Rapid Communications

Measurement of time-dependent *CP* violation in $B^0 \to K^0_S\pi^0\pi^0$ decays

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We report a measurement of time-dependent CP violation in $B^0 \to K^0_S\pi^0\pi^0$ decays using a data sample of 772×10^6 $B\bar{B}$ pairs collected by the Belle experiment running at the $\Upsilon(4S)$ resonance at the KEKB e^+e^- collider. This decay proceeds mainly via a $b \to s\bar{d}d$ "penguin" amplitude. The results are $\sin 2\phi_1^{\rm eff} = 0.92^{+0.27}_{-0.31}$ (stat.) ± 0.11 (syst.) and $\mathcal{A} = 0.28 \pm 0.21$ (stat.) ± 0.04 (syst.), which are the most precise measurements of CP violation in this decay mode to date. The value for the CP-violating parameter $\sin 2\phi_1^{\rm eff}$ is consistent with that obtained using decay modes proceeding via a $b \to c\bar{c}s$ "tree" amplitude.

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In the Standard Model (SM), CP violation in the quark sector is induced by a complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix [1]. At $\Upsilon(4S) \to B\bar{B}$ transitions, for neutral B meson decays into a CP eigenstate produced, the decay rate has a time dependence [2,3]

$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \times (1 + q[\mathcal{S}\sin(\Delta m_d \Delta t) + \mathcal{A}\cos(\Delta m_d \Delta t)]), \quad (1)$$

where $\mathcal{S}$ and $\mathcal{A}$ are CP-violating parameters; $q = 1$ for $\bar{B}^0$ decays and -1 for B^0 decays; Δt is the difference in decay times of the B^0 and $\bar{B}^0$ mesons; Δm_d is the mass difference between the two mass eigenstates of the $B^0 - \bar{B}^0$ system; and τ_{B^0} is the B^0 lifetime. As the $B^0 \to K^0_S\pi^0\pi^0$ decays proceed mainly via a $b \to s\bar{d}d$ "penguin" amplitude, and the final state is CP even [4], the SM expectation is $\mathcal{S} \approx -\sin 2\phi_1$ and $\mathcal{A} \approx 0$, where $\phi_1 = \arg[(-V_{cd}V^*_{cb})/(V_{td}V^*_{tb})]$ [5]. Deviations from these expectations could indicate new physics. The value of $\sin 2\phi_1$ is well measured using decays proceeding via a $b \to c\bar{c}s$ tree amplitude, and thus comparing our measurement of $\sin 2\phi_1^{\rm eff}$ to the $b \to c\bar{c}s$ value [6,7] provides a test of the SM [8]. We note that there is a $b \to u\bar{u}s$ tree amplitude that also contributes to $B^0 \to K^0_S\pi^0\pi^0$ decays and can shift $\phi_1^{\rm eff}$ from ϕ_1; however, this amplitude is doubly Cabibbo suppressed, and thus the resulting shift is very small [9]. Previously, the *BABAR* experiment studied this decay and measured $\sin 2\phi_1^{\rm eff} = -0.72 \pm 0.71 \pm 0.08$ [10]; here we present the first such measurement from the Belle experiment using a data sample 3.4 times larger than that of *BABAR*.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside the coil is instrumented to detect K^0_L mesons and to identify muons (KLM). The detector is described in detail elsewhere [11]. Two inner detector configurations were used. A 2.0 cm radius beampipe and a 3-layer silicon vertex detector was used for the first sample of $152 \times 10^6 B\bar{B}$ pairs, while a 1.5 cm radius beampipe, a 4-layer silicon detector and a small-cell inner drift chamber were used to record the remaining $620 \times 10^6 B\bar{B}$ pairs [12].

