Observation of Time-Dependent $CP$ Violation in $B^0 \rightarrow \eta' K^0$ Decays and Improved Measurements of $CP$ Asymmetries in $B^0 \rightarrow \phi K^0$, $K^0_S K^0_S$ and $B^0 \rightarrow J/\psi K^0$ Decays

K.-F. Chen, 27 K. Hara, 23 M. Hazumi, 8 T. Higuchi, 8 K. Miyabayashi, 24 Y. Nakahama, 48 K. Sumisawa, 8 O. Tajima, 8 Y. Ushiroda, 8 Y. Yusa, 52 K. Abe, 8 K. Abe, 46 I. Adachi, 6 H. Aihara, 48 D. Anipko, 1 K. Arinstein, 3 V. Aulchenko, 1 T. Aushev, 19, 14 T. Aziz, 44 A. M. Bakich, 43 V. Balagura, 14 S. Banerjee, 44 E. Barberio, 22 M. Barbero, 7 A. Bay, 19 K. Belous, 13 U. Bitenc, 15 I. Bizjak, 15 S. Blyth, 25 A. Bondar, 1 A. Bozek, 28 M. Bračko, 8, 21, 15 J. Brodzicka, 28 T. E. Browder, 7 P. Chang, 27 Y. Chao, 27 A. Chen, 25 W. T. Chen, 25 B. G. Cheon, 3 R. Chistov, 14 S.-K. Choi, 6 Y. Choi, 42 Y. K. Choi, 42 A. Chuvikov, 36 S. Cole, 43 J. Dalseno, 22 M. Danilov, 14 M. Dash, 52 J. Dragic, 8 A. Drutskoy, 4 S. Eidelman, 1 D. Epifanov, 1 S. Fratina, 15 A. Garmash, 39 T. Gershon, 8 A. Go, 25 G. Gokhroo, 44 P. Goldenzweig, 4 B. Golob, 20, 15 H. Ha, 17 J. Haba, 8 T. Hara, 33 K. Hayasaka, 23 H. Hayashii, 24 D. Heffernan, 33 T. Hokuue, 23 Y. Hoshi, 46 S. Hou, 25 W.-S. Hou, 27 T. Y. Ito, 8 M. Iwasaki, 48 Y. Iwasaki, 8 H. Kakuno, 48 J. H. Kang, 53 S. U. Kataoka, 24 N. Katayama, 8 H. Kawai, 2 T. Kawasaki, 30 H. R. Khan, 49 H. Kichimi, 8 H. J. Kim, 18 S. K. Kim, 40 Y. J. Kim, 5 K. Kinoshita, 1 S. Korpar, 21, 15 P. Križan, 20, 15 P. Krokovny, 8 R. Kulasiri, 4 R. Kumar, 34 C. C. Kuo, 25 A. Kusaka, 48 A. Kuzmin, 1 Y.-J. Kwon, 53 G. Leder, 12 J. Lee, 40 M. J. Lee, 40 T. Lesiak, 28 J. Li, 7 A. Limosani, 8 S.-W. Lin, 27 Y. Liu, 5 D. Liventsev, 14 G. Majumder, 44 F. Mandl, 12 T. Matsumoto, 50 A. Matyja, 28 W. Mitanoff, 12 H. Miyake, 33 H. Miyata, 30 Y. Miyazaki, 23 R. Mizuk, 14 D. Mohapatra, 52 G. R. Moloney, 22 A. Murakami, 38 T. Nagamine, 47 Y. Nagasaka, 9 I. Nakamura, 8 E. Nakano, 32 M. Nakao, 32 Z. Natan, 28 S. Nishida, 8 O. Nishio, 51 S. Noguchi, 24 T. Nozaki, 8 S. Ogawa, 45 T. Ohshima, 23 S. Okuno, 16 S. L. Olsen, 7 Y. Onuki, 37 W. Ostrowicz, 28 H. Ozaki, 8 P. Pakhlov, 14 G. Pakhlova, 14 H. Palka, 28 H. Park, 18 R. Pestonik, 15 L. E. Piilonen, 52 H. Sahoo, 7 Y. Sakai, 8 N. Satoyama, 41 T. Schietinger, 19 O. Schneider, 19 J. Schimann, 26 A. J. Schwartz, 4 R. Seidl, 10, 37 K. Senyo, 23 M. E. Sevior, 22 M. Shapkin, 13 H. Shibuya, 45 B. Shwartz, 1 J. B. Singh, 34 A. Sokolov, 13 A. Somov, 4 S. Stanic, 31 M. Starić, 15 H. Stocek, 43 T. Sumiyoshi, 50 S. Suzuki, 38 F. Takasaki, 8 K. Tamai, 8 N. Tamura, 30 M. Tanaka, 8 G. N. Taylor, 22 Y. Teramoto, 32 X. C. Tian, 36 K. Trabelsi, 7 T. Tsuboyama, 8 T. Tsukamoto, 8 S. Uehara, 8 T. Uglov, 14 K. Ueno, 27 Y. Unno, 3 S. Uno, 8 P. Urquijo, 22 Y. Usov, 1 G. Varner, 7 K. E. Varvell, 43 S. Villa, 19 C. C. Wang, 27 C. H. Wang, 26 M.-Z. Wang, 27 Y. Watanabe, 49 R. Wedd, 22 E. Won, 17 Q. L. Xie, 11 B. D. Yabsley, 43 A. Yamaguchi, 47 Y. Yamashita, 29 M. Yamauchi, 8 C. C. Zhang, 11 Z. P. Zhang, 39 V. Zhilich, 1 and A. Zupanc; 15 (The Belle Collaboration)

