Observation of Direct *CP* Violation in $B^0 \to \pi^+\pi^-$ Decays and Model-Independent Constraints on the Quark-Mixing Angle ϕ_2

H. Ishino,[45] K. Abe,[7] K. Abe,[42] I. Adachi,[7] H. Aihara,[44] D. Anipko,[1] K. Arinstein,[1] T. Aushev,[16,12] A. M. Bakich,[39] E. Barberio,[19] M. Barbero,[5] I. Bedny,[1] U. Bitenc,[13] I. Bizjak,[13] S. Blyth,[22] A. Bozek,[25] M. Bračko,[7,18,13] T. E. Browder,[5] M.-C. Chang,[4] P. Chang,[24] Y. Chao,[24] A. Chen,[22] K.-F. Chen,[24] W. T. Chen,[22] B. G. Cheon,[6] R. Chistov,[12] Y. Choi,[38] Y. K. Choi,[38] S. Cole,[39] J. Dalseno,[19] M. Dash,[48] A. Drutskoy,[3] S. Eidelman,[1] S. Fratina,[13] T. Gershon,[7] A. Go,[22] G. Gokhroo,[40] B. Golob,[17,13] A. Gorišek,[13] H. Ha,[14] J. Haba,[7] K. Hara,[20] K. Hayasaka,[20] M. Hazumi,[7] D. Heffernan,[30] T. Hokuue,[20] Y. Hoshi,[42] S. Hou,[22] Y. B. Hsiung,[24] T. Iijima,[20] A. Imoto,[21] K. Inami,[20] A. Ishikawa,[44] Y. Iwasaki,[7] J. H. Kang,[49] P. Kapusta,[25] S. U. Kataoka,[21] N. Katayama,[7] H. Kawai,[2] T. Kawasaki,[27] H. R. Khan,[45] A. Kibayashi,[45] H. Kichimi,[7] K. Kinoshita,[3] S. Korpar,[18,13] P. Križan,[17,13] P. Krokovny,[7] R. Kulasiri,[3] R. Kumar,[31] C. C. Kuo,[22] A. Kusaka,[44] A. Kuzmin,[1] Y.-J. Kwon,[49] M. J. Lee,[36] S. E. Lee,[36] T. Lesiak,[25] A. Limosani,[7] S.-W. Lin,[24] J. MacNaughton,[11] F. Mandl,[11] D. Marlow,[33] T. Matsumoto,[46] A. Matyja,[25] S. McOnie,[39] W. Mitaroff,[11] K. Miyabayashi,[21] H. Miyake,[30] H. Miyata,[27] Y. Miyazaki,[20] R. Mizuk,[12] D. Mohapatra,[48] Y. Nagasaka,[8] E. Nakano,[29] M. Nakao,[7] S. Nishida,[7] O. Nitoh,[47] T. Nozaki,[7] S. Ogawa,[41] T. Ohshima,[20] S. L. Olsen,[5] Y. Onuki,[34] H. Ozaki,[7] P. Pakhlov,[12] G. Pakhlova,[12] H. Park,[15] L. S. Peak,[39] R. Pestotnik,[13] L. E. Piilonen,[48] H. Sahoo,[5] Y. Sakai,[7] N. Satoyama,[37] T. Schietinger,[16] O. Schneider,[16] J. Schümann,[23] C. Schwanda,[11] A. J. Schwartz,[3] R. Seidl,[9,34] K. Senyo,[20] M. E. Sevior,[19] H. Shibuya,[41] B. Shwartz,[1] A. Somov,[3] N. Soni,[31] S. Stanič,[28] M. Starič,[13] H. Stoeck,[39] K. Sumisawa,[7] T. Sumiyoshi,[46] S. Y. Suzuki,[7] O. Tajima,[7] F. Takasaki,[7] K. Tamai,[7] N. Tamura,[27] M. Tanaka,[7] Y. Teramoto,[29] X. C. Tian,[32] K. Trabelsi,[5] T. Tsukamoto,[7] S. Uehara,[7] K. Ueno,[24] Y. Unno,[6] S. Uno,[7] P. Urquijo,[19] Y. Ushiroda,[7] Y. Usov,[1] G. Varner,[5] K. E. Varvell,[39] S. Villa,[16] C. H. Wang,[23] M.-Z. Wang,[24] Y. Watanabe,[45] E. Won,[14] C.-H. Wu,[24] Q. L. Xie,[10] B. D. Yabsley,[39] A. Yamaguchi,[43] Y. Yamashita,[26] M. Yamauchi,[7] L. M. Zhang,[35] Z. P. Zhang,[35] V. Zhilich,[1] and A. Zupanc[13]

