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Branching Fraction and CP Asymmetries of $B^0 \rightarrow K_S^0 K_S^0 K_S^0$
The amplitude of time-dependent CP violation (CPV) predicted for $b \rightarrow c\bar{s}q$ decays of neutral B mesons in the standard model (SM) is $\sin 2\beta$ where $\beta = \arg(-V_{cb}V_{cb}^*/V_{ub}V_{ub}^*)$ is the CP violating phase difference between mixing and decay amplitudes, with $V_{ij}$ the elements of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix [1]. This prediction has been well tested at the B factories in recent years [2]. The SM also predicts the amplitude of CPV in $b \rightarrow s\bar{q}q$ decays, defined as $\sin 2\beta_{\text{eff}}$, to be approximately $\sin 2\beta$. However, since $b \rightarrow s\bar{q}q$ decays are dominated by one-loop transitions that can potentially accommodate large virtual particle masses, contributions from physics beyond the SM could invalidate this prediction, making these decays especially sensitive to additional SM physics contributions that obscure the measurement of $\beta_{\text{eff}}$ [5], or are not CP eigenstates. Two decays to CP eigenstates that have been noted as having small theoretical uncertainties in the measurement of $\beta_{\text{eff}}$ are $B^0 \rightarrow \phi K_S^0$ [6–8] (CP odd) and $B^0 \rightarrow K_S^0 K^0_S K^0_S$ (CP even) [9].

In this Letter we present a measurement of time-dependent CP-violating asymmetries in the decay $B^0 \rightarrow K_S^0 K_Q^0 K_Q^0$, along with a measurement of the branching fraction (BF). Until recently the small branching fraction [10] and the absence of charged decay tracks originating at the $B^0$ decay vertex have limited the ability to extract CP parameters from $B^0 \rightarrow K_S^0 K^0_S K^0_S$. However, techniques recently developed to deal with the reconstruction of the $B^0$ decay vertex in $B^0 \rightarrow K_S^0 \pi^0$ have made this measurement possible [11].

The time-dependent CP asymmetry is obtained by measuring the proper-time difference $\Delta t \equiv t_{\text{CP}} - t_{\text{tag}}$ between a fully reconstructed decay $B^0 \rightarrow K_S^0 K^0_S K^0_S$ and the partially reconstructed tagging $B$ meson ($B_{\text{tag}}$). The asymmetry in the decay rate $f_+ (f_-)$ when the tagging meson is a $B^0$ ($\bar{B}$) is given as

$$f_\pm (\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \times \left[ 1 \pm S \sin(\Delta m_d \Delta t) \mp C \cos(\Delta m_d \Delta t) \right],$$

where the parameters $S$ and $C$ describe the amount of CP violation in decay and in the interference between decay with and without mixing, respectively. Neglecting CKM-suppressed amplitudes, we expect $S = -\sin 2\beta$ and $C = 0$ in the SM.

The results presented here are based on 226.6 ± 2.5 million $Y(4S) \rightarrow BB$ decays collected with the BABAR detector at the PEP-II asymmetric-energy $B$ factory at SLAC. We obtain a branching fraction of $(6.9^{+0.8}_{-0.6} \pm 0.6) \times 10^{-6}$, and CP asymmetries $C = -0.34^{+0.28}_{-0.25} \pm 0.05$ and $S = -0.71^{+0.22}_{-0.32} \pm 0.04$, where the first uncertainties are statistical and the second systematic.

The amplitude of CPV in $b \rightarrow s\bar{q}q$ decays, defined as $\sin 2\beta_{\text{eff}}$, is $0.0001$ with a $0.0012$ statistical uncertainty and a $0.0012$ systematic uncertainty. Furthermore, $\Delta t_{\text{BF}} = 4.7_{-0.3}^{+0.2}$, where the $0.3$ is statistical and the second systematic. As expected, we find $S = -0.34^{+0.28}_{-0.25} \pm 0.05$ and $C = 0$. This measurement is in agreement with the SM predictions.

We exploit topological observables to discriminate the jetlike $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) fragmentation. Monte Carlo (MC) studies show that contributions from other $B$ meson decays can be neglected. We exploit topological observables to discriminate the jetlike $e^+e^- \rightarrow q\bar{q}$ events from the more uniformly distributed $BB$ events. In the $Y(4S)$ rest frame we compute the angle $\theta^0_{\pi^0}$ between the thrust axis of the $B^0$...
candidate and that of the remaining particles in the event. While |cosθ∥ is highly peaked near 1 for e⁺e⁻ → q̅q̅ events, it is nearly uniformly distributed for B̅B events. We require |cosθ∥ < 0.9, eliminating ~68% of the background. In addition, we use a Fisher discriminant variable (F), based on the momenta and angles of tracks in the event [11], in the maximum-likelihood fit described below.

