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Evidence of time-dependent CP violation in the decay $B^0 \to D^{*+} D^{*-}$

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We report a measurement of the CP-odd fraction and the time-dependent CP violation in $B^0 \to D^{*+}D^{*-}$ decays, using 657×10^6 $B\bar{B}$ events collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. We measure a CP-odd fraction of $R_\perp = 0.125 \pm 0.043(\text{stat}) \pm 0.023(\text{syst})$. From the distributions of the proper-time intervals between a $B^0 \to D^{*+}D^{*-}$ decay and the other B meson in the event, we obtain evidence of CP violation with measured parameters $\mathcal{A}_{D^{*+}D^{*-}} = 0.15 \pm 0.13(\text{stat}) \pm 0.04(\text{syst})$ and $\mathcal{S}_{D^{*+}D^{*-}} = -0.96 \pm 0.25(\text{stat})^{+0.13}_{-0.16}(\text{syst})$.

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In the standard model (SM), the irreducible complex phase in the Cabibbo-Kobayashi-Maskawa quark-mixing matrix gives rise to CP violation [1]. In an $\Upsilon(4S)$ event, the time-dependent decay rate of a neutral B meson to a CP eigenstate is given by

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

where $q = +1(-1)$ when the other B meson in the event decays as a B^0 ($\bar{B}^0$), $\Delta t = t_{CP} - t_{\text{tag}}$ is the proper-time difference between the two B decays in the event, τ_{B^0} is the neutral B lifetime, and Δm_d is the mass difference between the two B^0 mass eigenstates. The CP-violating parameters are defined as

$$\mathcal{S} = \frac{2\Im(\lambda)}{|\lambda|^2 + 1}, \qquad \mathcal{A} = \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1}, \quad (2)$$

where λ is a complex observable depending on the B^0 and $\bar{B}^0$ decay amplitudes to the final state and the relation between the B meson mass eigenstates and its flavor eigenstates. At the quark level the $B^0 \to D^{*+}D^{*-}$ decay is a $b \to c\bar{c}d$ transition, where the tree amplitude is Cabibbo-Kobayashi-Maskawa suppressed. The contribution of penguin diagrams in this decay is estimated to be at the percent level [2]. If penguin corrections are neglected, the SM expectations for the CP parameters are $\mathcal{A}_{D^{*+}D^{*-}} = 0$ and $\mathcal{S}_{D^{*+}D^{*-}} = -\eta_{D^{*+}D^{*-}} \sin 2\phi_1$, where $\phi_1 = \arg[-V_{cd}V_{cb}^*]/[V_{td}V_{tb}^*]$ and $\eta_{D^{*+}D^{*-}}$ is the CP eigenvalue of $D^{*+}D^{*-}$, which is $+1$ when the decay proceeds through an S or D wave, or -1 for a P wave. A large measured deviation from this expectation can be a sign of new physics [3]. Recently, Belle reported a 4.1σ CP-violation effect in the $B^0 \to D^+D^-$ decay [4]; $\mathcal{S}$ was found to be consistent with $-\sin 2\phi_1$ whereas the measured $\mathcal{A}$ value indicated 3.2σ direct CP violation, which contradicts the SM and is not confirmed by *BABAR* [5]. This decay contains the same weak phase transition as $B^0 \to D^{*+}D^{*-}$, therefore a precise measurement of the latter is vital for a correct interpretation. The CP-violating parameters as well as the CP-odd fraction in $B^0 \to D^{*+}D^{*-}$ decays have been measured by both Belle [6] and *BABAR* [7]. Here, we report a new measurement with more than 4 times the statistics used in [6].

