Measurement of Time-Dependent CP-Violating Parameters in $B^0 \rightarrow K_S^0 K_S^0$ decays

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We report a measurement of the $CP$-violating parameters in $B^0 \to K_S^0 K_S^0$ decays based on a data sample of $657 \times 10^6 \ B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider. In this study, one neutral $B$ meson is fully reconstructed in the $B^0 \to K_S^0 K_S^0$ decay mode, and the flavor of the accompanying $B$ meson is identified by its decay products. The $CP$-violating parameters are measured from the asymmetry in the distributions of the proper-time interval between the two $B$ decays: $S_{K_S^0 K_S^0} = -0.38 \pm 0.38 \text{(stat)} \pm 0.05 \text{(syst)}$ and $A_{K_S^0 K_S^0} = -0.38 \pm 0.38 \text{(stat)} \pm 0.05 \text{(syst)}$.

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$B^0$ meson decays proceeding via flavor-changing $b \to d\bar{q}q$ or $s\bar{q}q$ transitions are sensitive to new physics (NP) contributions affecting the internal quark loop diagrams. Such NP contributions can add new weak phases and subsequently cause deviations from the standard model (SM) expectations for $CP$-violating parameters $f_{\text{tag}}$ that distinguishes between $B^0$ and $\bar{B}^0$, the decay rate has a time dependence $\hat{\mathcal{P}}$ given by

$$\mathcal{P}_{K_S^0 K_S^0}(\Delta t) = \frac{e^{-\Delta t/\tau_{B^0}}}{4\tau_{B^0}} \left[ 1 + q \cdot \{ S_{K_S^0 K_S^0} \sin(\Delta m_d \Delta t) + A_{K_S^0 K_S^0} \cos(\Delta m_d \Delta t) \} \right],$$

where $\Delta t = t_{K_S^0 K_S^0} - t_{\text{tag}}$, $\tau_{B^0}$ is the $B^0$ lifetime, $\Delta m_d$ is the mass difference between the two $B$ mass eigenstates, and $q = +1 \ (-1)$ for $f_{\text{tag}} = B^0$ ($\bar{B}^0$).

At the KEKB, the $\Upsilon(4S)$ resonance is produced with a Lorentz boost of $\beta\gamma = 0.425$ nearly along the $+z$ axis, which is defined as the direction antiparallel to the $e^+$ beamline. Since the $B^0$ and $\bar{B}^0$ mesons are approximately at rest in the $\Upsilon(4S)$ center-of-mass system (cms), $\Delta t$ can be determined from the displacement in $z$ between the $K_S^0 K_S^0$ and $f_{\text{tag}}$ decay vertices: $\Delta t \simeq (z_{K_S^0 K_S^0} - z_{\text{tag}})/(\beta\gamma c) \equiv \Delta z/(\beta\gamma c)$.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber, an array of aerogel threshold Cherenkov counters, a barrel-like arrangement of time-of-flight scintillation counters, an electromagnetic calorimeter, which are located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return located outside of the coil is instrumented to detect $K_L^0$ mesons and to identify muons. Two inner detector configurations were used. A 2.0 cm-radius beam pipe and a 3-layer SVD (SVD1) was used for the first data sample of $152 \times 10^6 \ B\bar{B}$ pairs, while a 1.5 cm-radius beam pipe, a 4-layer SVD (SVD2), and a small-cell inner drift chamber were used to record the remaining $505 \times 10^6 \ B\bar{B}$ pairs.

We reconstruct a $K_S^0 \to \pi^+\pi^-$ candidate from a pair of oppositely charged tracks having $|\Delta M_{K_S^0}| < 0.015$.
GeV/c² corresponding to three standard deviations (σ), where ∆M_{K_S}^{bc} is the difference between their invariant mass and the nominal K_S mass [4]. Both charged tracks are required to be displaced from the IP in the transverse (r-φ) plane by more than 100 μm. The angle in the transverse plane between the K_S momentum vector and the direction defined by the K_S vertex and the IP should be less than 50 mrad. In order to suppress incorrect combinations of the two charged tracks, the mismatch in the z direction at the K_S vertex point for the two charged tracks is required to be less than 15 cm.