Due to the asymmetric energies of the e^+ and e^- beams, the $\Upsilon(4S)$ is produced with a Lorentz boost of $\beta\gamma = 0.425$ nearly parallel to the $+z$ axis, which is defined as the direction opposite the e^+ beam. Since the $B^0\bar{B}^0$ pair is almost at rest in the $\Upsilon(4S)$ center-of-mass (CM) frame, the decay time difference Δt can be determined from the separation along z of the B^0 and $\bar{B}^0$ decay vertices: $\Delta t \approx (z_{CP} - z_{\rm tag})/(\beta\gamma c)$, where z_{CP} and $z_{\rm tag}$ are z-coordinates of the decay positions of the B^0 decaying to the CP eigenstate and the other (tag-side), respectively. To reconstruct the decay vertices without the presence of primary charged tracks, we extrapolate the reconstructed K^0_S momentum back to the region of the interaction point (IP) and use the IP profile in the transverse plane (perpendicular to the z axis) as a constraint. This method was used in a previous Belle analysis of $B^0 \to K^0_S\pi^0$ decays [13] and is described in detail in Ref. [14]. Compared to $B^0 \to K^0_S\pi^0$ decays, the K^0_S in three-body $B^0 \to K^0_S\pi^0\pi^0$ decays has lower momentum and thus tends to decay closer to the IP; this results in about a 20% larger yield of K^0_S decays to $\pi^+\pi^-$ inside the SVD volume with a correspondingly higher vertex reconstruction efficiency and greater precision in the B decay vertex position as discussed in Ref. [4].

In the determination of the event selection, Monte Carlo simulated events (MC) are used. For the signal, 1 million events for each of nonresonant, $K^*(892)^0\pi^0$ and $f_0K^0_S$, all of which decay into a $K^0_S\pi^0\pi^0$ final state, are generated using the EVTGEN [15] event generator package. These resonant states are also CP-eigenstates induced by same diagram as the nonresonant decay. Using these MC samples, all of the states are confirmed to be reconstructed and not to be affected by the selections. For the

background, a large number of $B\bar{B}$ and $q\bar{q}$ processes are simulated. Interactions of the particles in the Belle detector are reproduced using GEANT3 [16] with detector configuration information in each time period of the experiment.

Candidate K_S^0 decays are selected using multivariate analysis based on a neural network technique [17,18]. The input variables to select displaced vertices are as follows: the distance between two daughter pion tracks in the z direction, the flight distance in the x-y plane, the angle between the momentum of the $\pi^+\pi^-$ system and the K_S^0 candidate's vertex position vector with respect to the IP, and the shortest distance between the IP and daughter tracks of the K_S^0 candidate. In addition, we use the momenta of the K_S^0 and π, the angle between the K_S^0 and π, and hit information of daughters in the SVD and CDC. In this analysis we require that candidates satisfy the selection $0.480\ \mathrm{GeV}/c^2 < M_{\pi^+\pi^-} < 0.516\ \mathrm{GeV}/c^2$, where $M_{\pi^+\pi^-}$ is the reconstructed invariant mass of the charged pions. This range corresponds to approximately 3σ in the resolution of the mass.

Candidate $\pi^0 \to \gamma\gamma$ decays are reconstructed using photon candidates identified from ECL hits. We require that $M_{\gamma\gamma}$ satisfy $0.115\ \mathrm{GeV}/c^2 < M_{\gamma\gamma} < 0.152\ \mathrm{GeV}/c^2$, which corresponds to approximately 3σ in resolution. To improve the π^0 momentum resolution, we perform a mass-constrained fit to the two photons, assuming they originate from the IP.

In the case of multiple B^0 candidates in an event, we select the candidate that combines the π^0 of the smallest mass-constrained fit χ^2 value with the K_S^0 of the largest value of the neural network output variable.

To identify the decay $B^0 \to K_S^0\pi^0\pi^0$, we define two variables: the beam-constrained mass $M_{\mathrm{bc}} \equiv \sqrt{(E_{\mathrm{beam}}/c^2)^2 - |\vec{p}_B^{\,\mathrm{CM}}/c|^2}$ and the energy difference $\Delta E \equiv E_{\mathrm{beam}} - E_B^{\mathrm{CM}}$, where $\vec{p}_B^{\,\mathrm{CM}}$ and E_B^{CM} are the B momentum and energy, respectively, in the e^+e^- CM frame. The quantity E_{beam} is the beam energy in the CM frame. The variables M_{bc} and ΔE for signal events peak at the B^0 mass and at zero, respectively, but have tails to lower values due to lost energy in the π^0 reconstruction.

