Measurement of the Time-Dependent *CP* Asymmetry in the $B^0 \to \phi K^0$ Decay

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0031-9007/04/93(7)/071801(7)$22.50

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We present a measurement of the time-dependent CP asymmetry for the neutral B-meson decay $B^0 \to \phi K^0$. We use a sample of approximately 114×10^6 B-meson pairs taken at the $\Upsilon(4S)$ resonance with the *BABAR* detector at the PEP-II B-meson factory at SLAC. We reconstruct the CP eigenstates ϕK_S^0 and ϕK_L^0, where $\phi \to K^+K^-$, $K_S^0 \to \pi^+\pi^-$, and K_L^0 is observed via its hadronic interactions. The other B meson in the event is tagged as either a B^0 or $\overline{B}^0$ from its decay products. The values of the CP-violation parameters are $S_{\phi K} = 0.47 \pm 0.34(\mathrm{stat})^{+0.08}_{-0.06}(\mathrm{syst})$ and $C_{\phi K} = 0.01 \pm 0.33(\mathrm{stat}) \pm 0.10(\mathrm{syst})$.

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Decays of B mesons into charmless hadronic final states with a ϕ meson are dominated by $b \to s\bar{s}s$ gluonic penguin amplitudes, possibly with smaller contributions from electroweak penguins, while other standard model (SM) amplitudes are strongly suppressed [1]. In the SM, CP violation arises from a single complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [2]. Neglecting CKM-suppressed contributions, the time-dependent CP-violating asymmetries in the decays $B^0 \to \phi K^0$ and $B^0 \to J/\psi K^0$ are proportional to the same parameter $\sin 2\beta$ [3], where the latter decay is dominated by tree diagrams. Since many scenarios of physics beyond the SM introduce additional diagrams with heavy particles in the penguin loops and new CP-violating phases, comparison of CP-violating observables with SM expectations is a sensitive probe for new physics. Measurements of $\sin 2\beta$ in B decays to charmonium such as $B^0 \to J/\psi K^0_S$ have been reported by the *BABAR* [4] and Belle [5] Collaborations, and the world average for $\sin 2\beta$ is 0.731 ± 0.056 [6]. The Belle Collaboration states [7] that their result for $B^0 \to \phi K^0_S$, $\sin 2\beta = -0.96 \pm 0.50^{+0.09}_{-0.11}$, suggests that there is a large CP-violating phase in its decay amplitude, which cannot be explained by the SM.

In this Letter we report a measurement of the time-dependent CP asymmetry in the final state ϕK^0 based on an integrated luminosity of approximately 108 fb^{-1} collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector [8] at the PEP-II asymmetric e^+e^- collider [9] located at the Stanford Linear Accelerator Center.

From a $B^0\overline{B}^0$ meson pair we fully reconstruct one meson, B_{CP}, in the final state ϕK^0, and partially reconstruct the recoil B meson, B_{tag}. We examine B_{tag} for evidence that it decayed either as B^0 or $\overline{B}^0$ (flavor 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 $\Delta t = t_{CP} - t_{\mathrm{tag}}$ from the vertex separation of the two neutral B mesons along the beam (z) axis. The decay rate f_+ (f_-) when the tagging meson is a B^0 ($\overline{B}^0$) is given by

$$f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[1 \pm S_{\phi K}\sin(\Delta m_d \Delta t) \mp C_{\phi K}\cos(\Delta m_d \Delta t)], \quad (1)$$

where τ_{B^0} is the neutral B meson mean lifetime, and Δm_d is the $B^0\overline{B}^0$ oscillation frequency. The time-dependent CP-violating asymmetry is defined as $A_{CP} \equiv (f_+ - f_-)/(f_+ + f_-)$. In the SM, decays that proceed purely via the $b \to s\bar{s}s$ penguin transitions have CP parameters $S_{\phi K} = -\eta_f \sin 2\beta$ and $C_{\phi K} = 0$, where $\beta \equiv \arg[-V_{cd}V^*_{cb}/V_{td}V^*_{tb}]$. Here V_{ik} is the CKM matrix element for quarks i and k, and the CP eigenvalue is $\eta_f = -1\ (+1)$ for ϕK^0_S (ϕK^0_L).

