Evidence for CP Violation in $B^0 \to D^+D^-$ Decays

S. Fratina,[13] K. Abe,[8] K. Abe,[41] I. Adachi,[8] H. Aihara,[43] D. Anipko,[1] K. Arinstein,[1] T. Aushev,[17,12] A. M. Bakich,[39] E. Barberio,[20] A. Bay,[17] K. Belous,[11] U. Bitenc,[13] I. Bizjak,[13] A. Bondar,[1] A. Bozek,[26] M. Bračko,[8,19,13] J. Brodzicka,[26] T. E. Browder,[7] M.-C. Chang,[5] P. Chang,[25] Y. Chao,[25] A. Chen,[23] K.-F. Chen,[25] W. T. Chen,[23] B. G. Cheon,[3] R. Chistov,[12] Y. Choi,[38] Y. K. Choi,[38] S. Cole,[39] J. Dalseno,[20] M. Dash,[46] A. Drutskoy,[4] S. Eidelman,[1] A. Go,[23] B. Golob,[18,13] A. Gorišek,[13] H. Ha,[15] J. Haba,[8] K. Hara,[21] M. Hazumi,[8] D. Heffernan,[31] T. Hokuue,[21] Y. Hoshi,[41] W.-S. Hou,[25] T. Iijima,[21] K. Inami,[21] A. Ishikawa,[43] H. Ishino,[44] R. Itoh,[8] M. Iwasaki,[43] Y. Iwasaki,[8] H. Kaji,[21] J. H. Kang,[47] N. Katayama,[8] H. Kawai,[2] T. Kawasaki,[28] H. Kichimi,[8] H. J. Kim,[16] H. O. Kim,[38] S. K. Kim,[36] Y. J. Kim,[6] K. Kinoshita,[4] S. Korpar,[19,13] P. Križan,[18,13] P. Krokovny,[8] R. Kulasiri,[4] R. Kumar,[32] C. C. Kuo,[23] A. Kuzmin,[1] Y.-J. Kwon,[47] M. J. Lee,[36] S. E. Lee,[36] T. Lesiak,[26] A. Limosani,[8] S.-W. Lin,[25] D. Liventsev,[12] F. Mandl,[10] T. Matsumoto,[45] A. Matyja,[26] S. McOnie,[39] T. Medvedeva,[12] W. Mitaroff,[10] K. Miyabayashi,[22] H. Miyake,[31] H. Miyata,[28] Y. Miyazaki,[21] R. Mizuk,[12] G. R. Moloney,[20] T. Mori,[21] E. Nakano,[30] M. Nakao,[8] H. Nakazawa,[23] S. Nishida,[8] S. Noguchi,[22] S. Ogawa,[40] T. Ohshima,[21] S. Okuno,[14] S. L. Olsen,[7] Y. Onuki,[34] H. Ozaki,[8] P. Pakhlov,[12] G. Pakhlova,[12] C. W. Park,[38] H. Park,[16] L. S. Peak,[39] R. Pestotnik,[13] L. E. Piilonen,[46] Y. Sakai,[8] N. Satoyama,[37] T. Schietinger,[17] O. Schneider,[17] J. Schümann,[8] C. Schwanda,[10] A. J. Schwartz,[4] K. Senyo,[21] M. E. Sevior,[20] M. Shapkin,[11] H. Shibuya,[40] B. Shwartz,[1] J. B. Singh,[32] A. Somov,[4] N. Soni,[32] S. Stanič,[29] M. Starič,[13] H. Stoeck,[39] T. Sumiyoshi,[45] F. Takasaki,[8] K. Tamai,[8] M. Tanaka,[8] Y. Teramoto,[30] X. C. Tian,[33] I. Tikhomirov,[12] K. Trabelsi,[8] T. Tsukamoto,[8] S. Uehara,[8] K. Ueno,[25] T. Uglov,[12] Y. Unno,[3] S. Uno,[8] P. Urquijo,[20] Y. Usov,[1] G. Varner,[7] K. E. Varvell,[39] K. Vervink,[17] S. Villa,[17] C. H. Wang,[24] Y. Watanabe,[44] E. Won,[15] B. D. Yabsley,[39] A. Yamaguchi,[42] Y. Yamashita,[27] M. Yamauchi,[8] C. C. Zhang,[9] Z. P. Zhang,[35] V. Zhilich,[1] and A. Zupanc[13]