1Budker Institute of Nuclear Physics, Novosibirsk
2Chiba University, Chiba
3Chonnam National University, Kwangju
4University of Cincinnati, Cincinnati, Ohio 45221
5The Graduate University for Advanced Studies, Hayama, Japan
6Gyeongsang National University, Chinju
7University of Hawaii, Honolulu, Hawaii 96822
8High Energy Accelerator Research Organization (KEK), Tsukuba
9Hiroshima Institute of Technology, Hiroshima
10University of Illinois at Urbana-Champaign, Urbana, Illinois 61801
11Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
12Institute of High Energy Physics, Vienna
13Institute of High Energy Physics, Protvino
14Institute for Theoretical and Experimental Physics, Moscow
15J. Stefan Institute, Ljubljana
16Kanagawa University, Yokohama
17Korea University, Seoul
18Kyungpook National University, Taegu
19Swiss Federal Institute of Technology of Lausanne, EPFL, Lausanne
20University of Ljubljana, Ljubljana
21University of Maribor, Maribor
22University of Melbourne, Victoria
23Nagoya University, Nagoya
24Nara Women's University, Nara
25National Central University, Chung-li
26National United University, Miaoli
27Department of Physics, National Taiwan University, Taipei

Belle Preprint 2006-28
KEK Preprint 2006-40

arXiv:hep-ex/0608039v4 17 Jan 2007
Particles from physics beyond the standard model (SM) may contribute to $B^0$ meson decays mediated by flavor-changing $b \to s$ transitions via additional quantum loop diagrams, and potentially induce large deviations from the SM expectation for time-dependent $CP$ asymmetries [1]. In the decay chain $\Upsilon(4S) \to B^0\bar{B}^0 \to f_CP f_{\text{tag}}$, where one of the $B$ mesons decays at time $t_{CP}$ to a $CP$ eigenstate $f_{CP}$ and the other decays at time $t_{\text{tag}}$ to a final state $f_{\text{tag}}$ that distinguishes between $B^0$ and $\bar{B}^0$, the decay rate has a time dependence [2] given by

$$P(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left\{ 1 + q \cdot \left[ S_f \sin(\Delta m_d \Delta t) + A_f \cos(\Delta m_d \Delta t) \right] \right\}.$$  

