Measurements of *CP*-Violating Asymmetries in $B^0 \to K_s^0 \pi^0$ Decays

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We present a measurement of the time-dependent *CP*-violating (CPV) asymmetries in $B^0 \to K_S^0 \pi^0$ decays based on 124×10^6 $\Upsilon(4S) \to B\overline{B}$ decays collected with the *BABAR* detector at the PEP-II asymmetric-energy *B* factory at SLAC. In a sample containing 122 ± 16 signal decays, we obtain the magnitudes of the direct CPV asymmetry $C_{K_S^0\pi^0} = 0.40^{+0.27}_{-0.28} \pm 0.09$ and of the CPV asymmetry in the interference between mixing and decay $S_{K_S^0\pi^0} = 0.48^{+0.38}_{-0.47} \pm 0.06$ where the first error is statistical and the second systematic.

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The *BABAR* [1] and Belle [2] Collaborations recently reported observation of *CP* violation in *B* meson decays through measurements of the time-dependent *CP*-violating (CPV) asymmetry in B^0 decays into charmonium final states. In the framework of the Standard Model (SM), where *CP* violation is a consequence of the presence of a complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix [3], these measurements determine the parameter $\sin 2\beta$, with $\beta \equiv \arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$. The consistency of the observed value of $\sin 2\beta$ with the Standard Model expectations provides strong evidence that the CKM mechanism is the dominant source of *CP* violation in the quark sector. A major goal of the experimental studies of *B* decays is to provide additional information to examine the validity of this conclusion and search for evidence of new physics (NP) in possible deviations from the SM. One avenue for the observation of NP is provided by *CP* violation studies of decays dominated by penguin loop-level $b \to s\bar{q}q$ ($q = \{d, s\}$) transitions [4,5]. While in the SM the time-dependent CPV asymmetries in these decays measure $\sin 2\beta$, additional radiative loop contributions from NP processes may alter this expectation. Presently, the *B* factory experiments have explored time-dependent CPV asymmetries in three such decays, which in the SM are dominated by the penguin $b \to s\bar{s}s$ transition: $B^0 \to \eta' K_S^0$ [6,7], $B^0 \to K^+K^-K_S^0$ [6], and $B^0 \to \phi K_S^0$ [6,8]. The latter results hint at a possible deviation from the SM, but are inconclusive.

In this Letter we present the first measurement of the time-dependent CPV asymmetries in the decay $B^0 \to K_S^0\pi^0$, which has a measured branching fraction $\mathcal{B}(B^0 \to K_S^0\pi^0) = (11.9 \pm 1.5) \times 10^{-6}$ [9]. The CKM and color suppression of the tree-level $b \to s\bar{u}u$ transition leads to the expectation that this decay is dominated by a top quark mediated $b \to s\bar{d}d$ penguin diagram, which carries a weak phase $\arg(V_{tb}V_{ts}^*)$. If other contributions, such as the $b \to su\bar{u}$ tree amplitude are ignored, the time-dependent CPV asymmetry is governed by $\sin 2\beta$ [10]. The deviation from $\sin 2\beta$ due to standard model contributions with a different weak phase is estimated to be at most 0.2 [11].

The results presented here are based on 124×10^6 $\Upsilon(4S) \to B\overline{B}$ decays collected in 1999–2003 with the *BABAR* detector at the PEP-II e^+e^- collider, located at the Stanford Linear Accelerator Center. The *BABAR* detector, which is fully described in [12], provides charged particle tracking through a combination of a five-layer double-sided silicon micro-strip detector (SVT) and a 40-layer central drift chamber (DCH), both operating in a 1.5 T magnetic field in order to provide momentum measurements. Charged kaon and pion identification is achieved through measurements of particle energy loss (dE/dx) in the tracking system and Cherenkov cone angle (θ_c) in a detector of internally reflected Cherenkov light (DIRC). A segmented CsI(Tl) electromagnetic calorimeter (EMC) provides photon detection and electron identification. Finally, the instrumented flux return (IFR) of the magnet allows discrimination of muons from pions.