(Belle Collaboration)

[1]*Budker Institute of Nuclear Physics, Novosibirsk*
[2]*Chiba University, Chiba*
[3]*University of Cincinnati, Cincinnati, Ohio 45221*
[4]*Department of Physics, Fu Jen Catholic University, Taipei*
[5]*The Graduate University for Advanced Studies, Hayama*
[6]*Hanyang University, Seoul*
[7]*University of Hawaii, Honolulu, Hawaii 96822*
[8]*High Energy Accelerator Research Organization (KEK), Tsukuba*
[9]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing*
[10]*Institute of High Energy Physics, Vienna*
[11]*Institute of High Energy Physics, Protvino*
[12]*Institute for Theoretical and Experimental Physics, Moscow*
[13]*J. Stefan Institute, Ljubljana*
[14]*Kanagawa University, Yokohama*
[15]*Korea University, Seoul*
[16]*Kyungpook National University, Taegu*
[17]*Swiss Federal Institute of Technology of Lausanne, EPFL, Lausanne*
[18]*University of Ljubljana, Ljubljana*
[19]*University of Maribor, Maribor*
[20]*University of Melbourne, Victoria*
[21]*Nagoya University, Nagoya*
[22]*Nara Women's University, Nara*
[23]*National Central University, Chung-li*
[24]*National United University, Miao Li*
[25]*Department of Physics, National Taiwan University, Taipei*
[26]*H. Niewodniczanski Institute of Nuclear Physics, Krakow*
[27]*Nippon Dental University, Niigata*
[28]*Niigata University, Niigata*
[29]*University of Nova Gorica, Nova Gorica*
[30]*Osaka City University, Osaka*
[31]*Osaka University, Osaka*
[32]*Panjab University, Chandigarh*
[33]*Peking University, Beijing*

[34] *RIKEN BNL Research Center, Upton, New York 11973*
[35] *University of Science and Technology of China, Hefei*
[36] *Seoul National University, Seoul*
[37] *Shinshu University, Nagano*
[38] *Sungkyunkwan University, Suwon*
[39] *University of Sydney, Sydney, New South Wales*
[40] *Toho University, Funabashi*
[41] *Tohoku Gakuin University, Tagajo*
[42] *Tohoku University, Sendai*
[43] *Department of Physics, University of Tokyo, Tokyo*
[44] *Tokyo Institute of Technology, Tokyo*
[45] *Tokyo Metropolitan University, Tokyo*
[46] *Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061*
[47] *Yonsei University, Seoul*

(Received 19 February 2007; published 31 May 2007)

We report measurements of the branching fraction and CP violation parameters in $B^0 \to D^+D^-$ decays. The results are based on a data sample that contains 535×10^6 $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance, with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. We obtain $[1.97 \pm 0.20(\text{stat}) \pm 0.20(\text{syst})] \times 10^{-4}$ for the branching fraction of $B^0 \to D^+D^-$. The measured values of the CP violation parameters are $\mathcal{S} = -1.13 \pm 0.37 \pm 0.09$, $\mathcal{A} = 0.91 \pm 0.23 \pm 0.06$, where the first error is statistical and the second is systematic. We find evidence of CP violation in $B^0 \to D^+D^-$ at the 4.1σ confidence level. While the value of $\mathcal{S}$ is consistent with expectations from other measurements, the value of the parameter $\mathcal{A}$ favors large direct CP violation at the 3.2σ confidence level, in contradiction to standard model expectations.

