Observation of Large $CP$ Violation and Evidence for Direct $CP$ Violation in $B^0 \to \pi^+ \pi^-$ Decays

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We report the first observation of $CP$ violation in $B^0 \to \pi^+ \pi^-$ decays based on 152 $\times 10^6$ $Y(4S) \to \BB$ decays collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider. We reconstruct a $B^0 \to \pi^+ \pi^-$ $CP$ eigenstate and identify the flavor of the accompanying $B$ meson from its decay products. From the distribution of the time intervals between the two $B$ meson decay points, we obtain $\mathcal{A}_{\pi\pi} = +0.58 \pm 0.15$ (stat) $\pm 0.07$ (syst) and $S_{\pi\pi} = -1.00 \pm 0.21$ (stat) $\pm 0.07$ (syst). We rule out the $CP$-conserving case, $\mathcal{A}_{\pi\pi} = S_{\pi\pi} = 0$, at a level of 5.2 standard deviations. We also find evidence for direct $CP$ violation with a significance at or greater than 3.2 standard deviations for any $S_{\pi\pi}$ value.

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mesons are approximately at rest in the Υ(4S) center-of-mass system (c.m.s.). ∆t can be determined from ∆z, the displacement in z between the π⁺π⁻ and q_tag decay vertices: ∆t ≡ (z_tag - z_tag)/βγc ≡ ∆z/βγc. The reconstruction method of the vertex positions remains unchanged from the previous publication [5].

We use oppositely charged track pairs that are positively identified as pions to reconstruct B⁺0 → π⁺π⁻ candidates. The pion efficiency is 91%, and 10.4% of kaons are misidentified as pions. We select the B meson candidates using the energy difference ∆E ≡ E beam,max - E beam,min and the beam-energy constrained mass M beam ≡ \( \sqrt{(E^\text{beam,max})^2 - (p_{beam,min}^\text{c.m.s.})^2} \), where E beam,max is the c.m.s. beam-energy, and E beam,min and p beam,min are the c.m.s. energy and momentum of the B candidate. The signal region is defined as 5.271 GeV/c² < M beam < 5.287 GeV/c² and |∆E| < 0.064 GeV, corresponding to ±3σ from the central values. To suppress the e⁺e⁻ → q̄q continuum background, (q = u, d, s, c), we form signal and background likelihood functions, L_S and L_BKG, from the event topology variables and impose requirements on the likelihood ratio LR = L_S/(L_S + L_BKG) for candidate events. We use the same event topology variables and the procedure that were used for the B(B⁺0 → π⁻π⁺) measurement [9].

The flavor of the accompanying B meson is identified from inclusive properties of particles that are not associated with the reconstructed B⁺0 → π⁺π⁻ decay. We use two parameters, q [defined in Eq. (1)] and r, to represent the tagging information. The parameter r is an event-by-event, Monte Carlo (MC) determined flavor-tagging dilution factor that ranges from r = 0 for no flavor discrimination to r = 1 for unambiguous flavor assignment. It is used only to sort data into six r intervals. The wrong tag fractions for the six r intervals, w_r(1, 6), and differences between B⁺0 and B⁻0 decays, ∆w_r, are determined from data [10].

We optimize the expected sensitivity by using the improved likelihood ratio LR. We require LR > 0.86 for all r intervals. We include additional candidate events with lower signal likelihood ratio cuts (0.50, 0.45, 0.45, 0.45, 0.45, and 0.20) for different r intervals since the separation of continuum background from the B signal varies with r; we accept candidate events from 12 distinct regions in the L-r plane.