The B_{CP} candidate is reconstructed in the decay mode ϕK^0 with $\phi \to K^+K^-$; the K^0 is either a K^0_L or a $K^0_S \to \pi^+\pi^-$. We combine pairs of oppositely charged tracks extrapolated to a common vertex to form ϕ and K^0_S candidates. For the charged tracks from the ϕ decay we require at least 12 measured drift-chamber (DCH) coordinates and a minimal transverse momentum p_T of $0.1\ \mathrm{GeV}/c$. The tracks must also originate within 1.5 cm in xy and ± 10 cm along the z axis of the nominal beam spot. Tracks used to reconstruct the ϕ mesons are distinguished from pion and proton tracks via a requirement on a likelihood ratio that combines dE/dx information from the silicon vertex tracker (SVT) and the DCH for tracks with momentum $p < 0.7\ \mathrm{GeV}/c$. For tracks with higher p, dE/dx in the DCH and the Cherenkov angle and the number of photons as measured by the internally reflecting ring-imaging Cherenkov detector are used in the likelihood. The two-kaon invariant mass must be within $16\ \mathrm{MeV}/c^2$ of the nominal ϕ mass [6].

For tracks corresponding to K^0_S and B_{tag} daughters our requirements are less restrictive. A $K^0_S \to \pi^+\pi^-$ candidate is accepted if its two-pion invariant mass is within $15\ \mathrm{MeV}/c^2$ of the nominal K^0 mass [6], its reconstructed decay vertex is separated from the ϕ decay vertex by at least 3 standard deviations, and the angle between the line connecting the ϕ and K^0_S decay vertices and the K^0_S momentum direction is less than 45 mrad.

We identify a K^0_L candidate as in our $B^0 \to J/\psi K^0_L$ analysis [10] either as a cluster of energy deposits in the electromagnetic calorimeter (EMC) or as a cluster of hits in two or more layers of the instrumented flux return (IFR) that cannot be associated with any charged track in the event. The K^0_L energy is not well measured. Therefore, we determine the K^0_L laboratory momentum from its flight direction as measured from the EMC or IFR cluster and the constraint that the invariant ϕK^0_L mass agrees with the known B^0 mass. In those cases where the K^0_L is detected in both the IFR and EMC we use the angular information from the EMC, as it has a higher precision. In order to reduce background from π^0 decays, we reject an EMC K^0_L candidate cluster if it forms an invariant mass between 100 and 150 MeV/c^2 with any other cluster in the event under the $\gamma\gamma$ hypothesis, or if it has energy greater than 1 GeV and contains two shower maxima consistent with two photons from a π^0 decay. The remaining background of photons and overlapping showers is further reduced with the use of a neural network constructed from cluster shape variables, trained on Monte Carlo (MC) simulated $B^0 \to \phi K_L^0$ and measured radiative Bhabha events, and tested on measured $e^+e^- \to \phi(\to K_S^0 K_L^0)\gamma$ and $B^0 \to J/\psi K_L^0$ events. The final ϕK_L^0 sample consists of approximately equal numbers of IFR and EMC K_L^0 candidates.

The results are extracted from an extended unbinned maximum likelihood fit for which we parametrize the distributions of several kinematic and topological variables for signal and background events in terms of probability density functions (PDFs) [11]. The background arises primarily from random combinations of tracks produced in events of the type $e^+e^- \to q\bar{q}$, where $q = u, d, s, c$ (continuum). Background from other B decay final states with and without charm is estimated with MC simulations. Opposite CP contributions from the $K^+K^-K^0$ final state (K^+K^- S wave) are estimated with a moment analysis [12] on data to be less than 6.6% and treated as a systematic error. The shapes of event variable distributions are obtained from signal and background MC samples and high-statistics data control samples.

Each B_{CP} candidate is characterized by the energy difference $\Delta E = E_B^* - \frac{1}{2}\sqrt{s}$ and, except for $B^0 \to \phi K_L^0$, the beam-energy–substituted mass $m_{\mathrm{ES}} = \sqrt{(\frac{1}{2}s + \vec{p}_0 \cdot \vec{p}_B)^2/E_0^2 - p_B^2}$ [8]. The subscripts 0 and B refer to the initial $\Upsilon(4S)$ and the B_{CP} candidate, respectively, and the asterisk denotes the $\Upsilon(4S)$ rest frame. For signal events, ΔE is expected to peak at zero, and m_{ES} at the nominal B mass. We require $\Delta E < 0.08$ GeV for $B^0 \to \phi K_L^0$ and $|\Delta E| < 0.2$ GeV and $m_{\mathrm{ES}} > 5.2\ \mathrm{GeV}/c^2$ for $B^0 \to \phi K_S^0$. In the fit we also use the helicity angle θ_H, which is defined as the angle between the directions of the K^+ and the parent B_{CP} in the K^+K^- rest frame. The $\cos\theta_H$ distribution for pseudoscalar-vector B decay modes is $\cos^2\theta_H$, and for the combinatorial background it is nearly uniform.