DOI: 10.1103/PhysRevLett.98.221802 PACS numbers: 13.25.Hw, 11.30.Er

Within the standard model (SM), CP violation (CPV) arises from a complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix $\mathbf{V}$ [1]. In the decays $\Upsilon(4S) \to B_{CP}B_{\text{tag}}$, where the neutral B_{CP} meson decays to the D^+D^- final state at time t_{CP} and the associated B meson (B_{tag}) decays at time t_{tag}, the time-dependent decay rate is given by

$$\mathcal{P}_{\text{sig}} = \frac{e^{-|\Delta t|/\tau}}{4\tau}\{1 + q[\mathcal{S}\sin(\Delta m \Delta t) + \mathcal{A}\cos(\Delta m \Delta t)]\}, \tag{1}$$

where $\Delta t = t_{CP} - t_{\text{tag}}$, τ is the B^0 meson lifetime, Δm is the mass difference of the two B mass eigenstates [2], and $\mathcal{S}$ and $\mathcal{A}$ are the CPV parameters. The flavor q is determined from the final state of the B_{tag} meson: $q = +1(-1)$ when B_{tag} decays as $B^0(\bar{B}^0)$.

The dominant contribution to $B^0 \to D^+D^-$ decays is the tree-level $\bar{b} \to c\bar{c}\,\bar{d}$ transition shown in Fig. 1(a). If this diagram is the only contribution, then the mixing-induced CPV parameter for $B^0 \to D^+D^-$ is $\mathcal{S} = -\sin 2\phi_1$, where $\phi_1 = \arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$, while the direct CPV term $\mathcal{A}$ is zero [3]. The penguin contribution, shown in Fig. 1(b), is expected to change the value of the parameter $\mathcal{S}$ by less than a few percent and increase the value of $\mathcal{A}$ to about 0.03 [4,5]. However, particles from physics beyond the SM may give additional contributions within the loop diagrams mediating flavor-changing $b \to d$ transitions. Such contributions may potentially induce large deviations from the SM expectation for time-dependent CP asymmetries. As $\sin 2\phi_1$ has already been determined with high precision by measurements in $b \to c\bar{c}s$ charmonium modes [6,7], the objective here is to focus on deviations from expectations in $b \to c\bar{c}d$ transitions. The results of similar studies in $B^0 \to D^{*\pm}D^{(*)\mp}$ decays, which involve the same quark level weak decay, are consistent with the SM [8–11].

The results presented here are based on a data sample that contains $(535 \pm 7) \times 10^6$ $B\bar{B}$ pairs, collected with the Belle detector at the KEKB asymmetric-energy e^+e^- (3.5 on 8 GeV) collider [12]. KEKB operates at the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58$ GeV) with a peak luminosity that exceeds $1.7 \times 10^{34}\ \text{cm}^{-2}\,\text{s}^{-1}$. At KEKB, the $\Upsilon(4S)$ is produced with a Lorentz boost of $\beta\gamma = 0.425$ nearly along the electron beam line ($-z$ direction). Since the B^0 and $\bar{B}^0$ mesons are approximately at rest in the $\Upsilon(4S)$ center-of-mass (c.m.) system, Δt can be determined from the displacement in z between the B_{CP} and B_{tag} decay vertices: $\Delta t \simeq (z_{CP} - z_{\text{tag}})/\beta\gamma c \equiv \Delta z/\beta\gamma c$.

The Belle detector [13] is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector, a 50-

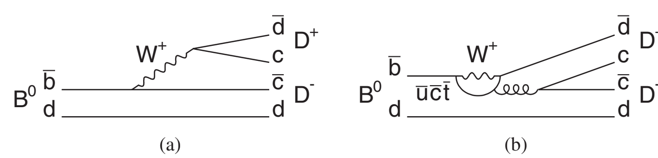


FIG. 1. The tree (a) and the penguin (b) contributions to the $B^0 \to D^+D^-$ decay.

layer central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals 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 silicon vertex detector was used for the first 152×10^6 $B\bar{B}$ pairs and a 1.5 cm beam pipe, a 4-layer silicon detector and a small-cell inner drift chamber were employed for the remaining 383×10^6 $B\bar{B}$ pairs [14].

