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

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Abstract

We report measurements of the branching fraction and $CP$ violation parameters in $B^0 \rightarrow D^+ D^-$ decays. The results are based on a data sample that contains $535 \times 10^6 B\bar{B}$ 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 $B^0 \rightarrow D^+ D^-$. The measured values of the $CP$ violation parameters are: $S = -1.13 \pm 0.37 \pm 0.09$, $A = 0.91 \pm 0.23 \pm 0.06$, where the first error is statistical and the second is systematic. We find evidence of $CP$ violation in $B^0 \rightarrow D^+ D^-$ at the 4.1$\sigma$ confidence level. While the value of $S$ is consistent with expectations from other measurements, the value of the parameter $A$ favors large direct $CP$ violation at the 3.2$\sigma$ confidence level, in contradiction to Standard Model expectations.

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Within the Standard Model (SM), $CP$ violation ($CPV$) arises from a complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix $V$ [1]. The dominant contribution to $B^0 \rightarrow D^+ D^-$ decays is the tree-level $b \rightarrow c\bar{d}$ transition shown in Fig. 1(a). If this diagram is the only contribution, then the mixing-induced $CP$ parameter for $B^0 \rightarrow D^+ D^-$ is $-\sin 2\phi_1$, where $\phi_1 = \arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$, while the direct $CPV$ term $A$ is zero. The second-order gluonic penguin contribution, shown in Fig. 1(b), is expected to change the value of the parameter $S$ by less than a few percent and increase the value of $A$ to about 3% [3]. However, particles from physics beyond the SM may give additional contributions within the loop diagrams mediating flavor-changing $b \rightarrow d$ 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 $b \rightarrow c\bar{s}s$ charmonium modes [4, 5], the objective here is to focus on deviations from expectations in $b \rightarrow c\bar{d}d$ transitions. Similar studies have been carried out for $B^0 \rightarrow D^{*\pm} D^{(*)\pm}$ decays, which involve the same quark level weak decay [6, 7, 8, 9].

The $CPV$ parameters $S$ and $A$ can be measured from the $\Delta t$ distribution of $B^0 \rightarrow D^+ D^-$ decays,

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

(1)

where $\Delta t = t_{CP} - t_{\text{tag}}$ is the time difference between decays of the two $B$ mesons arising from the $\Upsilon(4S)$. The parameters $t_{CP}$ and $t_{\text{tag}}$ are the proper decay times of the corresponding $B$ mesons, $\tau$ is the $B^0$ meson lifetime and $\Delta m$ is the mass difference of the two $B$ mass eigenstates [10]. The flavor $q$ is determined from the final state of the tagging $B$ meson: $q = +1 (-1)$ for $B_{\text{tag}} = B^0 (\bar{B}^0)$.

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 $e^+e^-$ collider $\sqrt{s} = 3.5$ on 8 GeV) collider [11]. KEKB operates at the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58$ GeV) with a
peak luminosity that exceeds $1.7 \times 10^{34}$ cm$^{-2}$s$^{-1}$. At KEKB, the Υ(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 Υ(4S) center-of-mass (CM) system, $\Delta t$ can be determined from the displacement in $z$ between the $B_{CP}$ and $B_{tag}$ decay vertices:

$$\Delta t \simeq \frac{(z_{CP} - z_{tag})}{\beta \gamma c} \equiv \frac{\Delta z}{\beta \gamma c}.$$ 

The Belle detector [12] is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector, a 50-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 $K^0_L$ 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 $152 \times 10^6 B\bar{B}$ 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 $383 \times 10^6 B\bar{B}$ pairs [13].

$D$ mesons are reconstructed using the $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to K_S\pi^+$ decay modes [14]. In this paper, 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 [15] 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 $L(K^\pm)/[L(K^\pm) + L(\pi^\pm)]$, which is required to be greater than 0.55 for kaon and less than 0.9 for pion candidates [16]. $K_S$ 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 $\Delta E = E^*_B - E^*_\text{beam}$ and the beam-energy-constrained mass $M_{bc} = \sqrt{(E^*_\text{beam}/c^2)^2 - (p^*_B/c)^2}$, where $E^*_B$, $E^*_\text{beam}$, and $p^*_B$ are the $B$ meson energy, the beam energy, and the $B$ meson momentum, respectively, in the CM 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 $\pi^+$ track. The mass of the $K^-\pi^+\pi^+$
or $K_S\pi^+$ combination is constrained to the $D^+$ meson mass to obtain better $M_{bc}$ and $\Delta E$ 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 $B_{tag}$ 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. Due to the imperfect flavor tagging, the distribution $P_{sig}$ of Eq. (1) is modified to