For the 1.4% of events with more than one candidate we select the combination with the smallest χ² = Σ[(m_i - m_KS)/(σ_i)]², where m_i (m_KS) is the measured (nominal K_S mass) and σ_i is the estimated uncertainty on the mass of the i-th K_S candidate. We also remove all B^0 candidates that have a K^0_SK^0_S or B^0B^0 mass combination within 3σ (45 MeV/c²) of the X_c0 or X_c2 mass. While we expect few X_c0 or X_c2 decay into K^0_SK^0_S in our final sample, these are b → c̅c̅s decays that would bias the CP-asymmetry measurement.

We extract the results from unbinned maximum-likelihood fits to the kinematic, event-shape (F) and Δt variables. We maximize the logarithm of an extended likelihood function

$$L = e^{-(N_S + N_B)} \times \prod_{i} [N_S P_S^i + N_B P_B^i],$$

where P_S and P_B are the probability density functions (PDFs) for signal (S) and continuum background (B), N_S is the total number of events, and N_B are the event yields to be determined from the fit. The product is over the selected events. The observables are sufficiently uncorrelated that we can construct the likelihoods as the products of one-dimensional PDFs. The PDFs for signal are parameterized from signal MC events. For background PDFs we determine the functional form from data in the sidband 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 fit results.

For the branching fraction fit we use only the kinematic and event-shape variables (P_BF = P(m_ES, P(ΔE,F))). There are two yields and six continuum PDF parameters floated in the fit. There are 721 K^0_SK^0_SK^0_S candidates that pass all the above criteria, and the fit to this data yields N_S = 88 ± 10 events and N_B = 633 ± 26 events. Figure 1 shows the m_ES and ΔE distributions for these events with the results of the fit plotted as curves. As a check we also add a fit component for random combinatorial B background, with PDF parameters determined from large MC samples. This fit finds 14 ± 11 candidates assigned to the B background. These candidates come from the continuum background; the signal yield changes by less than one candidate. A signal reconstruction efficiency of 5.6% is derived from a large MC sample in which the K_S reconstruction efficiency is carefully matched with that observed in large hadronic data samples. Assuming equal production rates of B^0B^0 and B^+B^-, we determine B(B^0 → K^0_SK^0_SK^0_S) = (6.9 ± 0.9 ± 0.6) × 10^-6.

The largest systematic error (5%) for the branching fraction measurement comes from our uncertainty on the efficiency of reconstructing K^0_S → π^+π^- decays [14]. We determine uncertainties of 4% for the effect of the candidate selection cuts and 5% for the parametrization of the PDFs used in the fit. The remaining uncertainties, including possible errors in modeling the K^0_SK^0_SK^0_S Dalitz plot distribution in determining the signal efficiency, combine to 2%.

The CP-fit PDF for a given tagging category is P_{CP} = P_BF P(Δt, σ, E, c) where c is the tagging efficiency for tag category c. The total likelihood L is the product of likelihoods for each tagging category, and the free parameters are determined by maximizing the quantity lnL. Along with the CPV asymmetries S and C, the fit extracts c for the background and other background parameters. The background PDFs include parameters for the Δt-resolution function R and for asymmetries in the rate of B^0 versus B̅^0 tags. We extract 25 parameters from the CP fit.

We use a neural network to determine the flavor of the B_tag meson from kinematic and particle-identification information [15]. Each event is assigned to one of six mutually exclusive tagging categories, designed to combine flavor tags with similar performance and Δt resolution. We parameterize the performance of this algorithm with a data sample (B_{flav}) of fully reconstructed B^0 → D_i(0)π^+/ρ^+/a_i^+ decays. The effective tagging efficiency obtained from this sample is Q_i = Σ (1 - 2w_i) = 0.305 ± 0.004, where w_i are the efficiencies and mistag probabilities, respectively, for events tagged in category i.

We compute the proper-time difference Δt = (z_{CP} - z_{tag})/γβc using the known boost of the e⁺e⁻ system and the measured Δz = z_{CP} - z_{tag}, the difference of the reconstructed decay vertex positions of the B^0 → K^0_SK^0_SK^0_S and B_tag candidate along the boost direction (z). A
description of the inclusive reconstruction of the $B_{\text{tag}}$ vertex is given in Ref. [16]. For the $B^0 \rightarrow K_S^0 K_S^0 K_S^0$ decay, where no charged particles are present at the decay vertex, we constrain the $B$ meson production vertex to the interaction point (IP) in the transverse plane using a geometric fit. 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 on the IP position, which follows from the size of the interaction region, is about 150 $\mu$m horizontally and 4 $\mu$m vertically. The uncertainty on $z_{CP}$, a convolution of the interaction region and the vertex of the $B^0 \rightarrow K_S^0 K_S^0 K_S^0$ decay, is about 75 $\mu$m. The uncertainty on $z_{tag}$ is about 200 $\mu$m and thus the uncertainty in $\Delta z$ is dominated by the uncertainty in the vertex of the tagging decay. The resulting resolution is comparable to that in $B^0 \rightarrow J/\psi K_S^0$ [11].