We search for $B^0 \to K_S^0\pi^0$ decays in hadronic events, which are selected based on charged particle multiplicity and event topology [13]. We reconstruct $K_S^0 \to \pi^+\pi^-$ candidates from pairs of oppositely charged tracks. The two-track combinations must form a vertex with $\pi^+\pi^-$ invariant mass within 3.5σ of the nominal K_S^0 mass [14] and reconstructed proper lifetime greater than 5 times its uncertainty. We form $\pi^0 \to \gamma\gamma$ candidates with an invariant mass $110 < m_{\gamma\gamma} < 160$ MeV from pairs of photon candidates in the EMC that are isolated from any charged tracks, carry a minimum energy of 30 MeV, and possess the expected lateral shower shapes. Finally, we construct $B^0 \to K_S^0\pi^0$ candidates by combining K_S^0 and π^0 candidates in the event. For each *B* candidate, two nearly independent kinematic variables are computed, namely, the energy-substituted mass $m_{ES} = \sqrt{(s/2 + \mathbf{p}_i\mathbf{p}_B)^2/E_i^2 - p_B^2}$, and the energy difference $\Delta E = E_B^* - \sqrt{s}/2$. Here, $(E_i, \mathbf{p}_i)$ is the four-vector of the initial e^+e^- system, $\sqrt{s} = \sqrt{E_i^2 - p_i^2}$ is the center-of-mass energy, $\mathbf{p}_B$ is the reconstructed momentum of the B^0 candidate, and E_B^* is its energy calculated in the e^+e^- rest frame. For signal decays, the m_{ES} distribution peaks near the B^0 mass with a resolution of ~ 3.1 MeV$/c^2$ and the ΔE distribution peaks near zero with a resolution of ~ 40 MeV. Both the m_{ES} and the ΔE distribution exhibit a low-side tail from energy leakage out of the EMC. We select candidates within the window $5.2 < m_{ES} < 5.29$ GeV$/c^2$ and $-150 < \Delta E < 150$ MeV, which includes the signal peak and a "sideband" region for background characterization. For the 1.7% of events with more than one candidate, we select the combination with the smallest $\chi^2 = \sum_{i=\pi^0,K_S^0}(m_i - m_i')^2/\sigma_{m_i}^2$, where m_i (m_i') is the measured (nominal) mass and σ_{m_i} is the estimated uncertainty on the mass of particle i.

For each $B^0 \to K_S^0\pi^0$ candidate, we examine the remaining tracks and neutral candidates in the event to determine if the other *B* meson, $B_{\rm tag}$, decayed as a B^0 or a $\overline{B}^0$ (flavor tag). Time-dependent CPV asymmetries are determined by reconstructing the distribution of the difference of the proper decay times, $\Delta t \equiv t_{CP} - t_{\rm tag}$, where the t_{CP} refers to the signal B^0 and $t_{\rm tag}$ to the other B. At the $\Upsilon(4S)$ resonance, the Δt distribution follows

$$\mathcal{P}_{\overline{B}^0}^{B^0}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \times \{1 \pm [S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)]\}, \quad (1)$$

where the upper (lower) sign corresponds to $B_{\rm tag}$ decaying as B^0 ($\overline{B}^0$), τ is the B^0 lifetime averaged over the two mass eigenstates, Δm_d is the mixing frequency, C_f is the magnitude of direct CPV in the decay to final state f, and S the magnitude of CPV in the interference between mixing and decay. For the case of pure penguin dominance, we expect $S_{K_S^0\pi^0} = \sin 2\beta$, and $C_{K_S^0\pi^0} = 0$.

We extract the CPV parameters from an unbinned maximum-likelihood fit to kinematic, event shape, flavor tag, and time structure variables, which are sufficiently independent that we can construct the likelihood from the product of one dimensional probability density functions (PDFs). The PDFs for signal events are parameterized from either more copious fully reconstructed B decays in data or from simulated samples. For background PDFs we select the functional form from data in the sideband regions of the other observables where backgrounds dominate. We include these regions in the fitted sample and simultaneously extract the parameters of the background PDFs along with the CPV measurements.

The sample of $B^0 \to K_S^0\pi^0$ candidates is dominated by random $K_S^0\pi^0$ combinations from $e^+e^- \to q\overline{q}$ ($q = \{u, d, s, c\}$) fragmentation. Monte Carlo studies show that contributions from other B meson decays can be neglected. We exploit topological observables to discriminate the jetlike $e^+e^- \to q\overline{q}$ events from the more uniformly distributed $B\overline{B}$ events. In the $\Upsilon(4S)$ rest frame, we compute the angle θ_S^* between the sphericity axis [15] of the B^0 candidate and that of the remaining particles in the event. While $|\cos\theta_S^*|$ is highly peaked near one for $e^+e^- \to q\overline{q}$ events, it is nearly uniformly distributed for $B\overline{B}$. We require $|\cos\theta_S^*| < 0.8$, eliminating 83% of the background. In addition, we include in the fit a Fisher discriminant variable, which is defined as $\mathcal{F} = 0.53 - 0.60L_0 + 1.27L_2$, where $L_j \equiv \sum_i |\mathbf{p}_i^*||\cos\theta_i^*|^j$, $\mathbf{p}_i^*$ is the momentum of particle i, and θ_i^* is the angle between $\mathbf{p}_i^*$ and the sphericity axis of the B^0 candidate.