Here $S_f$ and $A_f$ are $CP$-violation parameters, $\tau_{B^0}$ is the $B^0$ lifetime, $\Delta m_d$ is the mass difference between the two $B^0$ mass eigenstates, $\Delta t = t_{CP} - t_{\text{tag}}$, and the $b$-flavor charge $q = +1$ ($-1$) when the tagging $B$ meson is a $B^0$ ($\bar{B}^0$). In the SM, $CP$ violation arises only from the irreducible Kobayashi-Maskawa phase [3] in the weak-interaction quark-mixing matrix $\mathbf{V}$. The SM approximately predicts $S_f = -\xi_f \sin 2\phi_1 \mathbf{V}$ and $A_f = 0$ for both $b \to c\bar{s}s$ and $b \to s\bar{q}q$ transitions, where $\xi_f = +1$ ($-1$) corresponds to $CP$-even ($-odd$) final states, in the leading order. Recent SM calculations [6] for the effective $2\phi_1$ values, $\sin 2\phi_1$, obtained from $B^0 \to \phi K^0$, $\eta' K^0$, and $K^0_S K^0_L K^0_S$ agree with the $2\phi_1$ values, $\sin 2\phi_1$, as measured in $B^0 \to J/\psi K^0$ decays, at the level of 0.01. Thus comparison of measurements of $S_f$ and $A_f$ between modes is an important test of the SM.

Previous measurements of $CP$ asymmetries in $b \to s\bar{q}q$ transitions by Belle [1] and BaBar [8] differed from the SM expectation, although the deviation was not statistically significant. BaBar has since updated their results [9]. In this Letter we describe improved measurements of $S_f$ and $A_f$ in $B^0 \to \phi K^0$, $\eta' K^0$, and $K^0_S K^0_L K^0_S$ decays using a data sample of 492 fb$^{-1}$ (535 $\times$ 10$^6$ $B\bar{B}$ pairs), which is nearly twice that used for our previous measurements. The analysis has also been improved by the addition of the following decay chains: $B^0 \to \phi K^0$, $\phi \to K^0_S K^0_S$, $B^0 \to \eta' K^0$, $B^0 \to \eta' K^0_S$, $K^0_S \to \pi^+\pi^-\eta$. We also describe improved measurements of $\sin 2\phi_1$ and $A_f$ in $B^0 \to J/\psi K_S^0$ and $J/\psi K_L^0$ decays.
using the same data sample; our previous measurement used a 140 fb\(^{-1}\) data sample \[10\]. These modes have the largest statistics coupled with the smallest theoretical uncertainties and thus provide a firm reference point for the SM.

At the KEKB energy-asymmetric \(e^+e^-\) (3.5 GeV on 8.0 GeV) collider \[11\], the \(Y(4S)\) is produced with a Lorentz boost of \(\beta\gamma = 0.425\) nearly along the electron beamline \(z\). Since the \(B^0\) and \(\bar{B}^0\) mesons are approximately at rest in the \(\Upsilon(4S)\) collider \[11\], the \(\Upsilon(4S)\) can be determined from the displacement in \(z\) between the \(f_{CP}\) and \(f_{\text{tag}}\) decay vertices: \(\Delta t \simeq (z_{\text{CP}} - z_{\text{tag}})/(\beta\gamma) = \Delta z/(\beta\gamma c)\).

The Belle detector \[12\] 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), 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 of the coil is instrumented to detect \(K_{L}^0\) mesons and to identify muons (KLM).

Charged tracks reconstructed with the CDC, except for tracks from \(K_{S}^0 \to \pi^+\pi^-\) decays, are required to originate from the interaction point (IP). We distinguish charged kaons from pions based on a kaon (pion) likelihood \(L_{K/\pi}(r)\) derived from the TOF, ACC, and \(dE/dx\) measurements in the CDC. Photons are identified as isolated ECL clusters that are not matched to any charged track. Candidate \(K_{S}^0\) mesons are selected from ECL and/or KLM hit patterns that are consistent with the presence of a shower induced by a \(K_{L}^0\) meson.