This analysis is based on a data sample containing 657×10^6 $B\bar{B}$ pairs, collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider [8] operating at the $\Upsilon(4S)$ resonance. The $\Upsilon(4S)$ meson is produced with a Lorentz boost $\beta\gamma = 0.425$ nearly along the z axis, defined as the direction opposite to that of the positron beam. Since the B^0 and $\bar{B}^0$ are approximately at rest in the $\Upsilon(4S)$ center-of-mass (CM) frame, Δt can be determined from the displacement in z between the two decay vertices, $\Delta t \simeq \Delta z/(\beta\gamma c)$, where c is the speed of light.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector, a 50-layer central drift chamber, an array of aerogel threshold Cherenkov counters, a barrel-like arrangement of time-of-flight scintillation counters, 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 the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). A detailed description of the Belle detector can be found elsewhere [9]. Two different inner detector configurations were used. A first sample of 152×10^6 $B\bar{B}$ pairs were recorded with a 2.0 cm radius beampipe and a 3-layer silicon vertex detector; for the remaining 505×10^6 $B\bar{B}$ pairs, a 1.5 cm radius beampipe, a 4-layer silicon detector, and a small-cell inner drift chamber were used [10].

Charged particles are reconstructed requiring the transverse (longitudinal) distance between the track trajectory and the interaction point to be less than 2.0(4.0) cm. Neutral pions are reconstructed from pairs of photons with energies above 30 MeV and with a total momentum in the CM system $p_{\gamma\gamma} > 0.1$ GeV$/c$, which are required to have an invariant mass in the range 119 MeV$/c^2 < M_{\gamma\gamma} <$ 146 MeV$/c^2$. Neutral kaons are reconstructed via the de-

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cay $K_s^0 \to \pi^+\pi^-$ [11]. The $\pi^+\pi^-$ invariant mass is required to be within $\pm 9\ \mathrm{MeV}/c^2$ of the K_s^0 mass [12] and is constrained in mass and fitted to a common vertex. The $\pi^+\pi^-$ vertex is required to be displaced from the interaction point in the direction of the pion pair momentum. The neutral D mesons are reconstructed in the $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, $K_s^0\pi^+\pi^-$, $K_s^0\pi^+\pi^-\pi^0$, and K^+K^- modes, while D^+ decays are reconstructed in the $K^-\pi^+\pi^+$, $K_s^0\pi^+$, $K_s^0\pi^+\pi^0$, and $K^+K^-\pi^+$ modes. Unless specified otherwise charge-conjugated decays are implied throughout.

Charged kaons and pions are separated using a likelihood ratio, $\mathcal{R}_{K/\pi} = \mathcal{L}(K)/(\mathcal{L}(K) + \mathcal{L}(\pi))$, constructed from aerogel threshold Cherenkov counters information, central drift chamber dE/dx, and time-of-flight measurements. Charged tracks in 2-prong (3- or 4-prong) vertices are reconstructed as kaons if $\mathcal{R}_{K/\pi} > 0.1(0.6)$ and as pions when $\mathcal{R}_{K/\pi} < 0.9$. These requirements have an efficiency of 97% (85%) for kaons in 2-prong (3- or 4-prong) vertices and 98% for pions, respectively, with fake rates of 18% (14%) for kaons and 12% for pions. The invariant mass of the D candidates must be within $\pm 6\sigma(3\sigma)$ of the nominal value for 2-prong (3- or 4-prong) decays, where σ is the width of the main component of the channel-dependent D mass resolution obtained from signal Monte Carlo (MC) samples and ranges from $2.6\ \mathrm{MeV}/c^2$ to $7.5\ \mathrm{MeV}/c^2$. Candidate D^{*+} mesons are reconstructed in the $D^0\pi^+$ and $D^+\pi^0$ modes.

The pions from the D^* decays are referred to as slow pions because of their low momentum. Slow charged pions are constrained to originate from the point where the D trajectory intersects the beam profile. The mass difference, $\Delta M = |M(D^*) - M(D)|$ is required to be within $\pm 3(2.25)\ \mathrm{MeV}/c^2$ of the nominal value for the D^0 (D^+) channel. Finally, two oppositely charged D^* mesons are combined to form a B^0 candidate. Because of the smaller product branching fraction and the large background contribution, we do not include $(D^+\pi^0)(D^-\pi^0)$ combinations.