To identify B^0 → K_S^0 K_S^0 decay candidates, we use two kinematic variables: the energy difference ∆E ≡ E^{cms}_{beam} − E^{cms}_{beam} and the beam-energy constrained mass M_{bc} ≡ √((E^{beam}_{beam})^2 − (p_B^{cms})^2), where E^{beam}_{beam} is the beam energy in the cms and E^{cms}_{beam} and p_B^{cms} are the cms energy and momentum, respectively, of reconstructed B candidates. We select candidates satisfying |∆E| < 0.20 GeV and 5.20 GeV/c² < M_{bc} < 5.30 GeV/c². For the ∆t fit described below, we use candidates in a signal region defined as |∆E| < 0.10 GeV and 5.27 GeV/c² < M_{bc} < 5.30 GeV/c². We find that 0.2% of the selected events have multiple B^0 → K_S^0 K_S^0 candidates. In such events, we choose the B^0 → K_S^0 K_S^0 candidate having the smallest Σ(∆M_{K_S}^{bc})² value.

To suppress continuum e^+e^- → q̅q (q = u,d,s,c) events, we form a likelihood L_{sig} (L_{bkg}) for signal (continuum) events by combining a Fisher discriminant based on modified Fox-Wolfram moments [11] with the probability density function (PDF) for the cosine of the cms B^0 flight direction with respect to the +z axis. The former makes use of the difference in event shapes: signal events have a spherical topology while background events tend to be jet-like. We impose a requirement on the likelihood ratio R = L_{sig}/(L_{sig} + L_{bkg}) that retains 89% of the signal and rejects 71% of the continuum.

The b-flavor of the accompanying B meson is identified from inclusive properties of particles that are not associated with the reconstructed B^0 → K_S^0 K_S^0 candidate. The tagging information is represented by two parameters: q, as defined in Eq. (1), and r, which is an event-by-event Monte-Carlo-determined flavor-tagging dilution factor that ranges from r = 0 for no flavor discrimination to r = 1 for unambiguous flavor assignment [11]. Candidate events are selected to have r > 0.1, and are further divided into six r intervals. The wrong tag fraction w for each r interval and the differences ∆w between B^0 and B̅ decay are determined using semileptonic and hadronic b → c decay data [11].

The dominant background is continuum. We find the B̅B̅ decay background contribution to be negligibly small using a large sample of GEANT-based Monte Carlo (MC) simulated events [12]. Thus, we take into account only signal and continuum events in the nominal fit. The uncertainty due to a possible contribution from B̅B̅ decay background is included in the systematic errors.

The signal yield is extracted using a three-dimensional extended unbinned maximum likelihood (UML) fit to ∆E-M_{bc}-R distributions for the selected candidate events. For the signal component, we model the ∆E (M_{bc}) shape using a sum of two Gaussians (a single Gaussian). The parameters of the Gaussians and R distribution are obtained using MC simulation. For the background component, the ∆E (M_{bc}) shape is modeled as a first-order polynomial (an ARGUS [13]) function. The parameters of these functions are floated in the fit. The R background distribution is obtained from a data sample in the sideband region (M_{bc} < 5.26 GeV/c²). Possible correlations among ∆E, M_{bc} and R are found to be negligible for signal events from the signal MC, and to be very small for continuum events from the data sideband. We include the effect of the small correlations in the latter in the systematic errors. The fit yields 58±11 signal events among 476 B^0 → K_S^0 K_S^0 candidate events in the signal region, where the error is statistical only.

Figure 1 shows the projections of the ∆E, M_{bc} and R distributions for the candidate events.

