cluster-shape variables as inputs. The NN was trained on MC signal events and data events in the region $0.02 < \Delta E < 0.04$ GeV. We check the performance of the NN on data with K^0_L candidates in the larger $B^0 \to J/\psi K^0_L$ data sample.

The average number of candidates found per selected event is between 1.08 and 1.32, depending on the final state. In the case of events with multiple candidates we choose the candidate with the smallest value of a χ^2 constructed from the deviations from expected values of one or more of the daughter resonance masses, or with the best decay vertex probability for the B, depending on the decay channel. Furthermore, in the $\eta' K^0_L$ sample, if several B candidates have the same vertex probability, we choose the candidate with the K^0_L information taken from, in order, EMC and IFR, EMC only, or IFR only. From the simulation we find that this algorithm selects the correct-combination candidate in about two-thirds of the events containing multiple candidates.

We obtain the common CP-violation parameters and signal yields for each channel from a maximum likelihood fit with the input observables ΔE, $m_{\rm ES}$, $\mathcal{F}$, and Δt. The selected sample sizes are given in the first column of Table I. We estimate from the simulation a contribution to the input sample of less than 1.1% of background from other charmless B decay modes. These events have final states different from the signal, but similar kinematics, and exhibit broad peaks in the signal regions of some observables. We find that the $B\bar{B}$ background component is needed only for the channels with $\eta'_{\rho\gamma}$. We account for these with a separate component in the probability density function (PDF). For each component j (signal, $q\bar{q}$ combinatorial background, or $B\bar{B}$ background) and tagging category c, we define a total probability density function for event i as

$$\mathcal{P}^i_{j,c} \equiv \mathcal{P}_j(m^i_{\rm ES}) \cdot \mathcal{P}_j(\Delta E^i) \cdot \mathcal{P}_j(\mathcal{F}^i) \cdot \mathcal{P}_j(\Delta t^i, \sigma^i_{\Delta t}; c), \quad (2)$$

except for $\eta' K^0_L$ for which $\mathcal{P}_j(m^i_{\rm ES})$ is omitted. The factored form of the PDF is a good approximation since linear correlations are small.

We write the extended likelihood function for all events of the decay mode d as

$$\mathcal{L}_d = \prod_c \exp(-n_c) \prod_i^{N_c} \left[\sum_j n_j f_{j,c} \mathcal{P}^i_{j,c} \right], \quad (3)$$

where n_j is the yield of events of component j, $f_{j,c}$ is the fraction of events of component j for each category c, $n_c = n_{\rm sig} f_{{\rm sig},c} + n_{q\bar{q}} f_{q\bar{q},c} + n_{B\bar{B}} f_{B\bar{B},c}$ is the number of events found by the fitter for category c, and N_c is the number of events of category c in the sample. When combining decay modes we form the grand likelihood $\mathcal{L} = \prod \mathcal{L}_d$. 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 sample of fully reconstructed B^0 decays into flavor eigenstates ($B_{\rm flav}$ sample) [18].

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 following: 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 $\mathcal{P}_{q\bar{q}}(\Delta t; c)$ and $\mathcal{P}_{B\bar{B}}(\Delta t; c)$; an asymmetric Gaussian 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 a fourth-order polynomial for $\mathcal{P}_{B\bar{B}}(\Delta E)$; for $\mathcal{P}_{q\bar{q}}(m_{\rm ES})$ and $\mathcal{P}_{B\bar{B}}(m_{\rm ES})$ the function $x\sqrt{1-x^2}\exp[-\xi(1-x^2)]$, with $x \equiv 2m_{\rm ES}/\sqrt{s}$ and ξ a free parameter [21] and the same function plus a Gaussian, respectively.

For the signal and $B\bar{B}$ background components we determine the PDF parameters from simulation. We study large control samples of B decays to charm final states of similar topology to verify the simulated resolutions in ΔE and $m_{\rm ES}$, adjusting the PDFs to account for any differences found. The $q\bar{q}$ background parameters are free to vary in the final fit. Thus, for the six channels listed in Table I, we perform a single fit with 93 free parameters: S, C, signal yields (6), $\eta'_{\rho\gamma}K^0$ $B\bar{B}$ background yields (2), continuum background yields (6) and fractions (30), background Δt, $m_{\rm ES}$, ΔE, $\mathcal{F}$ PDF parameters (47). The parameters τ and Δm_d are fixed to world-average values [19].

We test and calibrate the fitting procedure by applying it to ensembles of simulated experiments with $q\bar{q}$ events drawn from the PDF into which we have embedded the expected number of signal and $B\bar{B}$ background events randomly extracted from the fully simulated MC samples. We find negligible bias for C. For S we find and apply multiplicative correction factors for bias from dilution due to cross-feed from $B\bar{B}$ background to signal events equal to 1.03 in the final states $\eta'_{\rho\gamma}K^0_{\pi^+\pi^-}$, $\eta'_{\eta(\gamma\gamma)\pi\pi}K^0_L$, and $\eta'_{\rho\gamma}K^0_{\pi^0\pi^0}$.