D mesons are reconstructed using the $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to K_S\pi^+$ decay modes [15]. In this Letter, the shorter notation $K\pi\pi$ is used when both D mesons are reconstructed in the $K\pi\pi$ channel while $K_S\pi$ is used when at least one of the D mesons is reconstructed in the $K_S\pi$ channel. Charged tracks that are not positively identified as electrons [16] and satisfy a loose requirement on the impact parameter relative to the interaction point (IP) are considered as pion and kaon candidates. For charged particle identification (PID), we combine information from the CDC, TOF, and ACC counters into a likelihood ratio $\mathcal{L}(K^\pm)/[\mathcal{L}(K^\pm) + \mathcal{L}(\pi^\pm)]$, which is required to be greater than 0.55 for kaon and less than 0.9 for pion candidates [17]. K_S candidates are reconstructed in the $K_S \to \pi^+\pi^-$ decay mode; the pion combination is required to have an invariant mass within 30 MeV$/c^2$ of the nominal K_S mass and a vertex displaced from the IP. The mass of the $D^\pm$ meson candidate is required to be within 10 MeV$/c^2$ (2.4σ) of the nominal $D^\pm$ mass. We select B meson candidates using the energy difference $\Delta E = E_B^* - E_{\rm beam}^*$ and the beam-energy-constrained mass $M_{\rm bc} = \sqrt{(E_{\rm beam}^*/c^2)^2 - (p_B^*/c)^2}$, where E_B^*, $E_{\rm beam}^*$, and p_B^* are the B meson energy, the beam energy, and the B meson momentum, respectively, in the c.m. system.

The K_S decay vertex is fitted from two pion tracks. The D^+ meson decay vertex is fitted from three charged tracks or from the K_S and π^+ track. The mass of the $K^-\pi^+\pi^+$ or $K_S\pi^+$ combination is constrained to the D^+ meson mass to obtain better $M_{\rm bc}$ and ΔE resolutions. The B^0 decay vertex is reconstructed from the two D meson tracks and the IP information. All remaining charged tracks are used to determine the decay vertex of the tag-side B meson. A loose requirement on the quality of the vertex fit is applied for both B mesons. The reconstruction of the $B_{\rm tag}$ vertex, vertex quality, and flavor tagging are not required for the branching fraction measurement.

The flavor of the accompanying B meson is determined from its decay products. Events are divided into six r bins according to the tagging quality r. The value of r ranges from 0 for events with no flavor information to 1 for unambiguous flavor assignment. Because of the imperfect flavor tagging, the distribution $\mathcal{P}_{\rm sig}$ of Eq. (1) is modified to

$$\mathcal{P}_{\rm sig} = \frac{e^{-|\Delta t|/\tau}}{4\tau}\{1 - q\Delta w + q(1-2w) \times [\mathcal{S}\sin(\Delta m\Delta t) + \mathcal{A}\cos(\Delta m\Delta t)]\}, \qquad (2)$$

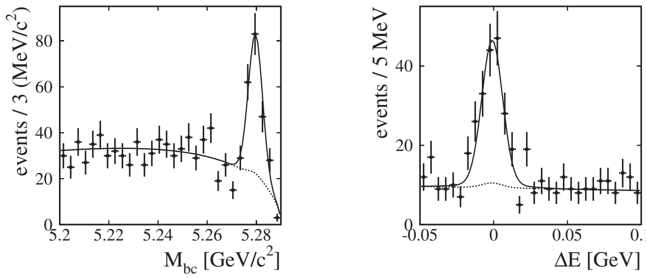
where w is the wrong tag fraction and Δw is the difference between the wrong tag fractions if the $B_{\rm tag}$ meson is a $\bar{B}^0$ or B^0. The values of w and Δw for each of the six bins in the tagging quality parameter r are determined separately using flavor specific B meson decays [18].

Continuum ($e^+e^- \to q\bar{q}$, where $q \in \{u, d, s, c\}$) events are suppressed by forming a likelihood ratio from $\cos\theta_B$, where θ_B is the polar angle between the B meson direction in the c.m. system and the beam axis, and a variable based on a combination of 16 modified Fox-Wolfram moments with the scalar sum of transverse momentum [19]. Note that since the $B\bar{B}$ and continuum events have significantly different distributions in the tagging quality variable r, the continuum suppression cut varies for events in different r bins.