In continuum events, particles appear bundled into jets. This topology can be characterized with several variables computed in the c.m. frame. One such quantity is the angle θ_T between the thrust axis of the B_{CP} candidate and the thrust axis formed from the other charged and neutral particles in the event. We also use the angle θ_B between the B_{CP} momentum and the beam axis, and the sum of the momenta p_i of the other charged and neutral particles in the event weighted by the Legendre polynomials $L_0(\theta_i)$ and $L_2(\theta_i)$ where θ_i is the angle between the momentum of particle i and the thrust axis of the B_{CP} candidate. For $B^0 \to \phi K_S^0$ candidates, we combine these variables into a Fisher discriminant $\mathcal{F}$ [13] after requiring $|\cos\theta_T| < 0.9$. In this mode background from other B decays is negligible, as demonstrated in MC simulation studies.

More stringent criteria must be applied to suppress backgrounds in the case of $B^0 \to \phi K_L^0$ candidates, and we require $|\cos\theta_T| < 0.8$ and $|\cos\theta_B| < 0.85$. We define the missing momentum $\vec{p}_{\mathrm{miss}}$, calculated in the laboratory frame from the sum of beam momenta and all tracks and EMC clusters, excluding the K_L^0candidate. We require the polar angle θ_{miss} of the missing momentum with respect to the beam direction to be greater than 0.3 rad. The cosine of the angle between $\vec{p}_{\mathrm{miss}}$ and the K_L^0 direction, θ_K, must satisfy $\cos\theta_K > 0.6$. In the plane transverse to the beam direction, the difference between the missing momentum projected along the K_L^0 direction and the calculated K_L^0 momentum must be greater than $-0.75\ \mathrm{GeV}/c$. In the Fisher discriminant we replace $|\cos\theta_B|$ by the cosine of the angle between the missing momentum and the K^+ from the ϕ decay. In the ϕK_L^0 sample about 1.4% of the events originate from charm B decays; 0.7% originate from charmless B decays. The dominant CP contamination is the mode $B \to \phi K^{*0}$, where the K^{*0} decays to $K_L^0\pi^0$; we expect four events in the region $\Delta E < 0.01$ GeV. In the likelihood fit we explicitly parametrize backgrounds from both charm and charmless B decays as derived from MC simulations.

All the other tracks and clusters that are not associated with the reconstructed $B^0 \to \phi K^0$ decay are used to form the B_{tag}, and its flavor is determined with a multivariate tagging algorithm [4]. The tagging efficiency ϵ and mistag probability w in four hierarchical and mutually exclusive categories is measured from fully reconstructed B^0 decays into the $D^{(*)-}X^+$ $((X^+ = \pi^+, \rho^+, a_1^+))$ and $J/\psi K^{*0}$ $(K^{*0} \to K^+\pi^-)$ flavor eigenstates (B_{flav} sample). The analyzing power $\epsilon(1-2w)^2$ is $(28.7 \pm 0.7)\%$.

A detailed description of the Δt reconstruction algorithm is given in Ref. [10]. The B_{CP} vertex resolution is dominated by the ϕ vertex. The average Δz resolution is 190 μm and is dominated by the tagging vertex in the event. Thus, we can characterize the resolution with the much larger B_{flav} sample, which we fit simultaneously with the CP samples. The amplitudes for the B_{CP} asymmetries and for the B_{flav} flavor oscillations are reduced by the same factor due to wrong tags. Both distributions are convoluted with a common Δt resolution function, and the backgrounds are accounted for by adding terms to the likelihood, incorporated with different assumptions about their Δt evolution and resolution function [10].

