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Measurement of CP asymmetries in $B^0 \to K_S^0 K_S^0 K_S^0$ decays

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We present measurements of the time-dependent *CP*-violating asymmetries in $B^0 \to K_S^0 K_S^0 K_S^0$ decays based on 384×10^6 $\Upsilon(4S) \to B\bar{B}$ decays collected with the *BABAR* detector at the PEP-II asymmetric-energy *B* Factory at SLAC. We obtain the *CP* asymmetry parameters $C = 0.02 \pm 0.21 \pm 0.05$ and $S = -0.71 \pm 0.24 \pm 0.04$, where the first uncertainties are statistical and the second systematic. These results are consistent with standard model expectations.

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In the standard model (SM) of particle physics, the decays $B^0 \to K_S^0 K_S^0 K_S^0$ are dominated by the $b \to s\bar{s}s$ gluonic penguin amplitude. A large violation of *CP* symmetry is predicted by the SM in the proper-time dependence of $b \to c\bar{c}s$ decays of neutral *B* mesons. Recent measurements of *CP* violation in $b \to c\bar{c}s$ decays [1] are in good agreement with the SM prediction [2]. The predicted amplitude of this *CP* violation (CPV) is $\sin2\beta$, where $\beta = \arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$ is defined in terms of the elements V_{ij} of the Cabibbo-Kobayashi-Maskawa (CKM) [3] quark mixing matrix. The SM also predicts that the amplitude of time-dependent CPV in $b \to s\bar{q}q$ $(q = d, s)$ decays, defined as $\sin2\beta_{\rm eff}$, is approximately equal to $\sin2\beta$. Contributions from loops involving non-SM particles can give large corrections to the time-dependent CPV amplitudes for these decays. The theoretical uncertainty in the SM prediction of $\sin2\beta_{\rm eff}$ is particularly small, less than 4%, for the decay $B^0 \to K_S^0 K_S^0 K_S^0$, which is a pure *CP*-even eigenstate [4]. A violation of $\sin2\beta_{\rm eff} \simeq \sin2\beta$ would be a clear sign of physics beyond the SM [5]. In this paper we present a measurement of the time-dependent *CP*-violating asymmetries in the decay $B^0 \to K_S^0 K_S^0 K_S^0$ [6].

The results presented here are based on $(383.6 \pm 4.2) \times 10^6$ $\Upsilon(4S) \to B\bar{B}$ decays collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider, located at the Stanford Linear Accelerator Center. The *BABAR* detector [7] measures the trajectories of charged particles with a five-layer double-sided silicon microstrip detector (SVT) and a 40-layer central drift chamber (DCH), both operating in a uniform 1.5 T magnetic field. Charged kaons and pions are identified using measurements of particle energy loss in the SVT and DCH, and of the Cherenkov cone angle in a detector of internally reflected Cherenkov light. A segmented CsI(Tl) electromagnetic calorimeter (EMC) provides photon detection and electron identification. Finally, the instrumented flux return of the magnet allows discrimination of muons from pions.

The time-dependent *CP* asymmetries are functions of the proper-time difference $\Delta t \equiv t_{CP} - t_{\rm tag}$ between a fully reconstructed $B^0 \to K_S^0 K_S^0 K_S^0$ decay (B_{CP}) and the other *B* meson decay in the event ($B_{\rm tag}$), which is partially reconstructed. The decay rate f_+ (f_-) when the tagging meson is a B^0 ($\bar{B}^0$) is given as

$$f_\pm(\Delta t) \propto \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[1 \pm S\sin(\Delta m_d \Delta t) \mp C\cos(\Delta m_d \Delta t)], \tag{1}$$

where τ_{B^0} is the B^0 lifetime and Δm_d is the $B^0 - \bar{B}^0$ mixing frequency. The parameters *C* and *S* describe the amount of *CP* violation in decay and in the interference between decays with and without mixing, respectively. Neglecting CKM-suppressed decay amplitudes, we expect $S = -\sin2\beta$ and $C = 0$ in the SM.