The selected D meson candidates are then subjected to mass- and vertex-constrained fits to improve their momentum and vertex resolution. To discriminate the signal B mesons from background, we use the energy difference $\Delta E \equiv E_B^{\mathrm{CM}} - E_{\mathrm{beam}}^{\mathrm{CM}}$ and the beam-constrained mass $M_{\mathrm{bc}} \equiv \sqrt{(E_{\mathrm{beam}}^{\mathrm{CM}})^2 - (p_B^{\mathrm{CM}})^2}$, where $E_{\mathrm{beam}}^{\mathrm{CM}}$ is the beam energy in the CM system and E_B^{CM} and p_B^{CM} are the energy and momentum of the B candidate in the CM system. After all the above selection requirements are applied, there are on average 1.7 B^0 candidates per event in the large signal region. This region is defined by $5.23\ \mathrm{GeV}/c^2 < M_{\mathrm{bc}} < 5.30\ \mathrm{GeV}/c^2$ and $-0.14\ \mathrm{GeV} < \Delta E < 0.14\ \mathrm{GeV}$.

We choose the B candidate with the smallest value of

$$\chi^2_{\mathrm{mass}} = \sum_{i=1}^{2}\left(\frac{\Delta M_i - \Delta M_i(\mathrm{PDG})}{\sigma_{\Delta M_i}}\right)^2 + \sum_{i=1}^{2}\left(\frac{M(D_i) - M(D_i)(\mathrm{PDG})}{\sigma_{M(D_i)}}\right)^2, \tag{3}$$

where PDG refers to the world average measurement in [12] and i denotes the two D mesons. The $e^+e^- \to q\bar{q}$ ($q = u$, d, s, and c) background is suppressed by requiring the ratio of the second- to zeroth-order Fox-Wolfram moments [13] to be less than 0.4.

We perform an unbinned two-dimensional maximum likelihood fit to the large signal region in the M_{bc} vs ΔE plane. The probability density function (PDF) used to model the M_{bc} distribution is the sum of a signal and background component. The signal PDF is described with a Gaussian function while the combinatorial background is modeled with an ARGUS function [14]. The ΔE signal distribution is fitted with the sum of two Gaussians where the width and mean of the second wide Gaussian, as well as the relative fraction of the two Gaussians, are fixed to the MC values. The ΔE background distribution is described with a second-order polynomial. Figure 1 shows two different projections of the two-dimensional distribu-

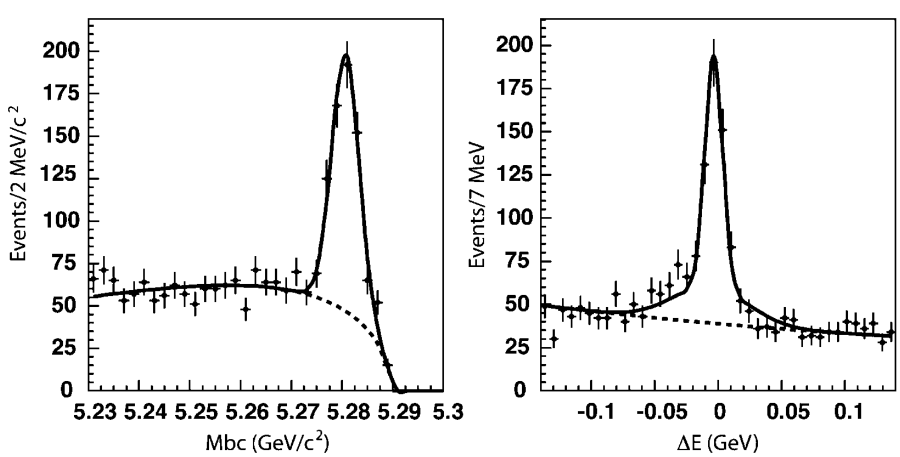

FIG. 1. (a) The M_{bc} distribution for $|\Delta E| < 0.04$ GeV. (b) The ΔE distribution for $M_{\mathrm{bc}} > 5.27\ \mathrm{GeV}/c^2$. The solid curve shows the result of the fit while the dotted curve is the background contribution.

tion and fit results. We obtain 553 ± 30 signal events in the large signal region. In the small signal region, defined by $5.27\ \mathrm{GeV}/c^2 < M_{\mathrm{bc}} < 5.30\ \mathrm{GeV}/c^2$ and $-0.04\ \mathrm{GeV} < \Delta E < 0.04$ GeV the signal purity is 55%.