Figure 1 shows the ∆E distribution for the B⁺0 → π⁺π⁻ candidates that are in the M beam signal region with LR > 0.86 after flavor tagging and vertex reconstruction. In the M beam and ∆E signal region, we find 483 candidates with LR > 0.86 and 1046 candidates with LR ≤ 0.86. The B⁺0 → π⁺π⁻ signal yield for LR > 0.86 is determined from an unbinned two-dimensional maximum likelihood fit to the M beam-∆E distribution (5.20 GeV/c² < M beam < 5.30 GeV/c² and -0.3 GeV < ∆E < 0.5 GeV) with a Gaussian signal function plus contributions from misidentified B⁺0 → K⁺π⁻ events, three-body B decays, and continuum background. The fit yields 232⁺20⁻19 π⁺π⁻ events and 82⁺14⁻11 K⁺π⁻ events in the signal region, where the errors are statistical only. Extrapolating from the size of the continuum background in this fit, we expect 169 continuum events in the signal region. For LR ≤ 0.86, the same procedure used in the previous publication [5] yields 141 ± 12 π⁺π⁻ events, 50 ± 8 K⁺π⁻ events, and 855 continuum events in the signal region. The contribution from three-body B decays is negligibly small in the signal region.

The ∆t resolution function Rππ for B⁺0 → π⁺π⁻ signal events is formed by convolving four components: the detector resolutions for z_tag and z_tag, the shift in the z_tag vertex position due to secondary tracks originating from charged particle decays, and the smearing due to the kinematic approximation used to convert ∆z to ∆t [9]. We assume Rππ = R_Kπ and denote them collectively as Rsig.

Aππ and Sππ are obtained from an unbinned maximum likelihood fit to the observed ∆t distribution. The probability density function (PDF) for B⁺0 → π⁺π⁻ signal events (PΣππ) is given by Eq. (1), modified to incorporate the effect of incorrect flavor assignment. The PDF for B⁺0 → K⁺π⁻ background events is PΣKπ(∆t, w_j, ∆w_j) = (1/4πβc)e^{-|∆t/τ_{tag}|}(1-qΔw_j + q*(1-2w_j)\cdot A_{Kπ}·cos(∆mππ|∆t)|). We use A_{Kπ} = 0 as a default and include an effect of a possible nonzero value for A_{Kπ} in the systematic error. The PDF for continuum background events is Pqπ(∆t) = (1 + q·A_{bkg})(f_s/2τ_{bkg})e^{-|∆t/τ_{tag}|} + (1 - f_s)Δ(∆t))/2, where f_s is the fraction of the background with effective lifetime τ_{bkg}, and δ is the Dirac delta function. We use A_{bkg} = 0 as a default. A fit to sideband events yields A_{bkg} = 0.010 ± 0.005. This uncertainty is included in the systematic error for A_{ππ} and S_{ππ}. All parameters of Pqπ(∆t) and Rqπ are determined from the events in the sideband region.

We define the likelihood value for each (ith) event as a function of A_{ππ} and S_{ππ}:
Here, the probability functions \( f_{\phi}^{m} \) (\( k = \pi \sigma, K_{\pi}, \text{or } q \bar{q} \)) are determined on an event-by-event basis as functions of \( \Delta E \) and \( M_{bc} \) for each LR-\( r \) interval \((m = 1, 12) \) [5]. The small number of signal and background events that have large values of \( \Delta t \) are accommodated by the outlier PDF, \( P_{\text{ol}} \), with fractional area \( f_{\text{ol}} \). In the fit, \( S_{\pi \pi} \) and \( \mathcal{A}_{\pi \pi} \) are the only free parameters determined by maximizing the likelihood function \( L = \prod \mathcal{L} \), where the product is over all \( B^{0} \to \pi^{+} \pi^{-} \) candidates.