We apply the B decay vertex reconstruction algorithm of Ref. [14]. The vertex position for a B^0 → K_S^0 K_S^0 decay is obtained using the K_S^0 → π^+π^- momentum vector and a constraint on the IP; the IP profile is the beam-energy constrained mass [9]. Both charged tracks are required to have a sufficient vertex position for a K_S^0 decay. The typical vertex reconstruction efficiency with SVD1 (SVD2) is determined to be 44% (61%) from the signal MC, and at least one additional layer with hits on both sides for SVD1, and at least two layers with hits on both sides for SVD2. Both K_S^0’s are used for the vertex reconstruction if the four pions have a sufficient number of hits in the SVD. The typical vertex reconstruction efficiency with SVD1 (SVD2) is determined to be 44% (61%) from the signal MC. The vertex position resolutions in the direction defined by the accompanying K_S^0 charged pion from the B decay. The typical vertex position resolution. The vertex position errors [15]; the dependence is calibrated to be negligible for signal events from the signal MC, and to be very small for continuum events from the data sideband. We include the effect of the small correlations in the latter in the systematic errors. The fit yields 58±11 signal events among 476 B^0 → K_S^0 K_S^0 candidate events in the signal region, where the error is statistical only.

Figure 1 shows the projections of the ∆E, M_{bc} and R distributions for the candidate events.
vertex positions are reconstructed using only a fraction $f_0$ [12]. The fraction $f_{K_S^0 K_S^0}$ is the event-by-event signal fraction depending on $\Delta E$, $M_{bc}$ and $R$. We also take into account the $r$ dependence of the signal fraction $f_{K_S^0 K_S^0}$; we determine the dependence using the signal MC and the sideband events for the signal and background components, respectively. For background events, the $\Delta t$ distribution $P_\sigma(\Delta t)$ is convolved with a function $R_\sigma(\Delta t)$, where the distribution $P_\sigma(\Delta t)$ is modeled as a sum of an exponential function and a delta function, and the function $R_\sigma(\Delta t)$ is the sum of two Gaussians. All parameters in $P_\sigma(\Delta t)$ and $R_\sigma(\Delta t)$ are determined from sideband events. We fix $\tau_{B^0}$ and $\Delta m_d$ to their world-average values [2]. To improve the statistical sensitivity to $A_{K_S^0 K_S^0}$ and $R$, we also use candidate events having no $\Delta t$ information, where both $K_S^0$'s decay outside the SVD and we do not reconstruct $B$ vertices; for these events, we use the PDF of Eq. (2) integrated over $\Delta t$. The only free parameters in the fit are $S_{K_S^0 K_S^0}$ and $A_{K_S^0 K_S^0}$, which are determined by maximizing the likelihood function $L = \prod_i P_i$, where the product is over all events. The fit to 476 $B^0 \to K_S^0 K_S^0$ candidate events, in which 216 candidate events have no $\Delta t$ information, yields

$$S_{K_S^0 K_S^0} = -0.38^{+0.69}_{-0.77} \text{(stat)} \pm 0.09 \text{(syst)}, \quad (3)$$

$$A_{K_S^0 K_S^0} = -0.38 \pm 0.38 \text{(stat)} \pm 0.05 \text{(syst)}, \quad (4)$$

where the systematic errors are described below. Figure 2 shows the $\Delta t$ distribution and raw asymmetry $A_{\text{CP}}$ in each $\Delta t$ interval, where $A_{\text{CP}} = (N_+ - N_-)/(N_+ + N_-)$, and $N_{+(-)}$ is the number of candidate events with $q = +1 (-1)$.

The systematic error is primarily due to uncertainties in the parameters of $R_\sigma(\Delta t)$ ($\pm 0.06$ on $S_{K_S^0 K_S^0}$ and $< 0.01$ on $A_{K_S^0 K_S^0}$), and uncertainties in the signal fraction $f_{K_S^0 K_S^0}$ ($\pm 0.04$ on $S_{K_S^0 K_S^0}$ and $\pm 0.03$ on $A_{K_S^0 K_S^0}$). We estimate a systematic error ($\pm 0.04$ on $S_{K_S^0 K_S^0}$ and $\pm 0.02$ on $A_{K_S^0 K_S^0}$) for uncertainties in the parameters of $P_\sigma(\Delta t)$ and $R_\sigma(\Delta t)$, and the possible contribution of, and asymmetry in, the $B\bar{B}$ decay background. The other contributions to the systematic errors come from uncertainties in the wrong tag fraction ($\pm 0.02$ on $S_{K_S^0 K_S^0}$, $\pm 0.01$ on $A_{K_S^0 K_S^0}$); fit biases ($\pm 0.02$, $\pm 0.01$), physics parameters ($\tau_{B^0}$ and $\Delta m_d$) ($0.01$, $0.01$), the vertex reconstruction ($0.01$, $0.02$), and the tag-side interference effect ($0.01$, $0.03$). Adding all these contributions in quadrature, we obtain systematic errors of $0.09$ for $S_{K_S^0 K_S^0}$ and $0.05$ for $A_{K_S^0 K_S^0}$.