After applying all of the event selection criteria, 6% of the signal events have more than one B^0 candidate. The B^0 with the smallest value of $(\Delta m_{D^+}/\sigma_{D^+})^2 + (\Delta m_{D^-}/\sigma_{D^-})^2$ is selected as the best candidate, where $\Delta m_D = M_{K\pi\pi/K_S\pi} - m_D$ is the difference from the nominal D meson mass and $\sigma_{D^\pm}$ are the widths of the signal peak in the $M_{K\pi\pi/K_S\pi}$ mass distribution.

The signal yield is obtained from an extended unbinned 2D maximum likelihood (ML) fit of the $M_{\rm bc}$ and ΔE distributions in the range $M_{\rm bc} > 5.20$ GeV$/c^2$ and -0.05 GeV $< \Delta E < 0.10$ GeV. A Gaussian function for the signal and an ARGUS [20] function for the background are used to describe the $M_{\rm bc}$ distribution. For the parametrization of the ΔE distribution we used two Gaussians with the same mean value to describe the signal and a linear function to describe the background. The fraction and the width of the wider Gaussian were fixed to the values obtained from Monte Carlo (MC) simulated signal decays [21]. The fit yields 150 ± 15 events in the peak, where the error is statistical only. The $M_{\rm bc}$ and ΔE distributions of reconstructed events and the projection of the fit result are shown in Fig. 2. The signal yields from separate fits to the $K\pi\pi$ and $K_S\pi$ decay modes are given in Table I. Nonresonant $B^0 \to D^-\bar{K}^0\pi^+$ and $B^0 \to D^-\bar{K}^{*0}(892)\pi^+$ decays are found to be a possible source of background peaking in the $M_{\rm bc}$ and ΔE distributions. The amount of this background was estimated from the D^+ mass sidebands in data and subtracted from the signal. We estimate the number of nonresonant decays in the signal region ($N_{\rm nr}$) to be 2.0 ± 1.8 and 1.4 ± 1.0 for the $K\pi\pi$ and $K_S\pi$ channels, respectively.

The combined branching fraction is calculated from the total number of reconstructed events and the average reconstruction efficiency and is found to be $\mathcal{B}(B^0 \to D^+D^-) = [1.97 \pm 0.20({\rm stat}) \pm 0.20({\rm syst})] \times 10^{-4}$, which is consistent with previous measurements [22,23] and has



(a) $M_{\rm bc}$, $|\Delta E| < 0.03$ GeV (b) ΔE, $M_{\rm bc} > 5.27$ GeV$/c^2$

FIG. 2. Distributions for the reconstructed events in $M_{\rm bc}$ (a) and ΔE (b). The full (dashed) curves show the projections of the result of the 2D unbinned maximum likelihood fit for all (background) events.

better accuracy. The uncertainty in the D meson branching fractions results in a 5% systematic error. The error in the pion and kaon track reconstruction efficiency was estimated using partially reconstructed D^* decays. The errors are added linearly for all six pion and kaon tracks, which yields a 6% uncertainty. The difference in PID efficiency for the simulated and real data is approximately 1% per track, which gives a 6% uncertainty. Smaller contributions come from the uncertainty in the K_S selection efficiency (1%), the number of $B\bar{B}$ events (1.3%), and the number of nonresonant decays (1.5%). The total systematic error of 10% is obtained from the quadratic sum of these uncertainties.