$$P_{sig} = \frac{e^{-|\Delta t|/\tau}}{4\tau} \left\{ 1 - q\Delta w + q(1 - 2w) \left[ S \sin(\Delta m \Delta t) + A \cos(\Delta m \Delta t) \right] \right\},$$

where $w$ is the wrong tag fraction, and $\Delta w$ is the difference between the wrong tag fractions if the $B_{tag}$ meson is a $\overline{B}^0$ or $B^0$. The values of $w$ and $\Delta w$ for each of the six bins in the tagging quality parameter $r$ are determined separately using flavor specific $B$ meson decays [17].

Continuum events are suppressed by forming a likelihood ratio from $\cos \theta_B$, where $\theta_B$ is the polar angle between the $B$ meson direction in the CM system and the beam axis, and a variable based on a combination of sixteen modified Fox-Wolfram moments with the scalar sum of transverse momentum [18]. Note that since the $B \overline{B}$ 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, 16% 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 $M_{bc}$ and $\Delta E$ distributions in the range $M_{bc} > 5.20\,\text{GeV}/c^2$ and $-0.05\,\text{GeV} < \Delta E < 0.10\,\text{GeV}$. A Gaussian function for the signal and an ARGUS [19] function for the background are used to describe the $M_{bc}$ distribution. For the parameterization of the $\Delta E$
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 [20]. Non-resonant $B^0 \to D^- K^{0*} \pi^+$ and $B^0 \to D^- K^{0}(892) \pi^+$ decays are found to be a possible source of background peaking in the $M_{bc}$ and $\Delta E$ 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 non-resonant decays in the signal region ($N_{nr}$) to be $2.0 \pm 1.8$ and $1.4 \pm 1.0$ for the $K\pi\pi$ and $K_S\pi$ channels, respectively. The fit yields $150 \pm 15$ events in the signal peak, where the error is statistical only. The $M_{bc}$ and $\Delta E$ 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.

![Graph](image)

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

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

The combined branching fraction is calculated from the total number of reconstructed events and the average reconstruction efficiency, and is found to be $B(B^0 \to D^+ D^-) = [1.97 \pm 0.20 \text{ (stat)} \pm 0.20 \text{ (syst)}] \times 10^{-4}$, which is consistent with previous measurements [21, 22] and has 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 non-resonant 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 $\Delta t$ distribution of 219 events in the signal region $5.27 \text{ GeV}/c^2 < M_{bc} < 5.29 \text{ GeV}/c^2$ and $|\Delta E| < 0.03 \text{ GeV}$. The $\Delta t$ distribution for signal events $P_{\text{sig}}$ described by Eq. (2) is modified by the inclusion of the background contribution and resolution effects. The event-by-event likelihood is given by

$$L_{\text{ev}} = f_{\text{sig}} P_{\text{sig}} \otimes R + f_{\text{nr}} P_{\text{nr}} \otimes R + f_{\text{bcg}} P_{\text{bcg}} \otimes R_{\text{bcg}}, \quad (3)$$

Subscripts sig, nr and bcg refer to signal, non-resonant and combinatorial background components, respectively. The fractions $f_i = f_i(M_{bc}, \Delta E, r)$ are determined on an event-by-event basis, $f_{\text{sig}} + f_{\text{nr}} + f_{\text{bcg}} = 1$. The function $R$ describes the detector resolution of the $\Delta t$ 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 CM system and the smearing of the tag-side vertex due to the tracks originating from the secondary vertices. An additional wide Gaussian component with $\sigma \approx 20 \text{ ps}$ is added to describe a small fraction of events (about 1%) with poorly reconstructed vertices. A more detailed description of the resolution function parameterization can be found in Ref. [23]. Resolution parameters for the $B_{CP}$ meson vertex are determined from a fit to the $\Delta t$ distribution of kinematically similar $B^0 \rightarrow D_s^+ D^-$ decays.