To reject background $B\bar{B}$ decays resulting in the $K_S^0\pi^0\pi^0$ final state, we define veto regions for the reconstructed invariant masses $M_{K_S^0\pi^0}$ and $M_{\pi^0\pi^0}$. Decays $B^0 \to D^0X$ and $B^0 \to K_S^0\pi^0$ are rejected by vetoing the regions $1.77\ \mathrm{GeV}/c^2 < M_{K_S^0\pi^0} < 1.94\ \mathrm{GeV}/c^2$ and $M_{K_S^0\pi^0} > 4.8\ \mathrm{GeV}/c^2$, respectively, for both π^0 candidates individually combined with the K_S^0 candidate. The veto region for $B^0 \to (c\bar{c})K_S^0$ is $2.8\ \mathrm{GeV}/c^2 < M_{\pi^0\pi^0} < 3.6\ \mathrm{GeV}/c^2$, where $(c\bar{c})$ is dominated by the charmonium mesons. Many of the two-body decays of the B^0 into a neutral meson and K_S^0 are CP eigenstates. Among such decay modes, $B^0 \to \eta' K_S^0$ becomes background if photons are not detected with the decays of $\eta' \to \eta\pi^+\pi^-$, $\eta \to 2\gamma$ and $K_S^0 \to \pi^0\pi^0$ so that $M_{\pi^0\pi^0} < 0.6\ \mathrm{GeV}/c^2$ is vetoed. In addition to those invariant masses of intermediate states, the absolute value of the cosine of the angle between the photons and the π^0 boost direction of the laboratory in the π^0 rest frame is required to be less than 0.9 to reject $B \to X_s\gamma$ decays, where X_s denotes the hadronic state governed by a radiative penguin decay.

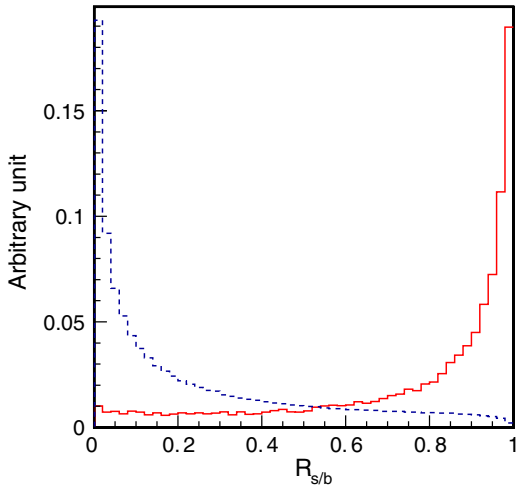

FIG. 1. Distribution of $\mathcal{R}_{\mathrm{s/b}}$, an event-shape-based likelihood ratio, for signal and $q\bar{q}$ MC illustrated by solid and broken lines, respectively.

To suppress $e^+e^- \to q\bar{q}$ continuum background events, a likelihood ratio $\mathcal{R}_{\mathrm{s/b}}$ is calculated using modified Fox-Wolfram moments [19,20] and the cosine of the angle between the beam direction and B^0 flight direction in the CM frame, $\cos\theta_B$. Figure 1 shows the $\mathcal{R}_{\mathrm{s/b}}$ distribution of the signal and $q\bar{q}$ MC. We impose a loose requirement $\mathcal{R}_{\mathrm{s/b}} > 0.50$, which rejects 84% of continuum background while retaining 90% of signal decays. We subsequently include a probability density function (PDF) for $\mathcal{R}_{\mathrm{s/b}}$ when fitting for the signal yield.

The vertex of the tag-side B is reconstructed from all charged tracks in the event, except for the K_S^0 daughters, using a vertex reconstruction algorithm described in Ref. [21]. To determine the B^0 flavor q, a multidimensional likelihood-based method for inclusive properties of particles not associated with the signal B^0 candidate is used [22]. The quality of the flavor tagging result is expressed by r, where $r = 0$ corresponds to no flavor discrimination, and $r = 1$ corresponds to unambiguous flavor assignment. Candidates with $r \leq 0.10$ are not considered further for CP violation measurement. The wrong tag fractions for six r intervals, $w_l (l = 1-6)$, and their differences between B^0 and $\bar{B}^0$ decays, Δw_l, are determined from large control samples of self-tagging $B^0 \to D^{*-}\ell^+\nu$, $B^0 \to D^{(*)-}h^+ (h = \pi, \rho)$ decays. The total effective tagging efficiency defined as $\Sigma(f_l \times (1-2w_l)^2)$ is determined to

be $(29.8 \pm 0.4)\%$, where f_l is the fraction of the events in the lth interval.