(The 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]*University of Hawaii, Honolulu, Hawaii 96822*
[6]*Hanyang University, Seoul*
[7]*High Energy Accelerator Research Organization (KEK), Tsukuba*
[8]*Hiroshima Institute of Technology, Hiroshima*
[9]*University of Illinois at Urbana-Champaign, Urbana, Illinois 61801*
[10]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing*
[11]*Institute of High Energy Physics, Vienna*
[12]*Institute for Theoretical and Experimental Physics, Moscow*
[13]*J. Stefan Institute, Ljubljana*
[14]*Korea University, Seoul*
[15]*Kyungpook National University, Taegu*
[16]*Swiss Federal Institute of Technology of Lausanne, EPFL, Lausanne*
[17]*University of Ljubljana, Ljubljana*
[18]*University of Maribor, Maribor*
[19]*University of Melbourne, Victoria*
[20]*Nagoya University, Nagoya*
[21]*Nara Women's University, Nara*
[22]*National Central University, Chung-li*
[23]*National United University, Miao Li*
[24]*Department of Physics, National Taiwan University, Taipei*
[25]*H. Niewodniczanski Institute of Nuclear Physics, Krakow*
[26]*Nippon Dental University, Niigata*
[27]*Niigata University, Niigata*
[28]*University of Nova Gorica, Nova Gorica*
[29]*Osaka City University, Osaka*
[30]*Osaka University, Osaka*

0031-9007/07/98(21)/211801(6) © 2007 The American Physical Society

[31]Panjab University, Chandigarh
[32]Peking University, Beijing
[33]Princeton University, Princeton, New Jersey 08544
[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 NSW
[40]Tata Institute of Fundamental Research, Bombay
[41]Toho University, Funabashi
[42]Tohoku Gakuin University, Tagajo
[43]Tohoku University, Sendai
[44]Department of Physics, University of Tokyo, Tokyo
[45]Tokyo Institute of Technology, Tokyo
[46]Tokyo Metropolitan University, Tokyo
[47]Tokyo University of Agriculture and Technology, Tokyo
[48]Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
[49]Yonsei University, Seoul

(Received 10 November 2006; revised manuscript received 14 February 2007; published 21 May 2007)

We report a new measurement of the time-dependent CP-violating parameters in $B^0 \to \pi^+\pi^-$ decays with 535×10^6 $B\bar{B}$ pairs collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider operating at the $\Upsilon(4S)$ resonance. We find 1464 ± 65 $B^0 \to \pi^+\pi^-$ events and measure the CP-violating parameters $\mathcal{S}_{\pi\pi} = -0.61 \pm 0.10(\mathrm{stat}) \pm 0.04(\mathrm{syst})$ and $\mathcal{A}_{\pi\pi} = +0.55 \pm 0.08(\mathrm{stat}) \pm 0.05(\mathrm{syst})$. We observe large direct CP violation with a significance greater than 5 standard deviations for any $\mathcal{S}_{\pi\pi}$ value. Using isospin relations, we measure the Cabibbo-Kobayashi-Maskawa quark-mixing matrix angle $\phi_2 = (97 \pm 11)^\circ$ for the solution consistent with the standard model and exclude the range $11^\circ < \phi_2 < 79^\circ$ at the 95% confidence level.

DOI: 10.1103/PhysRevLett.98.211801 PACS numbers: 13.25.Hw, 11.30.Er, 12.15.Hh, 14.40.Nd

In the standard model (SM) framework, CP violation is attributed to an irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) weak-interaction quark-mixing matrix [1]. In the decay chain of $\Upsilon(4S) \to B^0\bar{B}^0$, one B^0 decays into $\pi^+\pi^-$ at time $t_{\pi\pi}$, while the other decays at time t_{tag} into a flavor specific state f_{tag}. The time-dependent CP violation [2] is given as

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

where $\Delta t = t_{\pi\pi} - t_{\mathrm{tag}}$, τ_{B^0} is the B^0 lifetime, Δm_d is the $B^0\bar{B}^0$ mixing frequency [3], and $q = +1$ (-1) when $f_{\mathrm{tag}} = B^0(\bar{B}^0)$. $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ are the mixing-induced and direct CP-violating parameters, respectively.

The CP-violating parameters have been measured by the Belle [4] and *BABAR* [5] collaborations. Both experiments obtained consistent results for $\mathcal{S}_{\pi\pi}$. In contrast, *BABAR* measured an $\mathcal{A}_{\pi\pi}$ value consistent with zero, while Belle found evidence for large direct CP violation with a significance of 4 standard deviations (σ) using a data sample containing 275×10^6 $B\bar{B}$ pairs. Here, we report a new measurement with a large data sample (535×10^6 $B\bar{B}$ pairs) and improvements to the analysis method that increase its sensitivity. We confirm our earlier results and observe direct CP violation in $B^0 \to \pi^+\pi^-$ [6] decays at the 5.5σ level; the disagreement with the *BABAR* $\mathcal{A}_{\pi\pi}$ measurement [5] remains.