Time-dependent CP violation parameters are determined by an unbinned ML fit to the Δt distribution of 219 events, including 128 ± 14 signal events, in the signal region $5.27~\text{GeV}/c^2 < M_{\rm bc} < 5.29~\text{GeV}/c^2$ and $|\Delta E| < 0.03$ GeV. The Δt distribution for signal events $\mathcal{P}_{\rm sig}$ described by Eq. (2) is modified by the inclusion of the background contribution and resolution effects. The event-by-event likelihood is given by

$$\mathcal{L}_{\rm ev} = f_{\rm sig}\mathcal{P}_{\rm sig} \otimes \mathcal{R} + f_{\rm nr}\mathcal{P}_{\rm nr} \otimes \mathcal{R} + f_{\rm bcg}\mathcal{P}_{\rm bcg} \otimes \mathcal{R}_{\rm bcg}. \tag{3}$$

Subscripts sig, nr, and bcg refer to signal, nonresonant, and combinatorial background components, respectively. The fractions $f_i = f_i(M_{\rm bc}, \Delta E, r)$ are determined on an event-by-event basis, $f_{\rm sig} + f_{\rm nr} + f_{\rm bcg} = 1$. The function $\mathcal{R}$ describes the detector resolution of the Δt measurement. It takes into account the error in the determination of both B meson vertices as well as an additional kinematic smearing due to the momentum of the B meson in the c.m. system and the smearing of the tag-side vertex due to the tracks originating from the secondary vertices. An additional wide Gaussian component with $\sigma \approx 20$ ps is added to describe a small fraction of events (about 1%) with poorly reconstructed vertices. A more detailed description of the resolution function parametrization can be found in Ref. [24]. Resolution parameters for the B_{CP} meson vertex are determined from a fit to the Δt distribution of kinematically similar $B^0 \to D_s^+ D^-$ decays.

TABLE I. The product of D branching fractions $\mathcal{B}_{D^+} \times \mathcal{B}_{D^-}$, the detection efficiency ϵ, the number of events in the signal peak $N_{\rm peak}$, and the expected amount of the combinatorial background $N_{\rm bcg}$ in the $5.27~\text{GeV}/c^2 < M_{\rm bc} < 5.29~\text{GeV}/c^2$ and $|\Delta E| < 0.03$ GeV region, as extrapolated from the fit.

Channel	$\mathcal{B}_{D^+} \times \mathcal{B}_{D^-}$	ϵ [%]	$N_{\rm peak}$	$N_{\rm bcg}$
$K\pi\pi$	(0.904 ± 0.065)%	12.6	124.1 ± 13.6	110.8 ± 2.6
$K_S\pi$	(0.204 ± 0.015)%	12.1	25.7 ± 5.7	13.8 ± 0.9

The fraction of the nonresonant decays $f_{\rm nr}$ is assumed to be proportional to the signal fraction, $f_{\rm nr} = a f_{\rm sig}$, where $a = N_{\rm nr}/(N_{\rm peak} - N_{\rm nr})$ and $a_{K\pi\pi} = 0.016$, $a_{K_S\pi} = 0.058$. The Δt distribution of the nonresonant $B^0 \to D^- \bar{K}^0 \pi^+$ or $B^0 \to D^- \bar{K}^{*0}(892)\pi^+$ background is described by an exponential B^0 decay time distribution. We include the effect of possible CP asymmetry of these modes in the systematic error. About half of the combinatorial background events come from $B\bar{B}$ decays ($b \to c$ transition), which have an exponential decay Δt distribution. The other half are continuum events, for which the Δt distribution contains a δ-function component. Therefore, the Δt distribution of the background is described by

$$\mathcal{P}_{\rm bcg} = \frac{1}{2}\left[(1 - f_\delta)\frac{e^{-|\Delta t|/\tau_{\rm bcg}}}{2\tau_{\rm bcg}} + f_\delta \delta(\Delta t)\right]. \tag{4}$$

The background resolution function $\mathcal{R}_{\rm bcg}$ is taken to be a Gaussian. Parameters describing the background distribution are obtained from a fit to the Δt distribution of the data sideband, $M_{\rm bc} < 5.27~\text{GeV}/c^2$ and $\Delta E > 0.06$ GeV.

