Study of Time-Dependent *CP* Violation in $B^0 \to J/\psi\pi^0$ Decays

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We report a measurement of CP asymmetry parameters in the decay $B^0(\overline{B}^0) \to J/\psi\pi^0$, which is governed by the $b \to c\bar{c}d$ transition. The analysis is based on a 140 fb^{-1} data sample accumulated at the $\Upsilon(4S)$ resonance by the Belle detector at the KEKB asymmetric-energy e^+e^- collider. One neutral B meson in the $J/\psi\pi^0$ final state is fully reconstructed for events used in this analysis. The accompanying B meson flavor is identified by its decay products. From the distribution of proper-time intervals between the two B decays, we obtain the following CP-violating parameters: $S_{J/\psi\pi^0} = -0.72 \pm 0.42(\text{stat}) \pm 0.09(\text{syst})$ and $A_{J/\psi\pi^0} = -0.01 \pm 0.29(\text{stat}) \pm 0.03(\text{syst})$.

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In the standard model (SM), the Kobayashi-Maskawa (KM) quark-mixing matrix [1] has an irreducible complex phase that gives rise to CP violation in weak interactions. In particular, the SM predicts large CP-violating asymmetries in the time-dependent rates of B^0 and $\overline{B}^0$ decays into a common CP eigenstate f_{CP} [2]. In the decay chain $\Upsilon(4S) \to B^0\overline{B}^0 \to f_{CP}f_{\rm tag}$, where one of the B mesons decays at time t_{CP} to a final state f_{CP} and the other decays at time $t_{\rm tag}$ to a final state $f_{\rm tag}$ that distinguishes between B^0 and $\overline{B}^0$, the decay rate has a time dependenct probability given by [3]

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

where τ_{B^0} is the B^0 lifetime, Δm_d is the mass difference between the two B^0 mass eigenstates, $\Delta t \equiv t_{CP} - t_{\rm tag}$, and the b flavor $q = +1(-1)$ when the tagging B meson is a B^0 ($\overline{B}^0$). The CP-violating parameters $S_{f_{CP}}$ and $\mathcal{A}_{f_{CP}}$ are given by

$$S_{f_{CP}} \equiv \frac{2\Im(\lambda)}{|\lambda|^2 + 1}, \qquad \mathcal{A}_{f_{CP}} \equiv \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1}, \quad (2)$$

where λ is a complex parameter that depends on both the $B^0\overline{B}^0$ mixing and on the amplitudes for B^0 and $\overline{B}^0$ decay to f_{CP}. To a good approximation in the SM, $|\lambda|$ is equal to the absolute value of the ratio of the $\overline{B}^0 \to f_{CP}$ to $B^0 \to f_{CP}$ decay amplitudes.

CP violation in neutral B meson decays involving the $b \to c\bar{c}s$ transition has been established through measurements of the CP-violating parameter $\sin 2\phi_1$ by the Belle [4] and BABAR [5] Collaborations. The SM predicts $S_{f_{CP}} = -\xi_f \sin 2\phi_1$, where $\xi_f = +1(-1)$ corresponds to CP-even (-odd) final states; and $\mathcal{A}_{f_{CP}} = 0$ (or equivalently $|\lambda| = 1$) for tree diagrams in both $b \to c\bar{c}s$ and $b \to c\bar{c}d$. In contrast with the $b \to c\bar{c}s$ case, however, tree and penguin amplitudes all contribute to $b \to c\bar{c}d$ to the same order in the sine of the Cabibbo angle. Therefore, if penguin or other contributions are substantial, a precision measurement of the time-dependent CP asymmetry in $b \to c\bar{c}d$ may reveal values for $S_{J/\psi\pi^0}$ and $\mathcal{A}_{J/\psi\pi^0}$ that differ from the values for $b \to c\bar{c}s$. Measurements of CP asymmetries in $b \to c\bar{c}d$ transition-induced B decays such as $B^0 \to J/\psi\pi^0$ thus play an important role in probing these one-loop diagrams.