The intermediate meson states are reconstructed from the following decays: \(\pi^0 \to \gamma\gamma\), \(K_{S}^0 \to \pi^+\pi^-\) (denoted by \(K_{S}^0\)) or \(\rho^0\) (denoted by \(K_{S}^0\)) \(\eta \to \gamma\gamma\) or \(\pi^+\pi^-\pi^0\), \(\rho^0 \to \pi^+\pi^-\pi^0\), \(\eta' \to \rho^0\gamma\) or \(\eta\pi^+\pi^-\), \(\phi \to K^+K^-\) and \(J/\psi \to \ell^+\ell^-\) \(\ell = \mu, e\). We use all combinations of the intermediate states with the exception of \(\{\eta \to \pi^+\pi^-\pi^0\}, \{\eta' \to \rho^0\gamma\}, K_{S}^0, K_{S}^0\) candidates for \(B^0 \to f_{\text{tag}}\) decay candidates are almost the same as in our previous measurement \[7\] \[13\]. The \(K_{L}^0\) and \(K_{S}^0\) candidates for \(K_{S}^0\) are reconstructed with the same method as used for \(\phi K_{S}^0\) \[13\]. We reconstruct the \(B^0 \to K_{S}^0 K_{S}^0 K_{S}^0\) decay in the \(K_{S}^0 K_{S}^0 K_{S}^0\) or \(K_{S}^0 K_{S}^0 K_{S}^0\) final states. In addition, \(\phi \to K_{S}^0 K_{L}^0\) decays are used for \(B^0 \to \phi K_{S}^0\) sample. We identify candidate \(B^0 \to f_{CP}\) decays without a \(K_{S}^0\) meson using the energy difference \(\Delta E \equiv E_{\text{beam}} - E_{\text{beam}}\) and the beam-energy constrained mass \(M_{bc} \equiv \sqrt{(E_{\text{beam}})^2 - (p_{\text{beam}})^2}\), where \(E_{\text{beam}}\) is the beam energy, and \(E_{\text{beam}}\) and \(p_{\text{beam}}\) are the energy and momentum, respectively, of the reconstructed \(B\) candidate, all measured in the c.m. frame. The signal candidates are selected by requiring \(M_{bc} \in (5.27, 5.29)\) GeV/c\(^2\) and a mode-dependent \(\Delta E\) window. Only \(M_{bc}\) is used to identify the decay \(B^0 \to \phi K_{S}^0\) followed by \(\phi \to K_{S}^0 K_{S}^0\). Other candidate \(B^0 \to f_{CP}\) decays with a \(K_{S}^0\) are selected by requiring \(p_{\text{tag}}^2 \in (0.2, 0.45)\) GeV/c\(^2\) for \(B^0 \to J/\psi K_{S}^0\) candidates and \(p_{\text{tag}}^2 \in (0.2, 0.5)\) GeV/c\(^2\) for the others.

The dominant background for the \(b \to s\bar{q}q\) signal comes from continuum events \(e^+e^-\) \(\to q\bar{q}\) where \(q = u, d, s, c\). To distinguish these topologically jet-like events from the spherical \(B\) decay signal events, we combine a set of variables \[7\] that characterize the event topology into a signal (background) likelihood variable \(L_{\text{sig}}(L_{\text{bkg}})\), and impose loose mode-dependent requirements on the likelihood ratio \(R_{s/b} = L_{\text{sig}}/(L_{\text{bkg}})\).