The unbinned maximum likelihood fit to the 1529 \( B^{0} \to \pi^{+} \pi^{-} \) candidates (801 \( B^{0} \) tags and 728 \( B^{0} \) tags), containing \( 372^{+32}_{-31} \, \pi^{+} \pi^{-} \) signal events, yields \( \mathcal{A}_{\pi \pi} = 0.58 \pm 0.15 \) (stat) \( \pm 0.07 \) (syst) and \( S_{\pi \pi} = 0.19 \pm 0.21 \) (stat) \( \pm 0.07 \) (syst). The correlation between \( \mathcal{A}_{\pi \pi} \) and \( S_{\pi \pi} \) is 0.286. As before, we quote the rms values of the \( \mathcal{A}_{\pi \pi} \) and \( S_{\pi \pi} \) distributions of the MC pseudoexperiments as the statistical errors of our measurement [11]. The usual fit errors from the likelihood functions, called the MINOS errors in the previous publication [5], are \( 0.05^{+0.01}_{-0.06} \) for \( \mathcal{A}_{\pi \pi} \) and \( 0.06^{+0.02}_{-0.01} \) for \( S_{\pi \pi} \), respectively, in good agreement with the rms values above [12]. In Figs. 2(a) and 2(b), we show the \( \Delta t \) projections for the 264 \( B^{0} \) and 219 \( B^{0} \)-tagged events in the subset of data with \( LR > 0.86 \). We define the raw asymmetry in each \( \Delta t \) bin by \( A \equiv (N_{+} - N_{-})/(N_{+} + N_{-}) \), where \( N_{+(-)} \) is the number of observed candidates with \( q = +1(-1) \). Figures 2(c) and 2(d) show the raw asymmetries for two regions of the flavor-tagging parameter \( r \). The effective tagging efficiency and signal purity is much larger in the \( 0.5 < r \leq 1.0 \) region.

We test the goodness of fit from a \( \chi^{2} \) comparison of the results of the unbinned fit and the \( \Delta t \) projections for \( B^{0} \to \pi^{+} \pi^{-} \) candidates. We obtain \( \chi^{2}/\text{DOF} = 12.5/12 \) (7.6/12) for the \( \Delta t \) distribution of the \( B^{0} \) (\( B^{0} \)) tags.

An ensemble of MC pseudoexperiments indicates a 26.7\% probability of measuring \( CP \) violation at a level above the one we observe when the input values are \( \mathcal{A}_{\pi \pi} = 0.55 \) and \( S_{\pi \pi} = -0.84 \), which correspond to the values at the point of maximum likelihood in the physically allowed region \( (S_{\pi \pi}^{2} + \mathcal{A}_{\pi \pi}^{2} \leq 1) \); in this measurement, it is located at the physical boundary \( (A_{\pi \pi}^{2} + S_{\pi \pi}^{2} = 1) \).

The systematic error is primarily due to uncertainties in the vertexing \(( \pm 0.04 \) for \( \mathcal{A}_{\pi \pi} \) and \( \pm 0.05 \) for \( S_{\pi \pi} \)) and the background fractions \(( \pm 0.03 \) for \( \mathcal{A}_{\pi \pi} \) and \( \pm 0.02 \) for \( S_{\pi \pi} \)). We include the effect of tag side interference [13] on \( \mathcal{A}_{\pi \pi} \) (0.03) and \( S_{\pi \pi} \) (0.01). Other sources of systematic error are uncertainties in the wrong tag fraction, physics parameters \(( \Delta m_{f}, \, \tau_{\pi}, \text{and } \mathcal{A}_{K_{\pi}}) \), resolution function, background modeling, and fit bias. We add each contribution in quadrature to obtain the total systematic errors. The effect of the 3\% charge asymmetry in the kaon misidentification rate is negligibly small.