We use a neural network (NN) to determine the flavor of the $B_{\rm tag}$ meson from kinematic and particle identification information [16]. Each event is assigned to one of five mutually exclusive tagging categories, designed to combine flavor tags with similar performance and Δt resolution. We parameterize the performance of this algorithm in a data sample ($B_{\rm flav}$) of fully reconstructed $B^0 \to D^{(*)-}\pi^+/\rho^+/a_1^+$ decays. The average effective tagging efficiency obtained from this sample is $Q = \sum_c \epsilon_S^c(1 - 2w^c)^2 = 0.288 \pm 0.005$, where ϵ_S^c and w^c are the efficiencies and mistag probabilities, respectively, for events tagged in category $c \in \{1 \cdots 5\}$. For the background, the fraction of events (ϵ_B^c) and the asymmetry in the rate of B^0 versus $\overline{B}^0$ tags in each tagging category are extracted from the fit to the data.

We compute the proper time difference Δt from the known boost of the e^+e^- system and the measured $\Delta z = z_{CP} - z_{\rm tag}$, the difference of the reconstructed decay vertex positions of the $B^0 \to K_S^0\pi^0$ and $B_{\rm tag}$ candidate along the boost direction (z). A description of the inclusive reconstruction of the $B_{\rm tag}$ vertex is given in [13]. For the $B^0 \to K_S^0\pi^0$ decay, where no charged particles are present at the decay vertex, we exploit the fact that the flight distance of the B meson transverse to the beam direction ($\sim$30 μm) is small compared to the flight length along the beam ($\sim$260 μm). We then determine the decay point from the intersection of the K_S^0 trajectory with the interaction region by constraining the B vertex to the interaction point (IP) in the transverse plane. The position and size of the interaction region are determined on a run-by-run basis from the spatial distribution of vertices from two-track events. The uncertainty in the IP position, which follows from the size of the interaction region (about 200 μm horizontal and 4 μm vertical), is combined with the RMS of the transverse B flight length distribution to assign an uncertainty to the IP constraint.

Simulation studies indicate that the vertexing procedure provides an unbiased estimate of z_{CP}. The per-event estimate of the Δt error reflects the strong dependence of the z_{CP} resolution on the K_S^0 flight direction and the number of SVT layers traversed by its decay daughters. For the 37% of events where both tracks include at least one hit in the inner three SVT layers (at radii from 3.2 cm to 5.4 cm), the mean Δt resolution is comparable to that of decays for which the vertex is directly reconstructed from charged particles originating at the B decay point [13]. If both tracks have hits in the outer two SVT layers (at radii 9.1 cm to 14.4 cm) but one of the tracks has no hits in the inner three layers ($\sim$27% of the events), the resolution is nearly 2 times worse. The remaining events provide poor Δt measurements. For these events and for events with $\sigma_{\Delta t} > 2.5$ ps or $|\Delta t| > 20$ ps, we do not include Δt information in the fit. However, we account for the contribution of these events in the measurement of $C_{K_S^0\pi^0}$.

We obtain the PDF for the time dependence of signal decays from the convolution of Eq. (1) with a resolution function $\mathcal{R}(\delta t \equiv \Delta t - \Delta t_{\rm true}, \sigma_{\Delta t})$. The resolution function is parameterized as the sum of a "core" and a "tail" Gaussian, each with a width and mean proportional to the reconstructed $\sigma_{\Delta t}$, and a third Gaussian centered at zero with a fixed width of 8 ps [13]. We have verified in simulation that the parameters of $\mathcal{R}(\delta t, \sigma_{\Delta t})$ for $B^0 \to K_S^0\pi^0$ decays are similar to those obtained from the $B_{\rm flav}$ sample, even though the distributions of $\sigma_{\Delta t}$ differ considerably. Therefore, we obtain these parameters from a fit to the $B_{\rm flav}$ sample.