From an unbinned fit to the measured Δt distribution described by Eq. (3), we obtain the CP violation parameters for $B^0 \to D^+ D^-$,

$$\mathcal{S} = -1.13 \pm 0.37 \pm 0.09 \quad \text{and} \quad \mathcal{A} = +0.91 \pm 0.23 \pm 0.06, \tag{5}$$

where the first error is statistical and the second is systematic. The Δt distributions are shown in Fig. 3. The main contributions to the systematic error are fit bias (0.06 for $\mathcal{S}$ and 0.02 for $\mathcal{A}$), uncertainties in the resolution function (0.04 for $\mathcal{S}$ and 0.03 for $\mathcal{A}$), and signal fraction (0.035 for $\mathcal{S}$ and 0.015 for $\mathcal{A}$). Other uncertainties come from the errors on the parameters τ and Δm (0.023 for $\mathcal{S}$ and 0.007 for $\mathcal{A}$), wrong tag fractions (0.017 for $\mathcal{S}$ and 0.014 for $\mathcal{A}$), description of background Δt distribution (0.01 for $\mathcal{S}$ and $\mathcal{A}$), fraction and possible CP asymmetry of the nonresonant background (0.02 for $\mathcal{S}$ and 0.03 for $\mathcal{A}$), the effect of tag-side interference [25] (0.01 for $\mathcal{S}$ and 0.03 for $\mathcal{A}$), and requirements on the vertex quality and the fitting range (less than 0.01 for $\mathcal{S}$ and 0.01 for $\mathcal{A}$). The correlation coefficient between the two parameters is small (0.038).

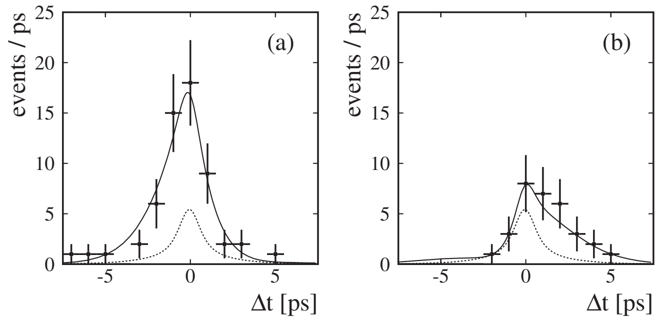


FIG. 3. The Δt distribution for events with good tagging information ($r > 0.5$) when the tag-side B-meson is reconstructed as B^0 (a) or $\bar{B}^0$ (b). The full and dashed curves show the projection of the fit result and background contribution, respectively.

To test the consistency of the fitting procedure, the same analysis was applied to the $B^0 \to D_s^+ D^-$ control sample. Since there is only one decay amplitude at the tree level and the leading penguin contributions have the same CKM structure as the tree contribution, no CPV is expected for this decay. The result is consistent with no CPV, $\mathcal{S} = -0.064 \pm 0.094$ and $\mathcal{A} = 0.091 \pm 0.060$, where the error is statistical only. We also fit the $B^0 \to D^+ D^-$ background sample ($M_{bc} < 5.27$ GeV$/c^2$ and $\Delta E > 0.06$ GeV) for a possible CP asymmetry and find none: $\mathcal{A} = -0.01 \pm 0.06$ and $\mathcal{S} = 0.03 \pm 0.10$. In addition, a time-integrated fit for the parameter $\mathcal{A}$ was performed to validate the result in $B^0 \to D^+ D^-$ decays. The signal yield was determined separately for events tagged as $B_{tag} = B^0$ and $B_{tag} = \bar{B}^0$ for each of the six r bins. The fit yields $\mathcal{A} = 0.86 \pm 0.32$, which is consistent with the time-dependent result.

Since our result fluctuated outside the physical region, $\mathcal{S}^2 + \mathcal{A}^2 \leq 1$, we use the Feldman-Cousins frequentist approach [26] to determine the statistical significance of our measurement. In order to form confidence intervals, we use the $\mathcal{A}$ and $\mathcal{S}$ distributions of the results of fits to the MC pseudoexperiments for various input values of $\mathcal{A}$ and $\mathcal{S}$ in a similar way as described in Ref. [27]. The systematic errors and possibility of tails that are wider than Gaussian tails are taken into account. The case of no CPV, $\mathcal{S} = \mathcal{A} = 0$, is ruled out at the $1 - 4.1 \times 10^{-5}$ confidence level (C.L.), corresponding to 4.1σ significance. The case of no direct CPV, $\mathcal{A} = 0$, is excluded at more than $1 - 1.4 \times 10^{-3}$ (3.2σ) C.L. for any value of $\mathcal{S}$.