The fraction of the non-resonant decays $f_{\text{nr}}$ is assumed to be proportional to the signal fraction, $f_{\text{nr}} = a f_{\text{sig}}$, where $a = N_{\text{nr}}/(N_{\text{peak}} - N_{\text{nr}})$ and $a_{K\pi\pi} = 0.016$, $a_{K_S\pi} = 0.059$. The

| channel | $B_D^+ \times B_D^-$ | $\epsilon$ [%] | $N_{\text{peak}}$ | $N_{\text{bcg}}$ |
|---------|----------------------|----------------|----------------|----------------|
| $K\pi\pi$ | (0.904$\pm$0.065)% | 12.6 | 124.1$\pm$13.6 | 110.8$\pm$2.6 |
| $K_S\pi$ | (0.204$\pm$0.015)% | 12.1 | 25.7$\pm$5.7 | 13.8$\pm$0.9 |
The \( \Delta t \) distribution of the non-resonant \( B^0 \to D^- K^0 \pi^+ \) or \( B^0 \to D^- K^0(892) \pi^+ \) background is described by the \( \Delta t \) distribution for signal with the parameters \( S \) and \( A \) set to zero. 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 \( (b \to c \text{ transition}) \), which have an exponential decay \( \Delta t \) distribution. The other half are continuum \( e^+e^- \to q\bar{q} \) events, for which the \( \Delta t \) distribution contains a \( \delta \)-function component. Therefore, the \( \Delta t \) distribution of the background is described by

\[
P_{\text{bcg}} = \frac{1}{2} \left[ (1 - f_\delta) \frac{e^{-|\Delta t|/\tau_{\text{bcg}}}}{2\tau_{\text{bcg}}} + f_\delta \delta(\Delta t) \right],
\]

(4)

The background resolution function \( R_{\text{bcg}} \) is taken to be a Gaussian. Parameters describing the background distribution are obtained from a fit to the \( \Delta t \) distribution of the data sideband, \( M_{\text{bc}} < 5.27 \text{ GeV}/c^2 \) and \( \Delta E > 0.06 \text{ GeV} \).

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

\[
S = -1.13 \pm 0.37 \pm 0.09 \quad \text{and} \quad A = +0.91 \pm 0.23 \pm 0.06,
\]

(5)

where the first error is statistical and the second is systematic. The \( \Delta t \) distributions are shown in Fig. 3. The main contributions to the systematic error are fit bias (0.06 for \( S \) and 0.02 for \( A \)), uncertainties in the resolution function (0.04 for \( S \) and 0.03 for \( A \)) and signal.
fraction (0.035 for $S$ and 0.015 for $A$). Other uncertainties come from the errors on the parameters $\tau$ and $\Delta m$ (0.023 for $S$ and 0.007 for $A$), wrong tag fractions (0.017 for $S$ and 0.014 for $A$), description of background $\Delta t$ distribution (0.01 for $S$ and $A$), fraction and possible $CP$ asymmetry of the non-resonant background (0.02 for $S$ and 0.03 for $A$), the effect of tag-side interference [24] (0.01 for $S$ and 0.03 for $A$) and requirements on the vertex quality and the fitting range (less than 0.01 for $S$ and 0.01 for $A$).

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 $CPV$, $S = -0.064 \pm 0.094$ and $A = 0.091 \pm 0.060$, where the error is statistical only. We also fit the background sample ($M_{bc} < 5.27 \text{GeV}/c^2$ and $\Delta E > 0.06 \text{GeV}$) for a possible $CP$ asymmetry and find none: $A = -0.01 \pm 0.06$ and $S = 0.03 \pm 0.10$. In addition, a time-integrated fit for the parameter $A$ was performed to validate the result in $B^0 \to D^+ D^-$ decays. The signal yield was determined separately for events tagged as $B_{\text{tag}} = B^0$ and $B_{\text{tag}} = B^0$ for each of the six $r$-bins. The fit yields $A = 0.86 \pm 0.32$, which is consistent with the time-dependent result.

We use the Feldman-Cousins frequentist approach [25] to determine the statistical significance of our measurement. In order to form confidence intervals, we use the $A$ and $S$ distributions of the results of fits to the MC pseudo-experiments for various input values of $A$ and $S$ in a similar way as described in Ref. [26]. The systematic errors and possibility of tails that are wider than Gaussian tails are taken into account. The case of no $CPV$, $S = A = 0$, is ruled out at the 4.1$\sigma$ confidence level (CL). The case of no direct $CPV$, $A = 0$, is excluded at more than 3.2$\sigma$ CL for any value of the parameter $S$.

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 [21]. We obtain values for the $CP$ parameters $S = -1.13 \pm 0.37 \pm 0.09$ and $A = 0.91 \pm 0.23 \pm 0.06$ and rule out the $CP$-conserving case, $S = A = 0$, at the 4.1 $\sigma$ confidence level. The value of $S$ is consistent with measurements of $b \to c\bar{c}s$ modes [10]. In addition, we observe evidence for direct $CP$ violation at the 3.2 $\sigma$ 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 [27]. Our measurement differs from a previous measurement by the BaBar collaboration [8] by about 2.2 $\sigma$. 

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