Simulation studies show that the procedure we use to determine the vertex for a $B^0 \rightarrow K_S^0 K_S^0 K_S^0$ decay provides an unbiased estimate of $z_{CP}$. The estimate of the $\Delta t$ error in an event reflects the strong dependence of the $z_{CP}$ resolution on the number of SVT layers traversed by the $K_S^0$ decay daughters. However, essentially all events have at least one $K_S^0$ candidate for which both tracks have at least one hit in the inner three SVT layers (at radii from 3.2 to 5.4 cm). In this case the mean $\Delta t$ resolution is comparable to that in decays in which the vertex is directly reconstructed from charged particles originating at the $B$ decay point [16]. For a small fraction (0.1%) of the signal events, at least one $K_S^0$ has tracks with hits in the outer two SVT layers (at radii from 9.1 to 1.44 cm) but none of the three $K_S^0$s have hits in the inner three layers. In this case the resolution is nearly 2 times worse but the event can still be used in the $CP$ fit. Events with $\sigma_{\Delta t} > 2.5$ ps or $|\Delta t| > 20$ ps are excluded from the $CP$ fit.

The resolution function $R$ is parameterized as the sum of a “core” and a “tail” Gaussian distribution, each with a width and mean proportional to $\sigma_{\Delta t}$, and a third Gaussian with a mean of zero and a width fixed at 8 ps [16]. We have verified with MC simulation that the parameters of $R$ for $B^0 \rightarrow K_S^0 K_S^0 K_S^0$ decays are similar to those obtained from the $B_{\text{flav}}$ sample. Therefore, we extract these parameters from a fit to the $B_{\text{flav}}$ sample. We find that the $\Delta t$ distribution of background candidates is well described by a delta function convolved with a resolution function having the same functional form as that for the signal. The parameters of the background function are determined in the fit.

The fit including $\Delta t$ and tagging information yields $S = -0.71^{+0.38}_{-0.32} \pm 0.04$ and $C = -0.34^{+0.28}_{-0.25} \pm 0.05$. Fixing $C = 0$, we obtain $\sin 2\beta = -S = 0.79^{+0.29}_{-0.36} \pm 0.04$. Figure 2 shows distributions of $\Delta t$ for $B^{+}$-tagged and $B^{0}$-tagged events, and the asymmetry $A(\Delta t) = (N_{B^+} - N_{B^0})/(N_{B^+} + N_{B^0})$, obtained by making a likelihood ratio cut to remove the background component.

Systematic uncertainties on the $CP$ parameters are given in Table I. The systematic errors are evaluated with large

| TABLE I. Systematic uncertainties on $S$ and $C$. |
|----------------|------|------|
| Resolution function | $0.017$ | $0.017$ |
| Vertex reconstruction | $0.020$ | $0.022$ |
| SVT alignment | $0.015$ | $0.008$ |
| Background asymmetry | $0.007$ | $0.022$ |
| Fit correlation | $0.016$ | $0.004$ |
| Tag-side interference | $0.008$ | $0.015$ |
| PDFs | $0.025$ | $0.026$ |
| Total | $0.044$ | $0.047$ |

FIG. 2 (color online). Distributions of $\Delta t$ for background subtracted events for $B_{\text{tag}}$ tagged as (a) $B^+$ or (b) $B^0$, and (c) the asymmetry $A(\Delta t)$. We use a likelihood ratio cut that removes 96% of the background while retaining 95% of the signal.
the possible interference between the suppressed $\bar{b} \to \bar{u}c\bar{d}$ and the favored $b \to c\bar{u}d$ amplitude for some tagside $B$ decays [17]. Finally, we include a systematic uncertainty to account for imperfect knowledge of the PDFs used in the fit. Most of the uncertainties on the PDFs are statistical and some are associated with data and MC differences. As an additional check, a $B$ background component is added to the $CP$ fit and we find the variation of the asymmetries to be negligible.

In summary, we have measured the $B^0 \to K^{*0}_{S}K^{0}_{S}$ branching fraction and the time-dependent CPV asymmetries. The BF measurement is in good agreement with previous measurements [10]. The measurements of $S$ and $C$ are in good agreement with the SM expectation.

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Note added.—We became aware of a submission by the Belle Collaboration [18] on the same subject, while this paper was under review.

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