A study of CP asymmetry in $B^0 \to J/\psi\pi^0$ decays has been reported by the BABAR Collaboration [6] based on 81 fb^{-1}. In this Letter we report a measurement of time-dependent CP-violating parameters in $B^0 \to J/\psi\pi^0$ decays using a data sample of 140 fb^{-1} (corresponding to 15.2×10^7 $B\overline{B}$ pairs) collected at the $\Upsilon(4S)$ resonance with the Belle detector [7] at the KEKB asymmetric-energy e^+e^- (3.5 on 8.0 GeV) collider [8]. The $\Upsilon(4S)$ is produced with a Lorentz boost of $\beta\gamma = 0.425$ nearly along the z axis defined as antiparallel to the positron beam. Since the B^0 and $\overline{B}^0$ mesons are nearly at rest in the $\Upsilon(4S)$ center-of-mass system (cms), Δt can be determined from Δz, the displacement in z between the f_{CP} and $f_{\rm tag}$ decay vertices: $\Delta t \simeq \Delta z/\beta\gamma c \equiv (z_{CP} - z_{\rm tag})/\beta\gamma c$.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a three-layer 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 of the coil is instrumented to detect K_L^0 mesons and to identify muons (*KLM*). The selection of hadronic events is described elsewhere [9].

J/ψ mesons are reconstructed via their decays into oppositely-charged lepton pairs (e^+e^- or $\mu^+\mu^-$). Both lepton tracks must be positively identified [9]. In the e^+e^- mode, ECL clusters that have no associated charged tracks and are within 50 mrad of the track's initial momentum vector are included in the calculation of the invariant mass ($M_{ee(\gamma)}$), in order to include photons radiated from electrons/positrons. The invariant masses of $e^+e^-(\gamma)$ and $\mu^+\mu^-$ combinations are required to fall within the ranges $-150\ {\rm MeV}/c^2 < [M_{ee(\gamma)} - M_{J/\psi}] < 36\ {\rm MeV}/c^2$ and $-60\ {\rm MeV}/c^2 < (M_{\mu\mu} - M_{J/\psi}) < 36\ {\rm MeV}/c^2$, respectively. Here $M_{J/\psi}$ denotes the world-average of the J/ψ mass [10].

Photon candidates are selected from clusters of up to 5×5 crystals in the ECL. Each photon candidate is required to have no associated charged track, and a cluster shape that is consistent with an electromagnetic shower. To select $\pi^0 \to \gamma\gamma$ decay candidates for the $B^0 \to J/\psi\pi^0$ mode, the energy of each photon is required to exceed 50 MeV in the ECL barrel ($32° < \theta < 129°$) or 100 MeV in the forward ($17° < \theta < 32°$) or backward ($129° < \theta < 150°$) end caps, where θ denotes the polar angle with respect to the z axis. Neutral pion candidates are formed from photon pairs that have an invariant mass in the range 0.118 GeV$/c^2$ to 0.150 GeV$/c^2$.

J/ψ and π^0 candidates are combined to form B candidates. The B candidate selection is carried out using two observables in the $\Upsilon(4S)$ cms: the beam-energy constrained mass $M_{\rm bc} \equiv \sqrt{E_{\rm beam}^2 - (\sum \vec{p}_i)^2}$ and the energy difference $\Delta E \equiv \sum E_i - E_{\rm beam}$, where $E_{\rm beam} = \sqrt{s}/2$ is the cms beam energy, and $\vec{p}_i$ and E_i are the cms three-momenta and energies of the B meson decay products, respectively. In this calculation, $\vec{p}_i$ and E_i are obtained after refitting with vertex and mass constraints for the J/ψ di-lepton decays and a mass constraint for the $\pi^0 \to \gamma\gamma$ decays in order to improve the ΔE and $M_{\rm bc}$ resolutions. The B meson signal region is defined as $5.27\ {\rm GeV}/c^2 < M_{\rm bc} < 5.29\ {\rm GeV}/c^2$ and $-0.10\ {\rm GeV} < \Delta E < 0.05\ {\rm GeV}$. The lower bound of ΔE is chosen to accommodate the negative ΔE tail due to shower leakage associated with π^0s, and avoid the background at $\Delta E \sim -0.2$ GeV due to $B^0 \to J/\psi K_S^0 (K_S^0 \to \pi^0\pi^0)$ events. The number of reconstructed $B^0 \to J/\psi\pi^0$ candidates is 103.