To obtain the *CP*-odd fraction we perform a time-integrated angular analysis in the transversity basis [15]. The differential decay rate as a function of the transversity angle is

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\mathrm{tr}}} = \frac{3}{4}(R_0 + R_\parallel)\sin^2\theta_{\mathrm{tr}} + \frac{3}{2}R_\perp\cos^2\theta_{\mathrm{tr}}, \qquad (4)$$

where $R_{0,\parallel}$ and $R_\perp$ are the fractions of the longitudinal, transverse parallel and transverse perpendicular components in the transversity basis. R_0 and $R_\parallel$ are the fractions of the *CP*-even polarization, while $R_\perp$ is the fraction of the *CP*-odd one. A one-dimensional fit to the $\cos\theta_{\mathrm{tr}}$ distribution allows the extraction of the *CP*-odd fraction, where θ_{tr} is the polar angle between the momentum of the charged slow pion in its mothers D^* rest frame and the normal to the other D^* decay plain. The measured distribution of $\cos\theta_{\mathrm{tr}}$ is distorted, in particular, due to the angular resolution of the slow pion. The shapes of the *CP*-odd and *CP*-even polarizations are obtained from a signal MC sample taking the $R_0/(R_0 + R_\parallel)$ fraction from the previous Belle analysis [6]. The background shape is obtained from the fit, but limited to be a symmetric polynomial, i.e. $a_{\mathrm{bkg}} \cdot \cos^2\theta_{\mathrm{tr}} + 1$. The signal-to-background ratio is determined on an event-by-event basis using the $M_{\mathrm{bc}} - \Delta E$ distribution. The fit to the large signal region yields

$$R_\perp = 0.125 \pm 0.043 \qquad (5)$$

and $a_{\mathrm{bkg}} = -0.02 \pm 0.04$. The fit result is shown in Fig. 2, superimposed on the $\cos\theta_{\mathrm{tr}}$ distribution in the small signal region. This result is compatible with previous Belle and *BABAR* measurements [6,7].

The systematic uncertainty on $R_\perp$ is obtained by varying the fixed parameters within their errors. The signal efficiency and the $R_0/(R_0 + R_\parallel)$ parameters give rise to systematic uncertainties of 0.003 and 0.009, respectively. When varying the number of signal events by $\pm 1\sigma$ and the signal shape in M_{bc} and $|\Delta E|$ such that the data points in the lower tail in $|\Delta E|$ are well described, a systematic uncertainty of 0.003 is obtained. A fast MC is used to estimate any possible fit bias; we find a small shift of 0.002. Tighter vertex quality cuts lead to a 0.013 difference in $R_\perp$. Finally, a peaking background contribution of 6.6% obtained from the MC is added, to which we conservatively assign a *CP*-odd behavior, leading to a 0.016 change in the central value. The different contributions are summed in quadrature to yield a systematic uncertainty of 0.023 in $R_\perp$.

To determine the *CP*-violating parameters, the signal B^0-meson decay vertex is reconstructed by fitting the momentum vector of the D meson with the beam spot profile. No information on the slow pions is used. After additional requirements on the number of silicon vertex detector hits and the vertex fit quality, we obtain 511 ± 28 events.