The contributions from \(B\bar{B}\) events to the background for \(B^0 \to f_{CP}\) candidates with a \(K_{S}^0\) are estimated with Monte Carlo (MC) simulated events. The small \((\sim 3\%)\) \(B\bar{B}\) combinatorial background in \(B^0 \to \eta' K_{S}^0 (\eta' \to \rho^0\gamma)\) is estimated using MC events. We reject \(K_{S}^0\) candidates if one of the \(K_{S}^0\) pairs has an invariant mass within \(\pm 2\sigma\) of the \(\chi_{0}\) mass or \(\pm 1\sigma\) of the \(D^0\) mass, where \(\sigma\) is the \(K_{S}^0\) mass resolution. The fraction of \(B^0 \to K^+K^-K_{S}^0\) and \(B^0 \to f_0(980)K_{S}^0 (f_0(980) \to K^+K^-)\) events in the \(B^0 \to \phi K_{S}^0\) sample is estimated to be \(2.75 \pm 0.14\%\) and zero within error, respectively, from the Dalitz plot for \(B \to K^+K^-K\) candidates \[14\].

The \(b\)-flavor of the accompanying \(B\) meson is identified from inclusive properties of particles that are not associated with the reconstructed \(B^0 \to f_{CP}\) decay. The tagging information is represented by two parameters, the \(b\)-flavor charge \(q\) and \(r\) \[15\]. The parameter \(r\) is an event-by-event, MC-determined flavor-tagging dilution factor that ranges from \(r = 0\) for no flavor discrimination to \(r = 1\) for unambiguous flavor assignment. For events with \(r > 0.1\), the wrong tag fractions for six \(r\) intervals, \(w_1 (l = 1, 6)\), and their differences between \(B^0\) and \(\bar{B}^0\) decays, \(\Delta w_1\), are determined using semileptonic and hadronic \(b \to c\) decays \[7\] \[10\]. If \(r \leq 0.1\), we set the wrong tag fraction to 0.5, and therefore the tagging information is not provided. The total effective tagging efficiency is determined to be \(0.29 \pm 0.01\).

The vertex position for the \(f_{CP}\) decay is reconstructed using charged tracks that have enough SVD hits \[10\]. The \(f_{\text{tag}}\) vertex is obtained with well-reconstructed tracks and imposing loose mode-dependent requirements on the flavor charge \(\mu, e\) and \(K_{L}^0\) candidates. The \(f_{\text{tag}}\) vertex is reconstructed with the reconstructed \(B\) candidate, all measured in the c.m. frame. The signal candidates are selected by requiring \(M_{bc} \in (5.27, 5.29)\) GeV/c\(^2\) and a mode-dependent \(\Delta E\) window. Only \(M_{bc}\) is used to identify the decay \(B^0 \to \phi K_{S}^0\) followed by \(\phi \to K_{S}^0 K_{S}^0\). Other candidate \(B^0 \to f_{CP}\) decays with a \(K_{S}^0\) are selected by requiring \(p_{\text{tag}}^2 \in (0.2, 0.45)\) GeV/c\(^2\) for \(B^0 \to J/\psi K_{S}^0\) candidates and \(p_{\text{tag}}^2 \in (0.2, 0.5)\) GeV/c\(^2\) for the others.
FIG. 1: $R_{s/b}$, $M_{bc}$ and $p_{tB}$ distributions for reconstructed candidates: $R_{s/b}$, $M_{bc}$ with $R_{s/b} \leq 0.5$ and $M_{bc}$ with $R_{s/b} > 0.5$ distributions for (a, b and c) $B^0 \rightarrow \eta' K^0_S$, (d, e and f) $B^0 \rightarrow \phi K^0_S$, and (g, h and i) $B^0 \rightarrow K^0_S K^0_S K^0_S$; $R_{s/b}$ and $p_{tB}$ for (j and k) $B^0 \rightarrow \eta' K^0_S$ and (l and m) $B^0 \rightarrow \phi K^0_S$. The solid curves and histograms show the fits to signal plus background distributions, and hatched areas show the background contributions. Background contributions are subtracted in figures (k) and (m).

is determined from MC events. The background has two components: continuum, which is modeled using events outside the signal region, and $B\bar{B}$ background, which is modeled with MC events. The signal distributions are determined to be $307 \pm 21$ for $B^0 \rightarrow \phi K^0_S$, $114 \pm 17$ for $B^0 \rightarrow \phi K^0_S$, $1421 \pm 46$ for $B^0 \rightarrow \eta' K^0_S$, $454 \pm 39$ for $B^0 \rightarrow \eta' K^0_S$, $185 \pm 17$ for $B^0 \rightarrow K^0_S K^0_S K^0_S$, $7484 \pm 87$ for $B^0 \rightarrow J/\psi K^0_S$ and $6512 \pm 123$ for $B^0 \rightarrow J/\psi K^0_S$, where errors are statistical only.