The data are divided into two subsamples, one where all three K_S^0 mesons decay into the $\pi^+\pi^-$ channel ($B_{CP(+-)}$) and another where one of the K_S^0 mesons decays into the $\pi^0\pi^0$ channel, while the other two decay into the $\pi^+\pi^-$ channel ($B_{CP(00)}$).

We form $\pi^0 \to \gamma\gamma$ candidates from pairs of photon candidates in the EMC. An energy deposit in the EMC is determined to be a photon candidate if no track intersects any of its crystals, it has a minimum energy of 50 MeV, and it has the expected lateral shower shape in the EMC. We reconstruct $K_S^0 \to \pi^0\pi^0$ candidates from π^0 pairs with an invariant mass in the range $480 < m_{\pi^0\pi^0} < 520$ MeV$/c^2$. We reconstruct $K_S^0 \to \pi^+\pi^-$ candidates from pairs of oppositely charged tracks, originating from a common vertex, with an invariant mass within 12 MeV$/c^2$ (about 4 standard deviations) of the nominal K_S^0 mass [2]. We also require the decay vertex to be along the expected flight path and the significance of the reconstructed flight distance $\tau_{K_S^0}/\sigma_{\tau_{K_S^0}}$ to be larger than 5.

For each $B_{CP(+-)}$ candidate two nearly independent kinematic variables are computed; the beam-energy-substituted mass $m_{\rm ES} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$, and the energy difference $\Delta E = E_B^* - \sqrt{s}/2$. Here, $(E_i, \mathbf{p}_i) \equiv q_{e^+e^-}$ is the four-momentum of the initial e^+e^- system in the laboratory frame and $\sqrt{s}$ is the center-of-mass energy, while $\mathbf{p}_B$ is the reconstructed momentum of the B^0 candidate in the laboratory frame and E_B^* is its energy calculated in the e^+e^- rest frame. For each $B_{CP(00)}$ candidate we use two different kinematic variables. They are the reconstructed B^0 mass m_B and the missing mass $m_{\rm miss} = \sqrt{(q_{e^+e^-} - \tilde{q}_B)^2}$, where $\tilde{q}_B$ is the four-momentum of the $B_{CP(00)}$ candidate after a mass constraint on the B^0 meson has been applied. Because of leakage effects in the EMC, which affect the photon energy measurement and therefore the π^0 reconstruction, the shape of the m_B distribution is asymmetric around the mean value. This results in this combination of variables being less correlated than ΔE and $m_{\rm ES}$, with better background suppression [8].

For B_{CP} signal decays, the $m_{\rm ES}$, $m_{\rm miss}$, and m_B distributions peak near the B^0 mass, while the ΔE distribution peaks near zero. For $B_{CP(+-)}$ candidates, we require $5.22 < m_{\rm ES} < 5.30\ {\rm GeV}/c^2$ and $|\Delta E| < 120\ {\rm MeV}$. For $B_{CP(00)}$ candidates, we require $5.11 < m_{\rm miss} < 5.31\ {\rm GeV}/c^2$ and $|m_B - m_B^{PDG}| < 150\ {\rm MeV}/c^2$, where m_B^{PDG} represents the world-average B^0 mass [2]. These selection windows include the signal peak and a "sideband" region which is used for characterization of the background.

The sample of B_{CP} candidates is dominated by random $K_S^0K_S^0K_S^0$ combinations from $e^+e^- \to q\bar{q}$ $(q = u, d, s, c)$ fragmentation (the $q\bar{q}$ continuum). We use topological observables to discriminate jetlike $e^+e^- \to q\bar{q}$ events from the more spherical $B\bar{B}$ events. In the e^+e^- rest frame we compute the angle θ_T^* between the thrust axis of the $B_{CP(+-)}$ ($B_{CP(00)}$) candidate's decay products and that of the remaining particles in the event. We require $|\cos\theta_T^*| < 0.90(0.95)$, which reduces the number of background events by 1 order of magnitude. We also use the Legendre monomials L_0 and L_2, for the characterization of the event shape [8]. The monomials are combined in a Fisher discriminant $\mathcal{F}$ [8] (ratio $l_2 = L_2/L_0$) for $B_{CP(+-)}$ ($B_{CP(00)}$) candidates, and it is used in the maximum-likelihood fit described below.