After applying all selection criteria, the signal yield is extracted from a three-dimensional unbinned maximum likelihood fit to $M_{\rm bc}$, ΔE, and $\mathcal{R}_{\rm s/b}$. For signal and $B\bar{B}$ background, the PDFs are modeled as binned histograms determined from MC simulation. A two-dimensional PDF is used for $M_{\rm bc}$ and ΔE, taking into account the correlation between these variables. The $q\bar{q}$ background PDF for $M_{\rm bc}$ is modeled by an ARGUS function [23], and that for ΔE is modeled by a second-order polynomial function. A binned histogram from the MC is used for the $q\bar{q}$ background PDF of $\mathcal{R}_{\rm s/b}$. From the 43225 events in the regions of $M_{\rm bc} > 5.2$ GeV/c^2, -0.25 GeV $< \Delta E <$ 0.25 GeV, and $\mathcal{R}_{\rm s/b} > 0.5$, the yields of signal, $q\bar{q}$ and $B\bar{B}$ are found to be 335 ± 37, 38599 ± 262 and 4290 ± 190, respectively. Figure 2 shows the data distribution in the signal-enhanced region $M_{\rm bc} > 5.27$ GeV/c^2, -0.15 GeV $< \Delta E < 0.10$ GeV, and $\mathcal{R}_{\rm s/b} > 0.9$, together with the fit projections, where the selection requirement on the plotted quantity is released.

To measure the CP violation parameters, an unbinned maximum likelihood fit is performed for the Δt distribution using q from the flavor tagging procedure and the signal fraction evaluated from the signal extraction fit. The PDF for the signal is set to take the form of Eq. (2) which is obtained by modifying Eq. (1) for wrong tagging and vertex resolution:

$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}(1 - q\Delta w + (1-2w)q[\mathcal{S}\sin(\Delta m_d \Delta t) + \mathcal{A}\cos(\Delta m_d \Delta t)]) \otimes R(\Delta t). \quad (2)$$

Here $R(\Delta t)$ is a convolved resolution function consisting of three components: the detector resolution for z_{CP} and $z_{\rm tag}$ vertices, the shift of $z_{\rm tag}$ due to secondary tracks, and the kinematic approximation used in calculating Δt from the vertex positions. These are determined using a large CP-conserving sample of semileptonic and hadronic B decays. For the background, which includes both $q\bar{q}$ and $B\bar{B}$, the PDF is modeled as a combination of two Gaussian functions and a delta function, as determined from the sideband regions 5.20 GeV/$c^2 < M_{\rm bc} <$ 5.26 GeV/c^2, -1.00 GeV $< \Delta E < -0.40$ GeV and 0.20 GeV $< \Delta E <$ 0.50 GeV. τ_B and Δm_d are fixed to world average values [24]. For the resolution function $R(\Delta t)$, a broad Gaussian function is included to account for a small outlier component. The number of events within the three-dimensional region of $M_{\rm bc} > 5.27$ GeV/c^2, -0.15 GeV $< \Delta E <$ 0.10 GeV and $\mathcal{R}_{\rm s/b} > 0.5$ with vertices and flavor information is 964, and the purity is 11.4%. From fitting these events we obtain $\mathcal{S} = -0.92^{+0.31}_{-0.27}$ and $\mathcal{A} = 0.28 \pm 0.21$, where the errors are statistical only. Figure 3 shows the Δt distribution of each flavor together with the background.

The systematic uncertainties are summarized in Table I. Systematic uncertainties originating from vertexing opposite the CP side, flavor tagging, and fixed physics parameters, and tag-side interference [25] are estimated from studying the large statistic data sample of the $B^0 \to (c\bar{c})K^0$