We determine $S_f$ and $A_f$ for each mode by performing an unbinned maximum-likelihood fit to the observed $\Delta t$ distribution. The probability density function (PDF) for the signal distribution, $P_{\text{sig}}(\Delta t; S_f, A_f, q, w_1, \Delta w_1)$, is given by Eq. (1) fixing $\tau_{BG}$ and $\Delta m_d$ at their world average values [17] and incorporating the effect of incorrect flavor assignment. The distribution is convolved with the proper-time interval resolution function $R_{\text{sig}}(\Delta t)$, which takes into account the finite vertex resolution [16]. We determine the following likelihood for each event:

$$P_t = (1 - f_{\text{ol}}) \sum_k f_k \int [P_k(\Delta t') R_k(\Delta t_i - \Delta t')] d(\Delta t') + f_{\text{ol}} P_{\text{ol}}(\Delta t_i),$$

(2)

where $k$ denotes signal, continuum and $B\bar{B}$ background components. In the $B^0 \rightarrow K^0_S K^0_S K^0_S$ and $J/\psi K^0_S$ samples the $B\bar{B}$ component is negligibly small and not included in the fit. The fraction of each component $f_k$ depends on the $r$ region and is calculated on an event-by-event basis as a function of the following variables: $\Delta E$ and $M_{bc}$ for $B^0 \rightarrow J/\psi K^0_S$; $p_{tB}$ for $B^0 \rightarrow J/\psi K^0_S$; $p_{tB}$ and $R_{s/b}$ for $B^0 \rightarrow \eta' K^0_S$ and $\phi K^0_S$; $M_{bc}$ and $R_{s/b}$ for $B^0 \rightarrow \phi(\rightarrow K^0_S K^0_S K^0_S)$; $\Delta E$, $M_{bc}$ and $R_{s/b}$ for the other modes. The PDF $P_{\text{sig}}(\Delta t)$ for background events is convolved with the resolution function $R_{\text{b}}$ for the background [7] [10]. The term $P_{\text{ol}}(\Delta t)$ is a broad Gaussian function that represents a small outlier component with a fraction of $f_{\text{ol}} [10]$. The only free parameters in the fits are $S_f$ and $A_f$, which are determined by maximizing the likelihood function $L = \prod_i P_i(\Delta t_i; S_f, A_f)$ where the product is over all events.

Table I summarizes the fit results for $\sin 2\phi_1^\text{eff}$ and $A_f$. These results are consistent with and supersede our previous measurements [7] [10]. Fits to each individual mode

| Mode | $\sin 2\phi_1^\text{eff}$ | $A_f$ |
|------|---------------------|------|
| $\phi K^0_S$ | $+0.50 \pm 0.21 \pm 0.06$ | $+0.07 \pm 0.15 \pm 0.05$ |
| $\eta' K^0_S$ | $+0.64 \pm 0.10 \pm 0.04$ | $-0.01 \pm 0.07 \pm 0.05$ |
| $K^0_S K^0_S K^0_S$ | $+0.30 \pm 0.32 \pm 0.08$ | $+0.31 \pm 0.20 \pm 0.07$ |
| $J/\psi K^0_S$ | $+0.642 \pm 0.031 \pm 0.017$ | $+0.018 \pm 0.021 \pm 0.014$ |