Various validity checks for the measurement are performed. We measure a branching fraction for $B^0 \to K^{+}K^{-}$ of $[1.1 \pm 0.2 \text{(stat)}] \times 10^{-6}$, which is consistent with our previous measurement [13]. The $B^0$ lifetime for the $B^0 \to K_S^0 K_S^0$ candidate events is measured to be $1.58 \pm 0.44 \text{ps}$, consistent with the world average value [9]. We also fit to the sideband events of the

![Figure 1](image-url)

FIG. 1: (a) $\Delta E$, (b) $M_{bc}$ and (c) $R$ projections for the $B^0 \to K_S^0 K_S^0$ candidate events (a) with $R > 0.6$ and $5.27 \text{GeV}/c^2 < M_{bc}$, (b) with $R > 0.6$ and $|\Delta E| < 0.1 \text{GeV}$ and (c) in the signal region. The solid histogram and curves show the fit projections and the hatched areas show the background component. The points with error bars are the data.

using a $B^0 \to J/\psi K_S^0$ data control sample, where the vertex positions are reconstructed using only a $K_S^0$ and the IP profile [14]. We determine the following likelihood value for each event $i$:

$$P_i = (1 - f_0) \int [f_{K_S^0 K_S^0} P_{K_S^0 K_S^0}(\Delta t')] R_\sigma(\Delta t_i - \Delta t') + (1 - f_{K_S^0 K_S^0}) P_\sigma(\Delta t') R_{\sigma}(\Delta t_i - \Delta t') |d(\Delta t')| + f_0 P_{\text{sig}}(\Delta t_i), \quad (2)$$

where the PDF $P_{\text{sig}}(\Delta t)$ is a broad Gaussian that represents an outlier component with a small fraction $f_0$.
$B^0 \rightarrow K_S^0 K_S^0$ data sample and find no $CP$ asymmetry. Using MC pseudo-experiments, we find that the statistical errors obtained in our measurement are consistent with expectations. We apply the same procedure to the $B^0 \rightarrow J/\psi K_S^0$ data sample without using the $J/\psi$ daughter tracks for the vertex reconstruction. We obtain $S_{J/\psi K_S^0} = 0.68 \pm 0.06$(stat), which is in agreement with the world average for $\sin 2\phi_1$ [17]. We conclude that the vertex resolution for $B^0 \rightarrow K_S^0 K_S^0$ decays is well-understood. We reconstruct $1993 \pm 53 B^+ \rightarrow K_S^0 \pi^+$ [18] events and, without using the charged pion of the $B$ decay for vertex reconstruction, apply the same fit procedure. We obtain $S_{K_S^0 \pi^+} = -0.13 \pm 0.13$(stat) and $A_{K_S^0 \pi^+} = 0.01 \pm 0.06$(stat), which are consistent with no $CP$ asymmetry.

In summary, we measure time-dependent $CP$-violating parameters in $B^0 \rightarrow K_S^0 K_S^0$ decays, which are dominated by flavor-changing $b \rightarrow d\bar{s}s$ penguin transitions, based on a data sample of $657 \times 10^6 B\bar{B}$ pairs recorded with the Belle detector. We obtain $S_{K_S^0 K_S^0} = -0.38^{+0.75}_{-0.09}$(stat) $\pm 0.09$(syst) and $A_{K_S^0 K_S^0} = -0.38 \pm 0.38$(stat) $\pm 0.05$(syst). No $CP$ asymmetry is found for these decays. These results are consistent with the SM prediction and also with the other measurement [4].

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