We perform a number of cross-checks. We measure the \( B^{0} \) lifetime with the \( B^{0} \to \pi^{+} \pi^{-} \) candidate events. The result, \( \tau_{B^{0}} = 1.46 \pm 0.09 \) ps, is consistent with the world-average value [14]. A comparison of the event yields and \( \Delta t \) distributions for \( B^{0} \) and \( B^{0} \)-tagged events in the sideband region reveals no significant asymmetry. We select \( B^{0} \to K^{+} \pi^{-} \) candidates by positively identifying the charged kaons. A fit to the 2358 candidates (1198 signal events) yields \( \mathcal{A}_{K_{\pi}} = -0.02 \pm 0.08 \), consistent with the counting analysis [15], and \( S_{K_{\pi}} = 0.14 \pm 0.11 \), which is consistent with zero. With the \( K^{+} \pi^{-} \) event sample, we determine \( \tau_{B^{0}} = 1.52 \pm 0.06 \) ps and \( \Delta m_{f} = 0.53^{+0.04}_{-0.03} \) ps \(^{-1} \), which are in agreement with the world-average values [14]. We check the measurement of \( \mathcal{A}_{\pi \pi} \) using time-independent fits to the \( M_{bc} - \Delta E \) distributions for the \( B^{0} \) and \( B^{0} \) tags. We obtain \( \mathcal{A}_{\pi \pi} = 0.73 \pm 0.19 \), which is consistent with the time-dependent \( CP \) fit result. We also perform an independent analysis based on a binned maximum-likelihood fit to the \( \Delta t \) distribution. The result is consistent with that of the unbinned maximum-likelihood fit quoted here.
The statistical significance of our measurement is determined from the same approach used in the previous publication [5]. Figure 3 shows the resulting two-dimensional confidence regions in the $\mathcal{A}_{\pi\pi}$ versus $S_{\pi\pi}$ plane. The case that CP symmetry is conserved, $\mathcal{A}_{\pi\pi} = S_{\pi\pi} = 0$, is ruled out at the 99.999976% confidence level (C.L.), i.e., $1 - \text{C.L.} = 2.5 \times 10^{-7}$, equivalent to 5.2$\sigma$ significance for Gaussian errors. The case of no direct CP violation, $\mathcal{A}_{\pi\pi} = 0$, is also ruled out with a significance of greater than 3.2$\sigma$ for any $S_{\pi\pi}$ value. If the source of CP violation is due to only $B\bar{B}$ mixing or $\Delta B = 2$ transitions, as in so-called superweak scenarios [16], then $(S_{\pi\pi}, \mathcal{A}_{\pi\pi}) = (-\sin 2\phi_1, 0)$. $1 - \text{C.L.}$ at this point is $8.4 \times 10^{-4}$, equivalent to 3.3$\sigma$ significance.

Adopting the notation of Ref. [17], the range of $\phi_2$ that corresponds to the 95.5% C.L. region for $\mathcal{A}_{\pi\pi}$ and $S_{\pi\pi}$ in Fig. 3 is $90^\circ \leq \phi_2 \leq 146^\circ$ for $0.15 < |P/T| < 0.45$, as used in the previous publication [5], and $\sin 2\phi_1 = 0.736$ [18]. The result is in agreement with constraints on the unitarity triangle from other indirect measurements [19]. The 95.5% C.L. region for $\mathcal{A}_{\pi\pi}$ and $S_{\pi\pi}$ excludes $|P/T| < 0.17$.

In summary, we have performed a new measurement of CP violation parameters in $B^0 \to \pi^+\pi^-$ decays. We obtain $\mathcal{A}_{\pi\pi} = 0.58 \pm 0.15$ (stat) $\pm 0.07$ (syst), and $S_{\pi\pi} = -1.00 \pm 0.21$ (stat) $\pm 0.07$ (syst). We rule out the CP-conserving case, $\mathcal{A}_{\pi\pi} = S_{\pi\pi} = 0$, at the 5.2$\sigma$ level. We find evidence for direct CP violation with a significance of greater than 3.2$\sigma$. The constraints on $\phi_2$ from our result are consistent with indirect measurements that assume the correctness of the SM.

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3] Throughout this Letter, the inclusion of the charge conjugate mode decay is implied unless otherwise stated.
11] The statistical errors are reduced by about a factor of two due to the increase in the data sample (0.75), the improvement in signal yield extraction (0.90) and continuum rejection (0.95), the use of a more accurate signal fraction (0.93), and other effects (0.93). The values in parentheses are the expected reduction factors.
12] The log-likelihood ratio $-2\ln L/L_{\text{max}}$ is now nearly parabolic, and the sensitivity to a large single event fluctuation [5] is greatly reduced.