To extract the CPV asymmetries, we maximize the logarithm of the likelihood function

$$\mathcal{L}(S_f, C_f, N_S, N_B, f_S, f_B, \vec{\alpha}) = \frac{e^{-(N_S+N_B)}}{(N_S+N_B)!} \times \prod_{i\in {\rm w}/\Delta t} [N_S f_S \epsilon_S^c \mathcal{P}_S(\vec{x}_i, \vec{y}_i; S_f, C_f) + N_B f_B \epsilon_B^c \mathcal{P}_B(\vec{x}_i, \vec{y}_i; \vec{\alpha})] \times \prod_{i\in {\rm w/o}\Delta t} [N_S(1-f_S)\epsilon_S^c \mathcal{P}'_S(\vec{x}_i; C_f) + N_B(1-f_B)\epsilon_B^c \mathcal{P}'_B(\vec{x}_i; \vec{\alpha})],$$

where the second (third) factor on the right-hand side is the contribution from events with (without) Δt information. The probabilities $\mathcal{P}_S$ and $\mathcal{P}_B$ are products of PDFs for signal (S) and background (B) hypotheses evaluated for the measurements $\vec{x}_i = \{m_{\rm ES}, \Delta E, \mathcal{F}, \text{tag, tagging category}\}$ and $\vec{y}_i = \{\Delta t, \sigma_{\Delta t}\}$. Along with the CPV asymmetries S_f and C_f, the fit extracts the yields N_S and N_B, the fractions of events with Δt information f_S and f_B, and the parameters $\vec{\alpha}$ which describe the background PDFs.

Fitting the data sample of 4179 $B^0 \to K_S^0\pi^0$ candidates, we find $N_S = 122 \pm 16$ signal decays with $S_{K_S^0\pi^0} = 0.48^{+0.38}_{-0.47} \pm 0.06$ and $C_{K_S^0\pi^0} = 0.40^{+0.27}_{-0.28} \pm 0.09$, where the uncertainties are statistical and systematic, respectively. The estimated number of signal decays is consistent with our measurement of the branching fraction [17]. The result for $C_{K_S^0\pi^0}$ is consistent with a fit that does not employ Δt information. Fixing $C_{K_S^0\pi^0} = 0$, we obtain $S_{K_S^0\pi^0} = 0.41^{+0.41}_{-0.48} \pm 0.06$. The evaluation of the systematic uncertainties is described below.

Figure 1 shows the $m_{\rm ES}$ distributions for a signal-enhanced sample. The event selection is based on a likelihood ratio $R = \mathcal{P}_S/(\mathcal{P}_B + \mathcal{P}_S)$ calculated without the displayed observable. The dashed and solid curves indicate background and signal-plus-background contributions, respectively, as obtained from the fit, but corrected for the selection on R. Figure 2 shows distributions of Δt for B^0- and $\overline{B}^0$-tagged events, and the asymmetry $\mathcal{A}_{K_S^0\pi^0}(\Delta t) = [N_{B^0} - N_{\overline{B}^0}]/[N_{B^0} + N_{\overline{B}^0}]$ as a function of Δt, also for a signal-enhanced sample.

To investigate possible biases introduced in the CPV measurements by the IP-constrained vertexing technique, we examine $B^0 \to J/\psi K_S^0$ decays in data, where $J/\psi \to \mu^+\mu^-$ and $J/\psi \to e^+e^-$. In these events we determine Δt in two ways: by fully reconstructing the B^0 decay vertex using the trajectories of charged daughters of the J/ψ and the K_S^0 mesons, or by neglecting the J/ψ contribution to the decay vertex and using the IP constraint and the K_S^0 trajectory only. This study shows that within statistical uncertainties, the IP-constrained Δt measurement is unbiased with respect to the more established technique and that the obtained values of $S_{J/\psi K_S^0}$ and $C_{J/\psi K_S^0}$ are consistent. A similar study of $B^\pm \to K_S^0\pi^\pm$ events, where the $\pi^\pm$ contribution to the decay vertex has been replaced by the IP constraint, yields $S_{K_S^0\pi^\pm} = 0.13 \pm 0.19$ and $C_{K_S^0\pi^\pm} = 0.06 \pm 0.11$, which is