Since we measure the correlations among the observables to be small in the data samples entering the fit, we take the probability density function $\mathcal{P}_{i,c}^j$ for each event j to be a product of the PDFs for the separate observables. For each event hypothesis i (signal, backgrounds) and tagging category c, we define $\mathcal{P}_{i,c}^j = \mathcal{P}_i(m_{ES}) \cdot \mathcal{P}_i(\Delta E) \cdot \mathcal{P}_i(\mathcal{F}) \cdot \mathcal{P}_i(\cos\theta_H) \cdot \mathcal{P}_i(\Delta t; \sigma_{\Delta t}, c)$, where for the ϕK_L^0 mode $\mathcal{P}_i(m_{ES}) = 1$ and for the flavor sample $\mathcal{P}_i(\mathcal{F}) \cdot \mathcal{P}_i(\cos\theta_H) = 1$. The $\sigma_{\Delta t}$ is the error on Δt for a given event. The likelihood function for each decay chain is then

$$\mathcal{L} = \prod_{c} \exp\Big(-\sum_{i} N_{i,c}\Big) \prod_{j}^{N_c} \Big[\sum_{i} N_{i,c} \mathcal{P}^{j}_{i,c}\Big], \qquad (2)$$

where $N_{i,c}$ is the yield of events of hypothesis i found by the fitter in category c, and N_c is the number of category c events in the sample. The total sample consists of 86 200 $B_{\rm flav}$, 2138 ϕK^0_S, and 4730 ϕK^0_L candidates. We find 70 ± 9 ϕK^0_S and 52 ± 16 ϕK^0_L signal events. The signal yields in both the ϕK^0 channels agree well with our determination of the branching fraction for $B^0 \to \phi K^0$ [14]. Figure 1 shows the $m_{\rm ES}$ (ΔE) distribution of ϕK^0_S (ϕK^0_L) events together with the result from the fit after a requirement on the likelihood (computed without the variable plotted) to enhance the sensitivity.

We determine the CP parameters $S_{\phi K}$ and $C_{\phi K}$ along with an additional 38 free parameters: the efficiency per tagging category (4 parameters), the average mistag fraction and the difference between $B^0$and $\overline{B}^0$ mistags for each tagging category (8), and the signal Δt resolution (9). For the background we parametrize time dependence (6), Δtresolution (3), and mistag fractions (8). We fix τ_{B^0} and Δm_d to the world averages [6]. The determination of the mistag fractions and Δt-resolution parameters is dominated by the high-statistics $B_{\rm flav}$ sample. The fit was tested with a parametrized simulation of a large number of data-sized experiments and full detector simulated events for the different signal and background samples. The likelihood of our data fit agrees with the likelihoods from fits to the simulated data. The expected error for $S_{\phi K}$ is 0.40 and for $C_{\phi K}$ is 0.29. Compared to the measured values 27% of the fits to the simulated data have a smaller error value for $S_{\phi K}$ and 12% have a higher error value for $C_{\phi K}$. The fit was also verified with our $J/\psi K^0_S$ data sample and a control sample of 232 ϕK^+ candidates where one expects $S_{\phi K^+} = C_{\phi K^+} = 0$. We measure $S_{\phi K^+} = 0.23 \pm 0.24$ and $C_{\phi K^+} = -0.14 \pm 0.18$ with statistical errors only. The simultaneous fit to the ϕK^0 and flavor decay modes yields

$$S_{\phi K} = 0.47 \pm 0.34({\rm stat})^{+0.08}_{-0.06}({\rm syst}),$$
$$C_{\phi K} = 0.01 \pm 0.33({\rm stat}) \pm 0.10({\rm syst}).$$

The result in the dominant channel $B^0 \to \phi K^0_S$ is $S_{\phi K} = 0.45 \pm 0.43$ and $C_{\phi K} = -0.38 \pm 0.37$ with statistical errors only. Figure 2 shows the Δt distributions of the B^0- and the $\overline{B}^0$-tagged subsets together with the raw asymmetry for the ϕK^0_S and ϕK^0_L events with the result of the combined time-dependent CP-asymmetry fit superimposed.