In summary, we measure the branching fraction for $B^0 \to D^+ D^-$ decays to be $(1.97 \pm 0.20 \pm 0.20) \times 10^{-4}$, superseding our previous measurement [22]. We obtain values for the CP parameters $\mathcal{S} = -1.13 \pm 0.37 \pm 0.09$ and $\mathcal{A} = 0.91 \pm 0.23 \pm 0.06$ and rule out the CP-conserving case, $\mathcal{S} = \mathcal{A} = 0$, at the 4.1σ confidence level. The value of $\mathcal{S}$ is consistent with measurements of $b \to c\bar{c}s$ modes [2]. In addition, we observe evidence for direct CP violation at the 3.2σ confidence level. Some extensions of the SM predict large contributions to the CP violating phases in $b \to c\bar{c}d$ decays that are consistent with our result [28]. Our measurement differs from a previous measurement by the *BABAR* Collaboration [10] by about 2.2σ.

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).

[1] N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).
[2] W.-M. Yao *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006).
[3] Another naming convention, $\beta = \phi_1$, is also used in the literature.
[4] M. Gronau, Phys. Rev. Lett. **63**, 1451 (1989).
[5] Z.-Z. Xing, Phys. Rev. D **61**, 014010 (1999).
[6] K.-F. Chen *et al.* (Belle Collaboration), Phys. Rev. D **72**, 012004 (2005); K. Sumisawa *et al.* (Belle Collaboration), Phys. Rev. Lett. **95**, 061801 (2005).
[7] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **71**, 091102(R) (2005); Phys. Rev. Lett. **94**, 191802 (2005); **95**, 011801 (2005).
[8] T. Aushev *et al.* (Belle Collaboration), Phys. Rev. Lett. **93**, 201802 (2004).
[9] H. Miyake *et al.* (Belle Collaboration), Phys. Lett. B **618**, 34 (2005).
[10] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **95**, 131802 (2005).
[11] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **95**, 151804 (2005).
[12] S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods Phys. Res., Sect. A **499**, 1 (2003), and other papers included in this volume.
[13] A. Abashian *et al.* (Belle Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 117 (2002).
[14] Z. Natkaniec *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **560**, 1 (2006).
[15] The inclusion of the charge conjugate mode decay is implied throughout this Letter.
[16] K. Hanagaki *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **485**, 490 (2002).
[17] E. Nakano, Nucl. Instrum. Methods Phys. Res., Sect. A **494**, 402 (2002).
[18] H. Kakuno *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **533**, 516 (2004).
[19] S.-H. Lee *et al.* (Belle Collaboration), Phys. Rev. Lett. **91**, 261801 (2003).

[20] H. Albrecht *et al.* (ARGUS Collaboration), Phys. Lett. B **241**, 278 (1990).
[21] Events are simulated with the Evtgen generator, D.-J. Lange, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 152 (2001); the detector response is simulated with GEANT, R. Brun *et al.*, GEANT 3.21, CERN Report No. DD/EE/84-1, 1984.
[22] G. Majumder *et al.* (Belle Collaboration), Phys. Rev. Lett. **95**, 041803 (2005).
[23] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **73**, 112004 (2006).
[24] H. Tajima *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **533**, 370 (2004).
[25] O. Long, M. Baak, R.-N. Cahn, and D. Kirkby, Phys. Rev. D **68**, 034010 (2003).
[26] G.-J. Feldman and R.-D. Cousins, Phys. Rev. D **57**, 3873 (1998).
[27] K. Abe *et al.* (Belle Collaboration), Phys. Rev. D **68**, 012001 (2003).
[28] Y. Grossman and M. Worah, Phys. Lett. B **395**, 241 (1997).