Charged leptons, kaons, pions, and Λ baryons that are not associated with the reconstructed $B^0 \to J/\psi\pi^0$ candidate are used to identify the b flavor of the accompanying B meson, which decays into $f_{\rm tag}$. Based on the measured properties of these tracks, two parameters, q and r, are assigned to each event. The first, q, has the discrete value $+1$ (-1) when the tagside B meson is more likely to be a B^0 ($\overline{B}^0$). The parameter r is an event-by-event MC-determined flavor-tagging quality factor that ranges from $r = 0$ for no flavor discrimination to $r = 1$ for an unambiguous flavor assignment. It is used only to sort data into six intervals of r, according to the estimated flavor purity. The wrong-tag probabilities, w_l and the difference in wrong-tag probabilities between B^0 and $\overline{B}^0$, Δw_l ($l = 1, 6$) are fixed using a data sample of self-tagged B^0 decay modes. The wrong-tag fractions for each r interval that are used in the final fit are given elsewhere [11].

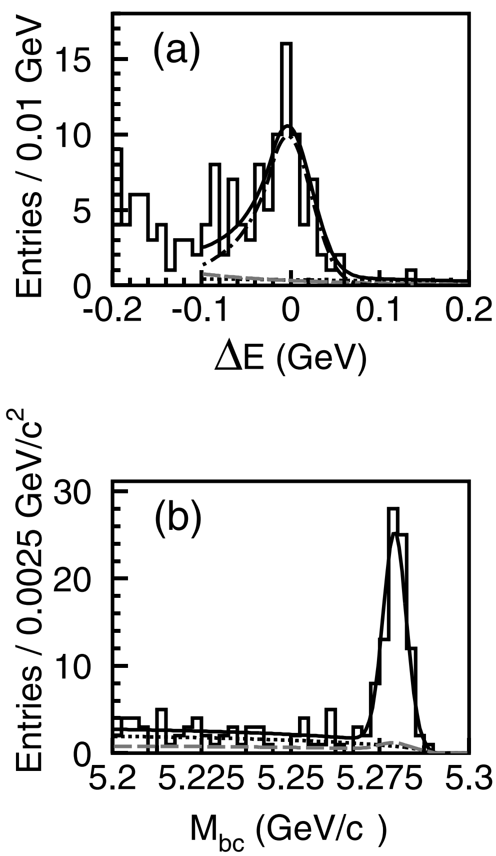

FIG. 1. (a) ΔE distribution for events in the $M_{\rm bc}$ signal region and (b) $M_{\rm bc}$ distribution for events in the ΔE signal region, for $B^0 \to J/\psi\pi^0$ candidates. The superimposed curves show fitted contributions from signal (dot-dashed line, plotted only in ΔE distribution), $B \to J/\psi X$ background (dotted line), combinatorial background (dashed line) and the sum of all the contributions (solid line).

The decay vertices of B mesons are reconstructed using tracks that have associated SVD hits. Each vertex position is required to be consistent with the interaction point profile smeared by the average transverse B meson decay length [12]. The vertex position for the $B^0 \to J/\psi\pi^0$ decay is reconstructed using lepton tracks from the J/ψ. The $f_{\rm tag}$ vertex is determined from all well-reconstructed tracks except those used for $B^0 \to J/\psi\pi^0$ reconstruction and tracks that form a K_S^0 candidate. After flavor-tagging and vertex reconstruction, 91 of the 103 $B^0 \to J/\psi\pi^0$ candidates remain. The ΔE and $M_{\rm bc}$ distributions for the candidate events are shown in Figs. 1(a) and 1(b).