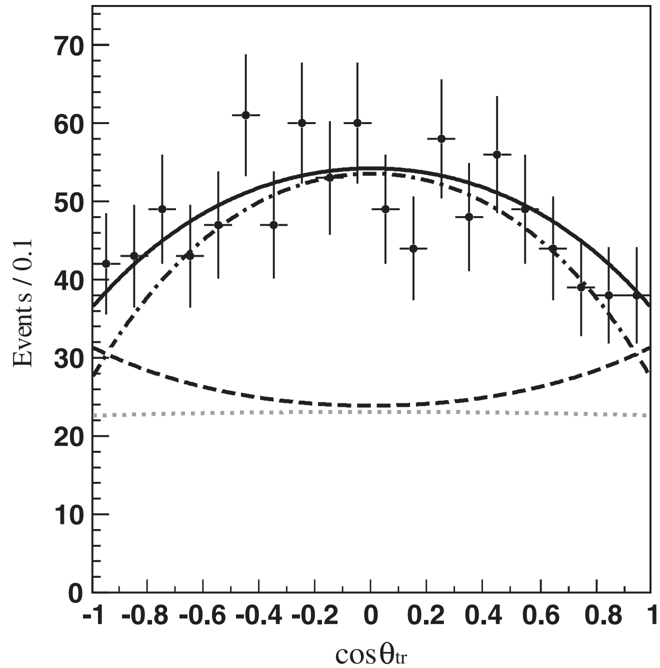

FIG. 2. The $\cos\theta_{\mathrm{tr}}$ distribution for events in the small signal region, the points with error bars represent data. The solid curve is the result of the fit, the dotted curve shows the background contribution. The *CP*-even and *CP*-odd contributions are the dotted-dashed and dashed curves, respectively, and are visible above the dotted background curve.

The tagside decay vertex and the flavor of the tagside B meson are obtained inclusively from properties of particles that are not associated with the reconstructed $B^0 \to D^{*+}D^{*-}$ decay [16]. The PDF used to describe the Δt distribution is

$$\mathcal{P}(\Delta t) = \int [f_{\mathrm{sig}}\mathcal{P}_{\mathrm{sig}}(\Delta t') + (1 - f_{\mathrm{sig}})\mathcal{P}_{\mathrm{bkg}}(\Delta t')] \cdot R_{\mathrm{res}}(\Delta t - \Delta t')d(\Delta t'). \qquad (6)$$

The signal fraction, f_{sig} and the *CP*-odd probability are obtained on an event-by-event basis, using the previous fits to the M_{bc}, ΔE and $\cos\theta_{\mathrm{tr}}$ distributions. The function $\mathcal{P}_{\mathrm{sig}}$ is given by Eq. (1) and modified event by event to incorporate the effect of incorrect flavor assignment. A dilution factor, $[1 - 2f_\perp(\cos\theta_{\mathrm{tr}})]$ for $\mathcal{S}$ takes into account the fraction of the *CP*-odd component. We assume $\mathcal{S}_{\mathrm{even}} = -\mathcal{S}_{\mathrm{odd}}$ ($\mathcal{A}_{\mathrm{even}} = \mathcal{A}_{\mathrm{odd}}$) and define it as $\mathcal{S}$ ($\mathcal{A}$). The tagging quality is parameterized by a variable r that ranges from $r = 0$ (no flavor discrimination) to $r = 1$ (unambiguous flavor assignment). The data is divided into seven r intervals. The wrong tag fraction w_r, possible tagging performance differences between B^0 and $\bar{B}^0$ decays (Δw_r), and the parameters of the resolution function R_{res} are determined using a high-statistics control sample of semileptonic and hadronic $b \to c$ decays [16,17]. However, the width of the main Gaussian component of the resolution is determined using a $B^0 \to D^{(*)+} D_s^{(*)-}$ control sample. The parameters of $\mathcal{P}_{\rm bkg}(\Delta t)$ are obtained from a fit to the Δt distribution in sideband ($M_{\rm bc} < 5.27\ {\rm GeV}/c^2$) events.

The free parameters in the fit are $\mathcal{A}_{D^{*+}D^{*-}}$ and $\mathcal{S}_{D^{*+}D^{*-}}$; these are determined by maximizing an unbinned likelihood function for all events in the large fit region. The result is

$$\mathcal{S}_{D^{*+}D^{*-}} = -0.96 \pm 0.25, \qquad \mathcal{A}_{D^{*+}D^{*-}} = +0.15 \pm 0.13, \tag{7}$$

with a statistical correlation of 11%. The significance of *CP* violation using the statistical uncertainty only is 3.4σ. Our measurements of $\mathcal{S}$ and $\mathcal{A}$ are consistent with the SM expectation for a tree-dominated $b \to c\bar{c}d$ transition. The large direct *CP* violation measured in $B^0 \to D^+ D^-$ [4] is thus not confirmed in this $b \to c\bar{c}d$ decay mode, in agreement with *BABAR*'s result [7]. We define the raw asymmetry in each Δt bin as $(N_+ - N_-)/(N_+ + N_-)$, where $N_+(N_-)$ is the number of observed candidates with $q = +1(-1)$. Figure 3 shows the Δt distribution and the raw asymmetry for events with a good-quality tag ($r > 0.5$) in the smalls signal region.