We consider systematic uncertainties in the CP coefficients $S_{\phi K}$ and $C_{\phi K}$ due to the event-yield determination in the two channels (± 0.01 for $S_{\phi K}$, ± 0.05 for $C_{\phi K}$), contributions from B^0 final states with opposite CP ($+0.06$, ± 0.02), the parametrization of PDFs for the event yield in signal and background (± 0.02, ± 0.05), composition and CP asymmetry of the background (± 0.03, ± 0.03), the assumed parametrization of the Δt resolution function (± 0.02, ± 0.01), the $m_{\rm ES}$ background parametrization (± 0.02, ± 0.05), a possible difference in

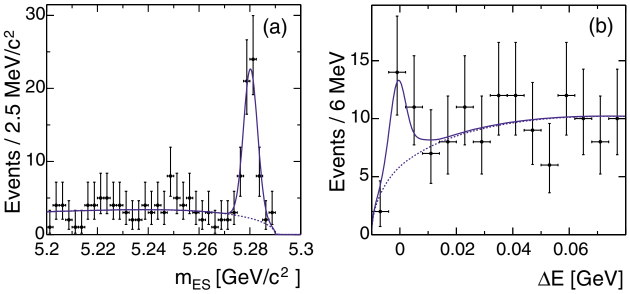

FIG. 1 (color online). Distribution of the event variable (a) m_{ES} for the ϕK^0_S final state and (b) ΔE for the ϕK^0_L final state after reconstruction and a requirement for the likelihood with total signal efficiency of 32% and 5%, respectively. The solid line represents the fit result for the total event yield and the dotted line for the background.

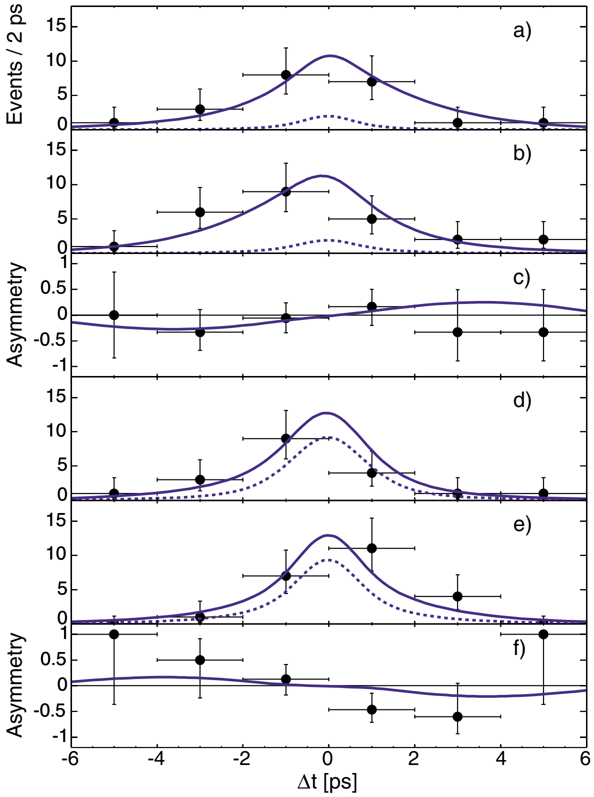

FIG. 2 (color online). Plots (a) and b) show the Δt distributions of B^0- and $\overline{B}^0$-tagged ϕK^0_S events. The solid lines refer to the fit for all events; the dashed lines correspond to the background. Plot (c) shows the asymmetry. A requirement for the event likelihood is applied. Plots (d)–(f) are the corresponding plots for ϕK^0_L events.

the efficiency for B^0 and $\overline{B}^0$ ($\pm$ 0.01, $\pm$0.02), the fixed values for Δm_d and τ_B ($\pm$ 0.00, $\pm$0.01), the beam-spot position ($\pm$ 0.01, $\pm$0.01), and uncertainties in the SVT alignment ($\pm$ 0.01, $\pm$0.01). The bias in the coefficients due to the fit procedure ($\pm$ 0.03, $\pm$0.01) is included in the uncertainty without making corrections to the final results. We estimate errors due to the effect of doubly CKM-suppressed decays [15] to be ($\pm$0.01, $\pm$0.03). We add these contributions in quadrature to obtain the total systematic uncertainty.

In summary, we have measured the time-dependent *CP* asymmetries in the combined *B*-meson final states ϕK^0_S and ϕK^0_L. We obtain values for the *CP*-violation parameters $S_{\phi K}$ and $C_{\phi K}$ that agree within 1 standard deviation with the ones measured in the charmonium channels [4,5]; the central value of $S_{\phi K}$ is also consistent with no *CP* asymmetry at the 1.3σ level. Our value of $S_{\phi K}$ differs by 2.3 standard deviations from that measured by the Belle Collaboration [7].

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