with $K^0_S$ and $K^0_L$ yield $(S_{\phi K^0_S}, A_{\phi K^0_S}) = (+0.67 \pm 0.11, -0.03 \pm 0.07)$, $(S_{\eta' K^0_S}, A_{\eta' K^0_S}) = (-0.46 \pm 0.24, +0.09 \pm 0.16)$, $(S_{\phi K^0_S}, A_{\phi K^0_S}) = (+0.50 \pm 0.23, +0.11 \pm 0.16)$, $(S_{\phi K^0_S}, A_{\phi K^0_S}) = (-0.46 \pm 0.56, -0.15 \pm 0.38)$, $(S_{J/\psi K^0_S}, A_{J/\psi K^0_S}) = (+0.643 \pm 0.038, -0.001 \pm 0.028)$ and $(S_{J/\psi K^0_S}, A_{J/\psi K^0_S}) = (-0.641 \pm 0.057, +0.045 \pm 0.033)$, where errors are statistical only. We define the background-subtracted asymmetry in each $\Delta t$ bin by $(N_+ - N_-)/(N_+ + N_-)$, where $N_+ (N_-)$ is the signal yield with $q = +1 (-1)$. Figures 1 (a)-(d) show the $\Delta t$ distributions and asymmetries
for good tag quality ($r > 0.5$) events. The sign of each $\Delta t$ measurement for final states with a $K_L^0$ is inverted in order to combine results with $K_S^0$ and $K_L^0$ mesons.

The dominant sources of systematic error for $\sin 2\phi_1^{\text{eff}}$ in $b \to s\bar{q}q$ modes come from the uncertainties in the resolution function for the signal (0.03 for the $B^0 \to \eta' K^0$ mode, 0.04 for the $\phi K^0$ mode, 0.05 for the $B^0 \to K_S^0 K_S^0 K^0$ mode) and in the background fraction (0.02, 0.04, 0.06). The effect of $f_0(980)K^0$ background in the $\phi K^0$ mode (0.02) is estimated using the BES measurement of the $f_0(980)$ lineshape [18] and is included in the background fraction systematic error. The dominant sources for $A_f$ in $b \to s\bar{q}q$ modes are the effects of tag-side interference [19] (0.02, 0.03, 0.04), the uncertainties in the background fraction (0.02, 0.03, 0.05), in the vertex reconstruction (0.02 for all modes) and in the resolution function (0.02, 0.01, 0.02). We study the possible correlations between $R_{s/b}$, $p_0^2$ and $r$ PDFs used for $\phi K_L^0$ and $\eta' K_L^0$, which are neglected in the nominal result, and include their effect in the systematic uncertainties in the background fraction. Other contributions come from uncertainties in wrong tag fractions, the background $\Delta t$ distribution, $\tau_{s^0}$ and $\Delta m_d$. A possible fit bias is examined by fitting a large number of MC events and is found to be small.

The dominant sources of systematic errors for the $B^0 \to J/\psi K^0$ mode are the uncertainties in the vertex reconstruction (0.012 for $\sin 2\phi_1$, 0.009 for $A_f$), in the resolution function for the signal (0.006, 0.001), in the background fraction (0.006, 0.002), in the flavor tagging (0.004, 0.003), a possible fit bias (0.007, 0.004) and the effect of the tag-side interference (0.001, 0.009). Other contributions amount to less than 0.001. We add each contribution in quadrature to obtain the total systematic uncertainty.

For the $B^0 \to \eta' K^0$ mode, we observe $CP$ violation with a significance equivalent to 5.6 standard deviations for a Gaussian error, where the significance is calculated using the Feldman-Cousins frequentist approach [20]. The results for $B^0 \to \eta' K^0$, $\phi K^0$ and $K_S^0 K_S^0 K^0$ decays are all consistent with the value of $\sin 2\phi_1$ obtained from the decay $B^0 \to J/\psi K^0$ within two standard deviations. No direct $CP$ violation is observed in these decay modes. Further measurements with much larger data samples are required to search for new, beyond the SM, $CP$-violating phases in the $b \to s$ transition.