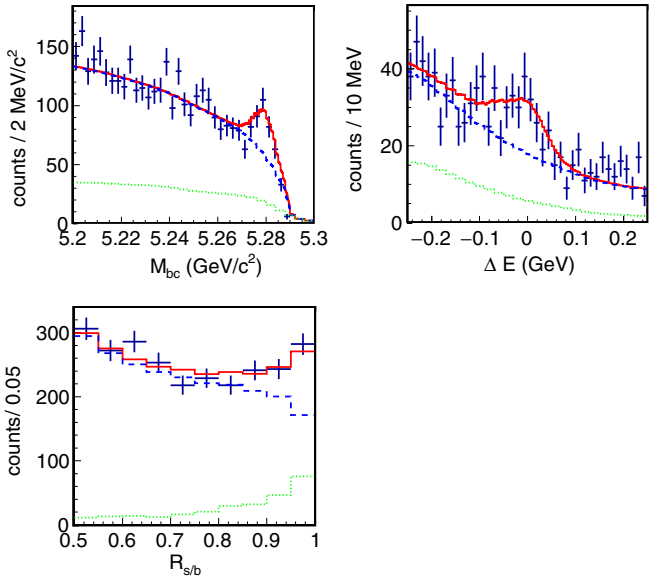

FIG. 2. $M_{\rm bc}$, ΔE and $\mathcal{R}_{\rm s/b}$ distributions (points with uncertainties) using signal-enhanced selections $M_{\rm bc} > 5.27$ GeV/c^2, -0.15 GeV $< \Delta E < 0.10$ GeV, and $\mathcal{R}_{\rm s/b} > 0.9$ except for the variable displayed. The fit result is illustrated by the solid curve, while the total and $B\bar{B}$ backgrounds are shown by broken and dotted curves, respectively.

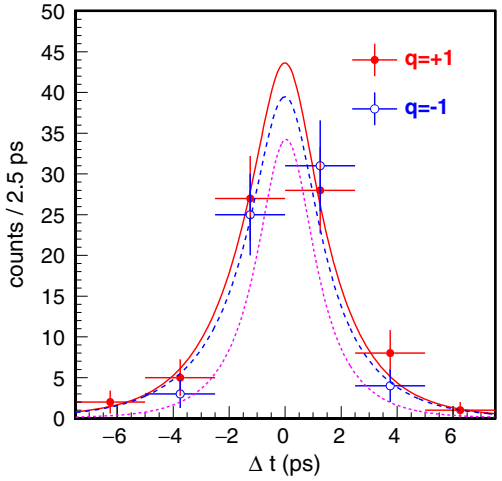

FIG. 3. Δt distribution shown by data points with uncertainties, and fit result with curves: filled circles with error bars along with a solid-line fit curve correspond to $q = +1$, while open circles with error bars along with a dashed-line fit curve correspond to $q = -1$. The background contribution is illustrated by the dotted line. Events with good flavor tagging quality ($r > 0.5$) are shown.

TABLE I. Systematic uncertainties.

	$\Delta \sin 2\phi_1^{\rm eff}$	$\Delta\mathcal{A}$
Vertexing	± 0.02	± 0.01
Flavor tagging	± 0.004	± 0.003
Resolution function	± 0.06	$^{+0.004}_{-0.003}$
Physics parameters	± 0.002	< 0.001
Fit bias	± 0.03	± 0.02
Background fraction	± 0.02	± 0.02
Background Δt	± 0.08	± 0.02
Tag-side interference	± 0.001	± 0.008
Total	± 0.11	± 0.04

analysis [6]. Uncertainty from vertex reconstruction using K_S^0 including the resolution function is estimated using a large control sample of $B^0 \to J/\psi K_S^0$ decays. Fit bias is estimated by fitting a large number of signal MC samples and evaluating the resulting deviation compared to the input. For the PDF shape, the uncertainty is estimated using a smeared distribution. For parameters fixed in the fit, such as the signal fraction and background Δt PDF, the uncertainties are estimated by shifting these parameters by their errors and refitting; the resulting changes in $\mathcal{S}$ and $\mathcal{A}$ are taken as the systematic uncertainties. Including the systematic uncertainty, we determine that $\sin 2\phi_1^{\rm eff} = 0.92^{+0.27}_{-0.31} \pm 0.11$ and $\mathcal{A} = 0.28 \pm 0.21 \pm 0.04$, where the first and second errors are statistic and systematic, respectively.

In summary, we measure CP violation parameters in the decay $B^0 \to K_S^0\pi^0\pi^0$ using $772 \times 10^6 B\bar{B}$ pairs and obtain

$$\mathcal{S} = -0.92^{+0.31}_{-0.27}(\text{stat}) \pm 0.11(\text{syst}),$$
$$\mathcal{A} = 0.28 \pm 0.21(\text{stat}) \pm 0.04(\text{syst}).$$

The result for $\mathcal{S}$ is consistent with the value measured from decays mediated by a $b \to c\bar{c}s$ transition, $\sin 2\phi_1 = 0.698 \pm 0.017$ [26]. The result for $\mathcal{A}$ is consistent with zero, i.e., no direct CP violation, as expected in the SM. This is the first result obtained by the Belle experiment for this mode (and it is the third CP-even eigenstate from $b \to sq\bar{q}$ transitions used by Belle for the $\sin 2\phi_1^{\rm eff}$ measurement after $B^0 \to \eta' K_L^0$ and $B^0 \to \phi K_L^0$).

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