The average B_{CP} candidate multiplicity in the $B_{CP(00)}$ sample is approximately 1.7, coming from multiple $K_S^0 \to \pi^0\pi^0$ combinations. In these events, we select the combination with the smallest $\chi^2 = \sum_i(m_i - m_{K_S^0})^2/\sigma_{m_i}^2$, where m_i ($m_{K_S^0}$) is the measured (world-average) K_S^0 mass [2] and σ_{m_i} is its estimated uncertainty. We use the same method in the $B_{CP(+-)}$ sample, where only 1.4% of events have more than one $B_{CP(+-)}$ candidate.

Since $B^0 \to \chi_{c0,2}K_S^0$ decays proceed through a $b \to c\bar{c}s$ transition, we remove all $B_{CP(+-)}$ ($B_{CP(00)}$) candidates with a $K_S^0K_S^0$ mass combination within 3σ (2σ) of the χ_{c0} or χ_{c2} mass. After these vetoes, the total reconstruction efficiency, including K_S^0 branching fractions, is about 6% (3%) for $B_{CP(+-)}$ ($B_{CP(00)}$) candidates, assuming a uniform Dalitz distribution.

The remaining background from $B\bar{B}$ events is estimated to be negligible for the $B_{CP(+-)}$ sample and is absorbed into the $q\bar{q}$ continuum component. For the $B_{CP(00)}$ sample, we extract the yield of $B\bar{B}$ background events simultaneously with the signal and $q\bar{q}$ event yields.

A multivariate tagging algorithm determines the flavor of the $B_{\rm tag}$ meson and classifies it in one of seven mutually exclusive tagging categories [1,9]. They rely upon the presence of prompt leptons, or one or more charged kaons and pions in the event, and have different purities. We measure the performance of this algorithm with a data sample ($B_{\rm flav}$) of fully reconstructed $B^0 \to D^{(*)-}\pi^+/\rho^+/a_1^+$ decays. The effective tagging efficiency is $Q \equiv \sum_c \varepsilon^c(1 - 2w^c)^2 = 0.304 \pm 0.003$, where ε^c (w^c) is the efficiency (mistag probability) for events tagged in category c.

We compute the proper-time difference $\Delta t = \Delta z/\gamma\beta c$ using the known boost of the e^+e^- system and the measured separation between the B_{CP} and $B_{\rm tag}$ decay vertices along the boost direction ($\Delta z = z_{CP} - z_{\rm tag}$) [9]. For the B_{CP} decay, where no charged particles are produced at the decay vertex, we determine the decay point by constraining the B production vertex to the interaction point (IP) in the plane orthogonal to the beam axis using only the $K_S^0 \to \pi^+\pi^-$ trajectories. The IP position is determined on a run-by-run basis from two-track events. We compute Δt and its uncertainty $\sigma_{\Delta t}$ from a geometric fit to the $\Upsilon(4S) \to B^0\bar{B}^0$ system that takes into account this IP constraint and a Gaussian constraint on the sum of the two B decay times ($t_{CP} + t_{\rm tag}$) to be equal to $2\tau_{B^0}$ with an uncertainty of $\sqrt{2}\tau_{B^0}$ [8,10]. In order to ensure a well-determined vertex separation between $B_{\rm rec}$ and $B_{\rm tag}$, we exclude events that have the error on Δt, determined from the vertex fit, $\sigma_{\Delta t} > 2.5$ ps and events with $|\Delta t| > 20$ ps. The mean uncertainty in z_{CP}, a convolution of the uncertainty in the interaction region position and the $z_{\rm tag}$ resolution, is 75 μm. The mean uncertainty on $z_{\rm tag}$ is about 200 μm, which dominates the Δz uncertainty. The resulting Δz resolution is comparable to that in $B^0 \to J/\psi K_S^0$ decays [8]. Simulation studies and a $B^0 \to J/\psi K_S^0$ data control sample show that the procedure we use to determine the vertex for a B_{CP} decay provides an unbiased estimate of z_{CP} [8].