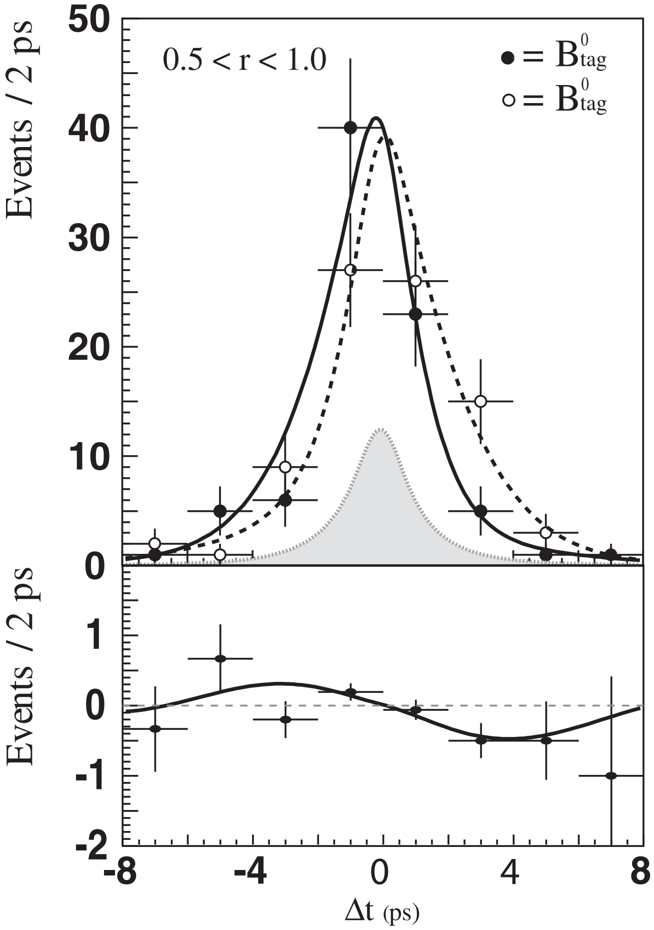

FIG. 3. Top: Δt distribution of well-tagged $B^0 \to D^{*+}D^{*-}$ candidates ($r > 0.5$) for $q = +1$ and $q = -1$. The shaded area is the background contribution while the solid and dashed curves are the superposition of the total PDFs for well-tagged $q = -1$ and $q = +1$ events, respectively. Bottom: fitted raw asymmetry of the top two distributions.

The systematic uncertainties on the *CP*-violation parameters are summarized in Table I.

The largest contribution comes from the $R_\perp$ fraction, which only affects $\mathcal{S}_{D^{*+}D^{*-}}$. The systematic uncertainty due to the signal-to-background ratio is determined by varying the signal yield with $\pm 1\sigma$, the shape parameters such that the data points in the lower tail in $|\Delta E|$ are well described, and the value of $R_\perp$ in a correlated way, as the signal purity also affects the angular analysis. $R_\perp$ is varied by 0.003, which is the systematic error in $R_\perp$ due to the signal purity and shape. The contribution of the resolution function and the background shape to the systematic error is estimated by varying each parameter by $\pm 1\sigma$. Varying the resolution parameters moves $\mathcal{S}_{D^{*+}D^{*-}}$ further away from zero. A fast MC is used to estimate the bias of the *CP* violating parameters for the measured values. The Δm_d and τ_{B0} parameters are varied around their world averages [12]. Systematic errors due to uncertainties in wrong tag fractions are estimated by varying the parameters w_l and Δw_l in each r region by their $\pm 1\sigma$ errors. The vertex quality cut is changed to $\xi < 125$ and the effect is included in the table. The Δt fit range is changed from $\Delta t < 70$ ps to $\Delta t < 10$ ps. A peaking background contribution is added with no *CP* violation. Finally, the tagside interference uncertainty is included [18]. The different sources are added in quadrature to yield ± 0.04 for $\mathcal{A}$ and $^{-0.16}_{+0.13}$ for $\mathcal{S}$, reducing the significance of *CP* violation to 3.1σ.