To assign an event-by-event signal probability for use in the maximum-likelihood fit to extract the CP-violating parameters, we determine event distribution functions in the ΔE–$M_{\rm bc}$ plane for both signal and background. The signal distribution is modeled with a two-dimensional function which is Gaussian in $M_{\rm bc}$ and a crystal ball line shape [13] in ΔE. Since the number of candidate events is not sufficient to obtain precisely the shape parameters of these functions, those are determined from MC simulation and held fixed in the fit, while the overall signal yield is allowed to float. The background distribution is studied using a large sample of MC events along with events outside the signal region. We split the backgrounds into two categories: B decays containing a J/ψ ($B \to J/\psi X$) and combinatorial background to which random combinations of particles in $B\overline{B}$ decays and continuum events contribute. According to a MC study, the $B \to J/\psi X$ background forms a small peak in the $M_{\rm bc}$ projection. Therefore we parametrize this contribution with a sum of a Gaussian and a phase-spacelike background function (ARGUS function) [14] in $M_{\rm bc}$ and an exponential function for ΔE. The amount of $B \to J/\psi X$ background is estimated by the MC study and fixed in the fit [15]. For the combinatorial background, we use a linear function for ΔE and an ARGUS function for $M_{\rm bc}$. From the fit, the purity of the $B^0 \to J/\psi\pi^0$ candidates is estimated to be $(86 \pm 11)\%$.

We determine $\mathcal{S}_{J/\psi\pi^0}$ and $\mathcal{A}_{J/\psi\pi^0}$ by performing an unbinned maximum-likelihood fit to the observed Δt distribution. The probability density function (PDF) expected for the signal distribution is given by

$$\mathcal{P}_{\rm sig}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\Big\{1 - q\Delta w_l + q(1-2w_l) \times [\mathcal{S}_{J/\psi\pi^0}\sin(\Delta m_d \Delta t) + \mathcal{A}_{J/\psi\pi^0}\cos(\Delta m_d \Delta t)]\Big\}, \quad (3)$$

to account for the effect of incorrect flavor assignment. The distribution is convolved with the proper-time interval resolution function $R_{\rm sig}(\Delta t)$, which takes into account the finite vertex resolution. $R_{\rm sig}(\Delta t)$ is formed by convolving four components: the detector resolutions for z_{CP} and $z_{\rm tag}$, the shift in the $z_{\rm tag}$ vertex position due to secondary tracks originating from charmed particle decays, and the kinematic approximation that the B mesons are at rest in the cms [12]. A small component of broad outliers in the Δz distribution, caused by misreconstruction, is represented by a Gaussian function $P_{\rm ol}(\Delta t)$. We use the same resolution function parameters as used in the $\sin 2\phi_1$ measurement [11]. We determine the following likelihood value for each event:

$$P_i(\Delta t_i; \mathcal{S}_{J/\psi\pi^0}, \mathcal{A}_{J/\psi\pi^0}) = (1 - f_{\rm ol})\int_{-\infty}^{\infty}[f_{\rm sig}\mathcal{P}_{\rm sig}(\Delta t')R_{\rm sig}(\Delta t_i - \Delta t') + f_{\rm bkg}^{J/\psi X}\mathcal{P}_{\rm bkg}^{J/\psi X}(\Delta t')R_{\rm bkg}^{J/\psi X}(\Delta t_i - \Delta t') + (1 - f_{\rm sig} - f_{\rm bkg}^{J/\psi X})\mathcal{P}_{\rm bkg}^{\rm comb}(\Delta t')R_{\rm bkg}^{\rm comb}(\Delta t_i - \Delta t')]d(\Delta t') + f_{\rm ol}P_{\rm ol}(\Delta t_i), \quad (4)$$