Most events have at least one K_S^0 candidate for which both tracks have at least one hit in the inner three SVT layers. We have verified on simulation and on data control samples that the parameters of the signal Δt resolution function for these B_{CP} signal decays are similar to those obtained from the $B_{\rm flav}$ sample [9]. When at least one K_S^0 has tracks with hits in the outer two SVT layers but not in the inner three layers, the resolution is nearly two times worse and the Δt information is not used.

We extract the event yields and *CP* parameters with an unbinned extended maximum-likelihood fit to the kinematic, event shape, and Δt variables. For each of the subsamples $k = 1, 2$ ($B_{CP(+-)}$, $B_{CP(00)}$) we use

$$\mathcal{L}_k = e^{-(\sum_j^n N_j)} \prod_i^{N_T} \sum_j^n N_j \mathcal{P}_j^i,$$

where $\mathcal{P}_j$ is the probability density function (PDF) for the jth fit component. N_j is the event yield of each of the n components: N_S signal events, $N_{q\bar{q}}$ continuum $q\bar{q}$ events and, for $B_{CP(00)}$ only, $N_{B\bar{B}}$ $B\bar{B}$ background events; N_T is the total number of events selected. For $B_{CP(+-)}$ ($B_{CP(00)}$) candidates, the PDF $\mathcal{P}_j$ is given by the product of $\mathcal{P}_j(m_{\rm ES})\mathcal{P}_j(\Delta E)\mathcal{P}_j(\mathcal{F})$ ($\mathcal{P}_j(m_{\rm miss})\mathcal{P}_j(m_B)\mathcal{P}_j(l_2)$)$\mathcal{P}_j^c(\Delta t, \sigma_{\Delta t})\varepsilon^c$, summed over the tagging categories c. The product $\mathcal{L}_1\mathcal{L}_2$ is maximized to determine the common *CP* asymmetry parameters S and C and the values of N_j, which are specific to each subsample.

TABLE I. Event yields and *CP* asymmetry parameters obtained in the fit. The errors are statistical only.

	$B_{CP(+-)}$	$B_{CP(00)}$	Combined
N_S	125 ± 13	64 ± 12	$\cdots$
$N_{q\bar{q}}$	732 ± 28	4942 ± 77	$\cdots$
$N_{B\bar{B}}$	$\cdots$	-14 ± 32	$\cdots$
S	$-1.06^{+0.25}_{-0.16}$	0.24 ± 0.52	-0.71 ± 0.24
C	$-0.08^{+0.23}_{-0.22}$	0.23 ± 0.38	0.02 ± 0.21

Along with S and C, the fit extracts ε^c and parameters describing the background.

A fit to 857 $B_{CP(+-)}$ and 4992 $B_{CP(00)}$ candidates returns the event yields reported in Table I. Figure 1 shows the $m_{\rm ES}$ and ΔE ($m_{\rm miss}$ and m_B) distributions for signal and background $B_{CP(+-)}$ ($B_{CP(00)}$) candidates. The extracted *CP* parameters for the two separate subsamples and the combined ones are shown in Table I. Using a Monte Carlo (MC) technique, in which we assume that the measured values for the *CP* parameters on the combined data sample are the true values, we find that the two subsamples agree within 1.6σ. The statistical significance of the *CP* violation is evaluated as $\sqrt{2 \cdot \Delta \ln(\mathcal{L}_1 \mathcal{L}_2)}$, where $\Delta \ln(\mathcal{L}_1 \mathcal{L}_2)$ is the change in the natural log of the combined likelihood for the no *CP*-violation hypothesis with respect to the maximum value. We estimate it to be 2.9 standard deviations.