Results from the fit for the signal yields and the CP parameters S and C are presented in Table I. In Fig. 1 we show the projections onto $m_{\rm ES}$ and ΔE for a subset of the data for which the ratio between the likelihood of signal events and the sum of likelihoods of signal and background events (computed without the variable plotted) exceeds a mode-dependent threshold that optimizes the sensitivity. In Fig. 2 we give the Δt and asymmetry projections of the events selected as for Fig. 1. We measure a correlation of 3.2% between S and C in the fit.

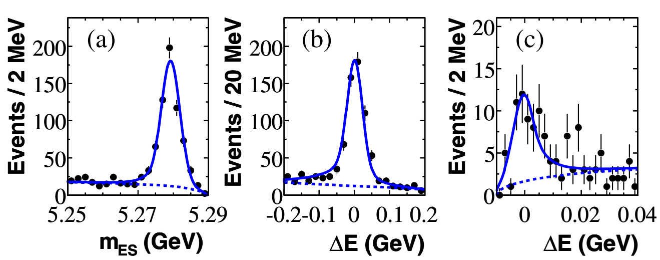

FIG. 1 (color online). Distributions projected (see text) onto (a) $m_{\rm ES}$ and (b) ΔE for $\eta' K^0_S$ candidates, and (c) ΔE for $\eta' K^0_L$ candidates. The solid lines shows the full fit result and the dashed lines show the background contributions.

We perform several crosschecks of our analysis technique including time-dependent fits for B^+ decays to the charged final states $\eta'_{\eta(\gamma\gamma)\pi\pi}K^+$, $\eta'_{\rho\gamma}K^+$, and $\eta'_{\eta(3\pi)\pi\pi}K^+$; fits removing one fit variable at a time; fits without $B\bar{B}$ PDFs; fits with multiple $B\bar{B}$ components; fits allowing for nonzero CP information in $B\bar{B}$ events; fits with $C = 0$. In all cases, we find results consistent with expectation. The value $S = 0.62 \pm 0.11$ for $\eta' K^0_S$ differs from our previous measurement $S = 0.30 \pm 0.14$ [12] due to the improved event reconstruction (with a contribution of $+0.08$) and selection ($+0.12$) and to the additional data collected ($+0.12$). With a model of the data sample changes introduced by our revised event reconstruction and new data, we find that our current result has a statistical probability of 35% (50%) for an assumed true value of S of 0.61 (0.70).

We have studied the systematic uncertainties arising from several sources (in decreasing order of magnitude): variation of the signal PDF shape parameters within their errors, modeling of the signal Δt distribution, use of Δt signal parameters from the $B_{\rm flav}$ sample, 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], $B\bar{B}$ background, SVT alignment, and position and size of the beam spot. The $B_{\rm flav}$ sample is used to determine the errors associated with the signal Δt resolutions, tagging efficiencies, and mistag rates. We take the uncertainties in τ_B and Δm_d from published measurements [19]. Summing

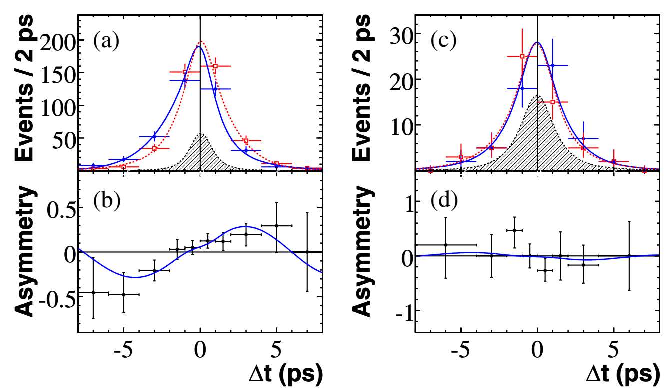

FIG. 2 (color online). Projections (see text) onto Δt for (a) $\eta' K^0_S$ and (c) $\eta' K^0_L$ of the data (points with error bars for B^0 tags in solid circles and $\bar{B}^0$ tags in empty rectangles), fit function (solid and dashed lines for B^0 and B^0 tagged events, respectively), and background function (shaded regions). We show the asymmetry between B^0 and $\bar{B}^0$ tags for (b) $\eta' K^0_S$ and (d) $\eta' K^0_L$; the lines represent the fit functions.

all systematic errors in quadrature, we obtain 0.03 for S and 0.03 for C.

In conclusion, we have used a sample containing 1252 ± 50 flavor-tagged $\eta' K^0$ events to measure the time-dependent CP violation parameters, $S = 0.58 \pm 0.10 \pm 0.03$ and $C = -0.16 \pm 0.07 \pm 0.03$. This sample is 2.1 times as large as that of our previous measurement [12]. Our result for S is consistent with the world average of $\sin 2\beta$ measured in $B^0 \to J/\psi K_S^0$ [19]. We observe mixing-induced CP violation in B^0 decays to $\eta' K^0$ with a significance (systematic uncertainties included) of 5.5 standard deviations. Our result for direct-CP violation is 2.1 standard deviations from zero.

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