We performed various cross checks such as a fit to the *CP* asymmetries of the control sample $B^0 \to D^{(*)+} D_s^{(*)-}$, which gives $A = -0.02 \pm 0.03({\rm stat})$ and $S = -0.07 \pm 0.04({\rm stat})$; these values are consistent with no *CP* asym-

TABLE I. Systematic errors on the *CP*-violating parameters for $B^0 \to D^{*+}D^{*-}$ decays.

Source	$\mathcal{A}_{D^{*+}D^{*-}}$	$\mathcal{S}_{D^{*+}D^{*-}}$
CP-odd fraction $R_\perp$	± 0.004	± 0.109
Signal purity and shape	± 0.020	± 0.030
Standard resolution function	± 0.004	$^{+0.000}_{-0.102}$
Resolution from control sample	± 0.002	± 0.030
Background shape	± 0.000	± 0.006
Fit bias	± 0.010	± 0.031
Δm_d, τ_{B^0}	± 0.002	± 0.004
Flavor tagging	± 0.011	± 0.020
Vertex cuts	± 0.003	± 0.028
Δt fit range	± 0.010	± 0.004
Peaking background	± 0.010	$^{+0.000}_{-0.027}$
Tag-side interference	± 0.034	± 0.007
Total	± 0.044	$^{+0.126}_{-0.164}$

metry. The lifetime fit to the $B^0 \to D^{*+}D^{*-}$ sample is consistent with the world average value [12].

In summary, we have performed new measurements of the CP-odd fraction $R_\perp = 0.125 \pm 0.043(\text{stat}) \pm 0.023(\text{syst})$ and CP-violation parameters $\mathcal{A}_{D^{*+}D^{*-}} = 0.15 \pm 0.13(\text{stat}) \pm 0.04(\text{syst})$ and $\mathcal{S}_{D^{*+}D^{*-}} = -0.96 \pm 0.25(\text{stat})^{+0.13}_{-0.16}(\text{syst})$ for the decay $B^0 \to D^{*+}D^{*-}$ using $657 \times 10^6 B\bar{B}$ events. We obtain evidence of CP violation with 3.1σ significance including systematic uncertainties. These measurements are consistent with and supersede our previous results [6]. They are also in agreement with the SM prediction for $b \to c$ tree amplitudes and do not confirm the large direct CP violation seen in the $B^0 \to D^+D^-$ decay.

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[1] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).
[2] X. Y. Pham *et al.*, Phys. Lett. B **458**, 375 (1999).
[3] Y. Grossman *et al.*, Phys. Lett. B **395**, 241 (1997).
[4] S. Fratina *et al.* (Belle Collaboration), Phys. Rev. Lett. **98**, 221802 (2007).
[5] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **99**, 071801 (2007).
[6] H. Miyake *et al.* (Belle Collaboration), Phys. Lett. B **618**, 34 (2005).
[7] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. D **79**, 032002 (2009).
[8] S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods Phys. Res., Sect. A **499**, 1 (2003), and other papers included in this volume.
[9] A. Abashian *et al.* (Belle Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 117 (2002).
[10] Z. Natkaniec (Belle SVD2 Group), Nucl. Instrum. Methods Phys. Res., Sect. A **560**, 1 (2006).
[11] K.-F. Chen *et al.* (Belle Collaboration), Phys. Rev. D **72**, 012004 (2005).
[12] C. Amsler *et al.* (Particle Data Group), Phys. Lett. B **667**, 1 (2008).
[13] G.C. Fox and S. Wolfram, Phys. Rev. Lett. **41**, 1581 (1978).
[14] H. Albrecht *et al.* (ARGUS Collaboration), Phys. Lett. B **241**, 278 (1990).
[15] The *BABAR* Collaboration *The BaBar Physics Book*, edited by P.F. Harrison and H.R. Quinn (SLAC Report No. 504, p. 213 1998).
[16] H. Kakuno *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **533**, 516 (2004).
[17] K. Abe *et al.* (Belle Collaboration), Phys. Rev. D **71**, 072003 (2005).
[18] O. Long, M. Baak, R.N. Cahn, and D. Kirkby, Phys. Rev. D **68**, 034010 (2003).
[19] H. Tajima *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **533**, 370 (2004).