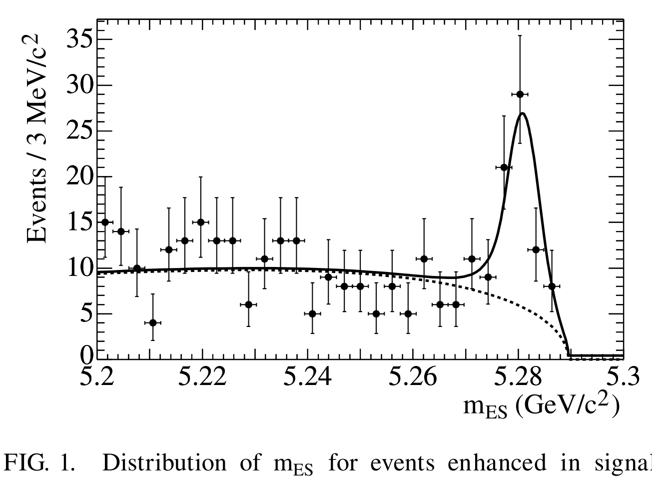

FIG. 1. Distribution of $m_{\rm ES}$ for events enhanced in signal decays. The dashed and solid curves represent the background and signal-plus-background contributions, respectively.

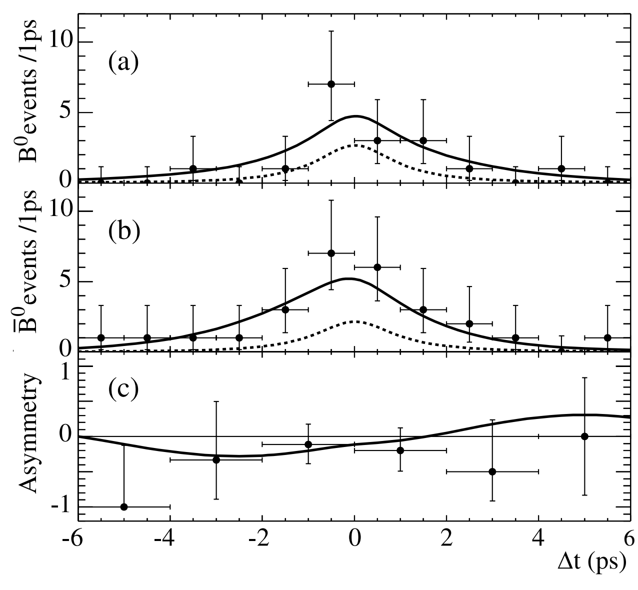

FIG. 2. Distributions of Δt for events enhanced in signal decays with $B_{\rm tag}$ tagged as (a) B^0 or (b) $\overline{B}^0$, and (c) the asymmetry $\mathcal{A}_{K_S^0\pi^0}(\Delta t)$. The dashed and solid curves represent the fitted background and signal-plus-background contributions, respectively. The asymmetry projection corresponds to approximately 36 signal and 25 background events.

consistent with the expectation $S_{K_S^0\pi^\pm} = 0$ and our previous measurement of the charge asymmetry [17]. We also find that the B^0 lifetime measured in $B^0 \to K_S^0\pi^0$ decays and in IP-constrained $B^0 \to J/\psi K_S^0$ decays agrees with the world average [14].

To quantify possible systematic effects we examine large samples of simulated $B^0 \to K_S^0\pi^0$ and $B^0 \to J/\psi K_S^0$ decays. We employ the difference in resolution function parameters extracted from these samples to evaluate uncertainties due to the use of the resolution function $\mathcal{R}$ extracted from the $B_{\rm flav}$ sample. We assign a systematic uncertainty of 0.03 on $S_{K_S^0\pi^0}$ and 0.02 on $C_{K_S^0\pi^0}$ due to the uncertainty in $\mathcal{R}$. We compare fits to a large sample of simulated nominal and IP-constrained $B^0 \to J/\psi K_S^0$ events to account for any potential bias due to the vertexing technique. This latter study yields the difference $\delta S_{J/\psi K_S^0} = 0.04$, which we assign as the dominant systematic uncertainty on $S_{K_S^0\pi^0}$. We include a systematic uncertainty of 0.03 on $S_{K_S^0\pi^0}$ and 0.01 on $C_{K_S^0\pi^0}$ to account for a possible misalignment of the SVT. We consider large variations of the IP position and resolution, which we find to have negligible impact. We assign a systematic uncertainty of 0.09 to $C_{K_S^0\pi^0}$ due to possible asymmetries in the rate of B^0 versus $\overline{B}^0$ tags in background events. Finally, we include a systematic uncertainty of 0.02 on both $S_{K_S^0\pi^0}$ and $C_{K_S^0\pi^0}$ to account for imperfect knowledge of the PDFs used in the fit.

In summary, we have performed a measurement of the time-dependent CPV asymmetries in $B^0 \to K_S^0\pi^0$. These results supersede our previous measurement of $C_{K_S^0\pi^0}$ [17], which only relied on time-integrated observables, and introduce the first measurement of $S_{K_S^0\pi^0}$.

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