where $f_{\rm ol}$ is the outlier fraction, $f_{\rm sig}$ and $f_{\rm bkg}^{J/\psi X}$ are the signal and $B \to J/\psi X$ background probabilities calculated as functions of ΔE and $M_{\rm bc}$, $\mathcal{P}_{\rm bkg}^{J/\psi X}(\Delta t)$ and $\mathcal{P}_{\rm bkg}^{\rm comb}(\Delta t)$ are the PDFs for $B \to J/\psi X$ and combinatorial background events, respectively. $\mathcal{P}_{\rm bkg}^{\rm comb}(\Delta t)$ is modeled as a sum of exponential and prompt components, and is convolved with the corresponding resolution function $R_{\rm bkg}^{\rm comb}$, which is modeled by a sum of two Gaussians. The parameters in $\mathcal{P}_{\rm bkg}^{\rm comb}(\Delta t)$ and $R_{\rm bkg}^{\rm comb}$ are determined by a fit to the Δt distribution of a background-enhanced control sample, i.e., events not in the ΔE–$M_{\rm bc}$ signal region. $\mathcal{P}_{\rm bkg}^{J/\psi X}(\Delta t)$ is a lifetime distribution determined by MC simulation. The contributions of $CP = -1$ and $+1$ components in the $B \to J/\psi X$ background in the signal region are found to be almost the same and the CP violation effect is largely cancelled. We model $R_{\rm bkg}^{J/\psi X}$ using the signal resolution function because vertex reconstruction for both signal and $B \to J/\psi X$ background events is based on lepton tracks from J/ψ. We fix τ_{B^0} and Δm_d at their world-average values [16]. The only free parameters in the final fit are $\mathcal{S}_{J/\psi\pi^0}$ and $\mathcal{A}_{J/\psi\pi^0}$, which are determined by maximizing the likelihood function

$$L = \prod_i P_i(\Delta t_i; \mathcal{S}_{J/\psi\pi^0}, \mathcal{A}_{J/\psi\pi^0}), \quad (5)$$

where the product runs over all events.

A fit to the candidate events results in the CP-violating parameters,

$$\begin{aligned} \mathcal{S}_{J/\psi\pi^0} &= -0.72 \pm 0.42({\rm stat}) \pm 0.09({\rm syst}), \\ \mathcal{A}_{J/\psi\pi^0} &= -0.01 \pm 0.29({\rm stat}) \pm 0.03({\rm syst}), \end{aligned} \quad (6)$$

where the sources of systematic errors are described below. Figures 2(a) and 2(b) show the Δt distributions for

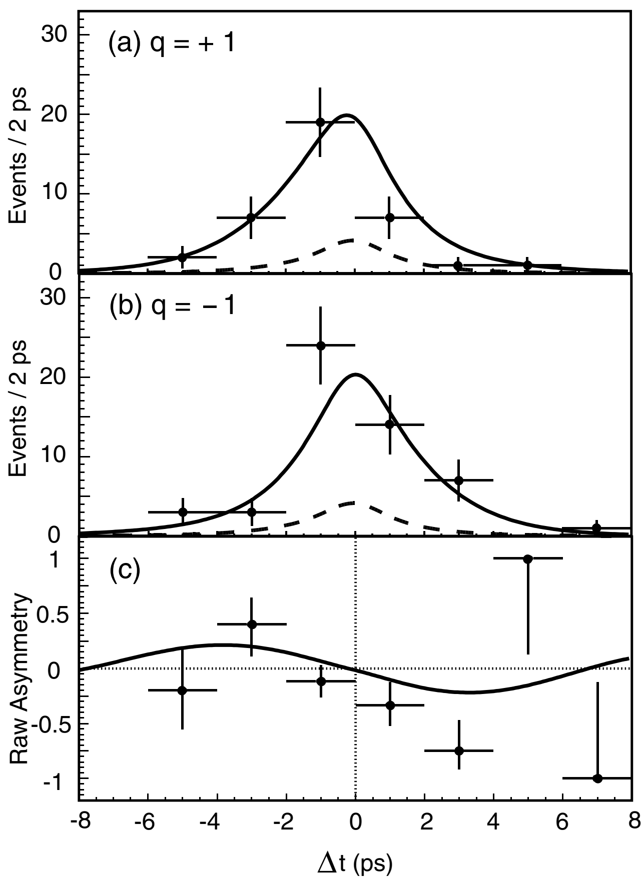

FIG. 2. The Δt distributions for (a) $\overline{B}^0 \to J/\psi\pi^0$ ($q = +1$) and (b) $B^0 \to J/\psi\pi^0$ ($q = -1$) candidates. (c) The asymmetry, A, in each Δt bin. The solid line shows the result of the unbinned maximum-likelihood fit, and the dashed line shows the background distributions.