Figure 2 shows distributions of Δt for B^0 and $\bar{B}^0$-tagged events, and the asymmetry $\mathcal{A}(\Delta t) = (N_{B^0} - N_{\bar{B}^0})/(N_{B^0} + N_{\bar{B}^0})$.

Systematic uncertainties on the *CP* parameters are given in Table II. The systematic errors are evaluated using large samples of simulated B_{CP} decays and the $B_{\rm flav}$ data sample. We perform fits to the simulated B_{CP} signal with parameters obtained either from signal or $B_{\rm flav}$ events to account for possible differences in the Δt resolution function. We use the differences in the resolution function and tagging parameters extracted from these samples to vary the signal parameters. We account for possible biases due to the vertexing technique by comparing fits to a large simulated sample of IP-constrained (neglecting the J/ψ contribution to the vertex and using the K^0_S trajectory only) and nominal $B^0 \to J/\psi K^0_S$ events. Several SVT misalignment scenarios are applied to the simulated B_{CP} events to estimate detector effects. We consider variations of 20 μm in the direction orthogonal to the beam axis for the IP position and resolution and find they have a negligible impact. The systematic error due to correlations between the variables used in

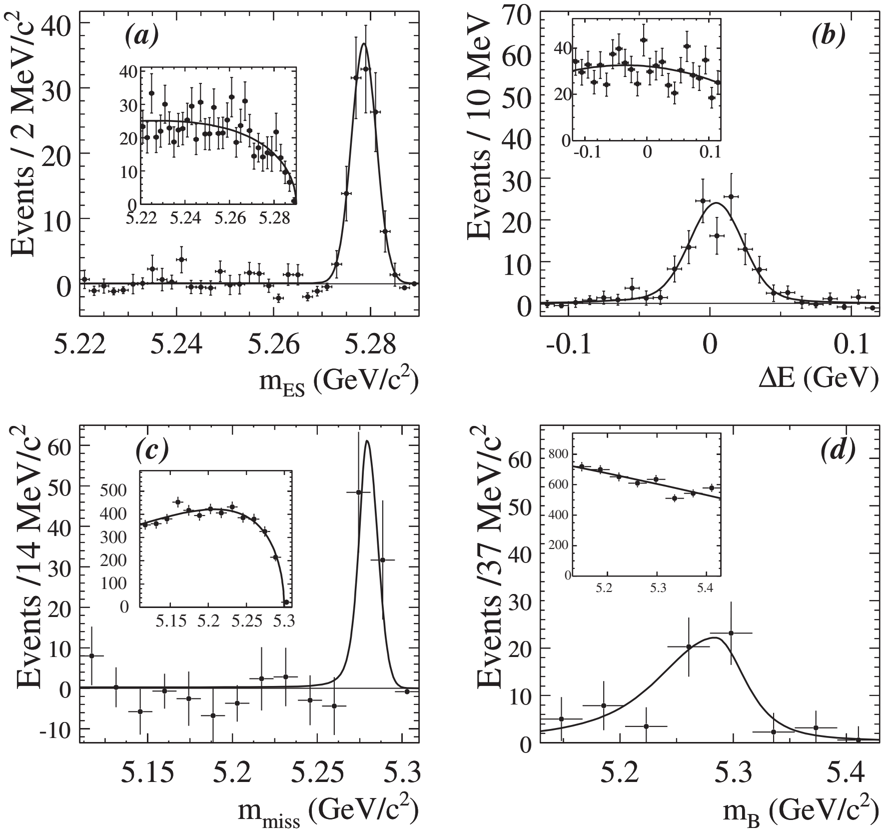

FIG. 1. Signal and background distributions of (a) $m_{\rm ES}$ and (b) ΔE for $B_{CP(+-)}$ candidates and of (c) $m_{\rm miss}$ and (d) m_B for $B_{CP(00)}$ candidates. The signal and background distributions have been separated using the technique described in [13]. The curves represent the PDF projections. The background distributions are shown in the insets.