We thank the KEKB group for excellent operation of the accelerator, the KEK cryogenics group for efficient solenoid operations, and the KEK computer group and the NII for valuable computing and Super-SINET network support. We acknowledge support from MEXT and JSPS (Japan); ARC and DEST (Australia); NSFC and KIP of CAS (China); DST (India); MOEHRD, KOSEF and KRF (Korea); KBN (Poland); MIST (Russia); ARRS (Slovenia); SNSF (Switzerland); NSC and MOE (Taiwan); and DOE (USA).

\begin{thebibliography}{9}
\bibitem{1} Y. Grossman and M. P. Worah, Phys. Lett. B 395, 241 (1997); D. London and A. Soni, Phys. Lett. B 407, 61 (1997); T. Moroi, Phys. Lett. B 493, 366 (2000); D. Chang, A. Masiero and H. Murayama, Phys. Rev. D 67, 075013 (2003); S. Baek, T. Goto, Y. Okada and K. Okumura, Phys. Rev. D 64, 095001 (2001).
\bibitem{2} A. B. Carter and A. I. Sanda, Phys. Rev. D 23, 1567 (1981); I. I. Bigi and A. I. Sanda, Nucl. Phys. B 193, 85 (1981).
\bibitem{3} M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973).
\bibitem{4} N. Cabibbo, Phys. Rev. Lett. 10, 531 (1963).
\bibitem{5} Another naming convention $\beta (= \phi_1)$ is also used in literatures.
\bibitem{6} M. Beneke and M. Neubert, Nucl. Phys. B 675, 333 (2003); M. Beneke, Phys. Lett. B 620, 143 (2005); H.-Y. Cheng, C.-K. Chua and A. Soni, Phys. Rev. D 72, 014006 (2005); Phys. Rev. D 72, 094003 (2005); A. R. Williamson and J. Zupan, Phys. Rev. D 74, 014003 (2006); M. Gronau, J. L. Rosner and J. Zupan, Phys. Rev. D 74, 093003 (2006).
\bibitem{7} Belle Collaboration, K. F. Chen et al., Phys. Rev. D 72, 012004 (2005). Belle Collaboration, K. Sumisawa et al., Phys. Rev. Lett. 95, 061801 (2005).
\bibitem{8} BaBar Collaboration, B. Aubert et al., Phys. Rev. D 71, 091102(R) (2005); Phys. Rev. Lett. 94, 191802 (2005); Phys. Rev. Lett. 95, 011801 (2005).
\bibitem{9} BaBar Collaboration, B. Aubert et al., Phys. Rev. Lett. 98, 031801 (2007).
\bibitem{10} Belle Collaboration, K. Abe et al., Phys. Rev. D 71,
[11] S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods Phys. Res., Sect. A 499, 1 (2003), and other papers included in this volume.

[12] Belle Collaboration, A. Abashian et al., Nucl. Instrum. Methods Phys. Res., Sect. A 479, 117 (2002); Y. Ushiroda (Belle SVD2 Group), Nucl. Instrum. Methods Phys. Res., Sect. A 511, 6 (2003).

[13] Belle Collaboration, K. Abe et al., hep-ex/0507037

[14] Belle Collaboration, A. Garmash et al., Phys. Rev. D 69, 012001 (2004); Phys. Rev. D 71, 092003 (2005).

[15] H. Kakuno et al., Nucl. Instrum. Methods Phys. Res., Sect. A 533, 516 (2004).

[16] H. Tajima et al., Nucl. Instrum. Methods Phys. Res., Sect. A 533, 370 (2004).

[17] W.-M. Yao et al., J. Phys. G 33, 1 (2006).

[18] BES Collaboration, M. Ablikim et al., Phys. Lett. B 607, 243 (2005).

[19] O. Long, M. Baak, R. N. Cahn and D. Kirkby, Phys. Rev. D 68, 034010 (2003).

[20] G. J. Feldman and R. D. Cousins, Phys. Rev. D 57, 3873 (1998).