$\overline{B}^0 \to J/\psi\pi^0$ ($q = +1$) and $B^0 \to J/\psi\pi^0$ ($q = -1$) event samples, respectively. Figure 2(c) shows the raw asymmetry in each Δt bin without background subtraction, which is defined by

$$A \equiv \frac{N_{q=+1} - N_{q=-1}}{N_{q=+1} + N_{q=-1}}, \tag{7}$$

where $N_{q=+1}$ ($N_{q=-1}$) is the number of observed candidates with $q = +1(-1)$. The curve shows the result of the unbinned maximum-likelihood fit to the Δt distributions.

The major systematic errors come from uncertainties in the vertex reconstruction ($\pm$ 0.06 for $S_{J/\psi\pi^0}$ and ± 0.02 for $\mathcal{A}_{J/\psi\pi^0}$), the wrong-tag fraction ($\pm$ 0.03 and ± 0.01), the potential CP-violating effect in $B \to J/\psi X$ background ($\pm$ 0.03 and ± 0.01), the signal probability ($\pm$ 0.02 and ± 0.02), and possible fit bias ($\pm$ 0.03 and ± 0.01). The contributions from other systematic error sources, uncertainties in the background Δt distribution, resolution function, and physics parameters (τ_{B^0}, Δm_d), are found to be much smaller. The quadratic sum of all the contributions amounts to ± 0.09 for $S_{J/\psi\pi^0}$ and ± 0.03 for $\mathcal{A}_{J/\psi\pi^0}$.

In summary, we have performed a measurement of the CP-violating parameters in the $B^0 \to J/\psi\pi^0$ decay. The resultant values are $S_{J/\psi\pi^0} = -0.72 \pm 0.42(\text{stat}) \pm 0.09(\text{syst})$ and $\mathcal{A}_{J/\psi\pi^0} = -0.01 \pm 0.29(\text{stat}) \pm 0.03(\text{syst})$. These values are consistent with those obtained for $B^0 \to J/\psi K_S^0$ and other decays governed by $b \to c\bar{c}s$ transition, as expected from the SM if the tree diagram dominates.

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[1] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

[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).

[3] A general review of the formalism is given in I. I. Bigi, V. A. Khoze, N. G. Uraltsev, and A. I. Sanda, *CP Violation*, edited by C. Jarlskog (World Scientific, Singapore, 1989), p. 175.

[4] Belle Collaboration, K. Abe *et al.*, Phys. Rev. Lett. **87**, 091802 (2001); Belle Collaboration, K. Abe *et al.*, Phys. Rev. D **66**, 032007 (2002); Belle Collaboration, K. Abe *et al.*, Phys. Rev. D **66**, 071102(R) (2002).

[5] BABAR Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **87**, 091801 (2001); BABAR Collaboration, B. Aubert *et al.*, Phys. Rev. D **66**, 032003 (2002); BABAR Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **89**, 201802 (2002).

[6] BABAR Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **91**, 061802 (2003).

[7] Belle Collaboration, A. Abashian *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 117 (2002).

[8] S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods Phys. Res., Sect. A **499**, 1 (2003), and other papers included in this volume.

[9] Belle Collaboration, K. Abe *et al.*, Phys. Rev. D **67**, 032003 (2003).

[10] Particle Data Group, K. Hagiwara *et al.*, Phys. Rev. D **66**, 010001 (2002), and 2003 off-year partial update to the 2004 edition.

[11] Belle Collaboration, K. Abe *et al.*, hep-ex/0308036.

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

[13] T. Skwarnicki, Ph.D. thesis, Institute for Nuclear Physics, Krakow, 1986; DESY Internal Report, DESY F31-86-02.

[14] ARGUS Collaboration, H. Albrecht *et al.*, Phys. Lett. B, **241**, 278 (1990).

[15] The dominant contribution comes from two-body B meson decays including a J/ψ meson, with well-measured branching fractions ($B \to J/\psi K^{(*)}$).

[16] In the likelihood function, we use the following $B^0\overline{B}^0$-mixing parameter and B meson lifetimes [10]: $\Delta m_d = 0.502 \pm 0.007$ ps^{-1}, $\tau_{B^0} = 1.537 \pm 0.015$ ps and $\tau_{B^+} = 1.671 \pm 0.018$ ps.