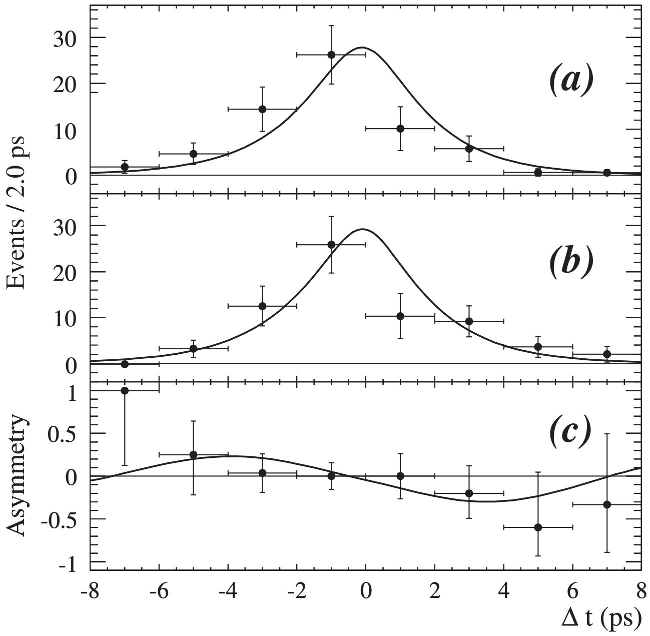

FIG. 2. Distributions of Δt for events weighted using the technique described in [13] for $B_{\rm tag}$ tagged as (a) B^0 or (b) $\bar{B}^0$, and (c) the asymmetry $\mathcal{A}(\Delta t)$. The points are the weighted data and the curves are PDF projections.

the fit is determined from a fit to a sample of randomly selected signal MC events added to background events generated from the background PDFs used in the fit. The values of the effective *CP* parameters for the $B\bar{B}$ background, which are fixed to zero in the nominal fit, are varied over the whole physically allowed range. The largest deviations in S and C resulting from this variation are used as systematic uncertainties. The world-average values of Δm_d and of the B^0 mean lifetime, τ_{B^0}, held fixed in the fit, are varied by their uncertainties [2]. We account for the possible interference between the suppressed $\bar{b} \rightarrow \bar{u}c\bar{d}$ and the favored $b \rightarrow c\bar{u}d$ amplitudes for some $B_{\rm tag}$ decays [11]. Finally, we include a systematic uncertainty to account for imperfect knowledge of the PDFs used in the fit. Most of this uncertainty is due to MC statistics, the rest to differences between data control samples and MC simulation.

TABLE II. Systematic uncertainties on S and C.

	$\sigma(S)$	$\sigma(C)$
Vertex reconstruction	0.016	0.003
Resolution function	0.005	0.007
Flavor tagging	0.009	0.015
SVT alignment and IP position	0.016	0.008
Fit correlation	0.004	0.025
$B\bar{B}$ *CP*, Δm_d, and τ_{B^0}	0.008	0.009
Tag-side interference	0.001	0.011
PDFs	0.026	0.031
Total	0.037	0.046

In summary, we measured the $B^0 \rightarrow K^0_S K^0_S K^0_S$ time-dependent *CP* asymmetries, $S = -0.71 \pm 0.24 \pm 0.04$ and $C = 0.02 \pm 0.21 \pm 0.05$ where the first errors are statistical and the second systematic. The statistical correlation between S and C is -14.1%. These results agree well with the SM expectation. This measurement, which is limited by the small statistics of the sample, constrains, but does not exclude contributions from physics beyond the SM, such as the low-energy supersymmetry [5]. These results supersede our previously published *CP* asymmetry results for $B^0 \rightarrow K^0_S K^0_S K^0_S$ [12] and are consistent with the measurements performed by the Belle Collaboration reported in [1].

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