One of the CKM angles, ϕ_2 [7], can be measured using $\mathcal{S}_{\pi\pi} = \sqrt{1 - \mathcal{A}^2_{\pi\pi}}\sin(2\phi_2 + \kappa)$, where κ is determined using isospin relations [8]. Measurements of ϕ_2 using $B \to \pi\pi$, $B \to \rho\pi$ [9] and $\rho\rho$ decays [10] give consistent results; the combined ϕ_2 value, together with measurements of other CKM angles and sides, is consistent with the unitarity [11,12]. We combine our $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ measurements with the world average (W.A.) values of other quantities to obtain a new constraint from $B \to \pi\pi$ on ϕ_2. Multiple solutions are found; for the solution consistent with other CKM measurements in the context of the SM, the constraint is more restrictive than those obtained from other B decay modes.

The data sample used in this analysis was collected with the Belle detector [13] at the KEKB e^+e^- asymmetric-energy (3.5 on 8 GeV) collider [14] operating at the $\Upsilon(4S)$ resonance produced with a Lorentz boost factor of $\beta\gamma = 0.425$ nearly along the electron beam direction (z axis). Since the two B mesons are produced approximately at rest in the $\Upsilon(4S)$ center-of-mass system (c.m.s.), the decay time difference Δt is determined from the distance between the two B meson decay vertices along the z-direction (Δz): $\Delta t \cong \Delta z / c\beta\gamma$. In the Belle detector, a silicon vertex detector and a 50-layer central drift chamber (CDC) are used for charged particle tracking, and an array of aerogel threshold Cherenkov counters as well as the dE/dx measurements in the CDC provide the particle identification (PID) information to distinguish charged pions and kaons. The devices are placed inside a superconducting solenoid coil providing a 1.5 T magnetic field.

We employ the event selection of Ref. [4] except for the PID requirement, which is removed. This increases the signal detection efficiency by 23%. The PID information is instead used in a likelihood fit in this analysis, improving the measurement errors for the CP-violating parameters by about 10% compared with the previous analysis. We reconstruct $B^0 \to \pi^+\pi^-$ candidates using oppositely charged track pairs. We select B meson candidates using the energy difference $\Delta E \equiv E_B^* - E_{\rm beam}^*$ and the beam energy constrained mass $M_{\rm bc} \equiv \sqrt{(E_{\rm beam}^*)^2 - (p_B^*)^2}$, where $E_{\rm beam}^*$ is the c.m.s. beam energy, and E_B^* and p_B^* are the c.m.s. energy and momentum of the B candidate. We define the signal box as $5.271\ {\rm GeV}/c^2 < M_{\rm bc} < 5.287\ {\rm GeV}/c^2$ and $|\Delta E| < 0.064$ GeV.

The standard Belle algorithm identifies the flavor of $f_{\rm tag}$ using properties of its decay products, and provides q defined in Eq. (1) and a variable r [15]. The parameter r ranges from $r = 0$ (no flavor discrimination) to $r = 1$ (unambiguous flavor assignment). The candidate events are categorized into six r intervals ($l = 1, 6$). The wrong tag fraction in each l bin, w_l, and the differences between B^0 and $\bar{B}^0$ decays, Δw_l, are determined using data.

To discriminate the continuum background ($e^+e^- \to q\bar{q}$, $q = u, d, s, c$), we form a signal ($q\bar{q}$) likelihood function, $\mathcal{L}_{S(B)}$, from features of the event topology and require r-dependent thresholds of $\mathcal{R} = \mathcal{L}_S/(\mathcal{L}_S + \mathcal{L}_B)$ for the candidates, as the separation between signal and $q\bar{q}$ background depends on r. The thresholds are determined to be 0.50, 0.45, 0.45, 0.45, 0.45, and 0.20 for each l bin by optimizing the expected sensitivity using signal Monte Carlo (MC) events and events in the sideband region $5.20\,{\rm GeV}/c^2 < M_{\rm bc} < 5.26\,{\rm GeV}/c^2$ or $+0.1\,{\rm GeV} < \Delta E < +0.5\,{\rm GeV}$. We further divide the data sample into two categories having $\mathcal{R}$ above or below 0.85 to take into account the correlation between the ΔE shape of $q\bar{q}$ background and $\mathcal{R}$. We thus have 12 distinct bins of $\mathcal{R}$ *vs* r; these bins are labeled $\ell = 1, 6$ ($\ell = 7, 12$) for the six r intervals with $\mathcal{R} > 0.85$ ($\mathcal{R} < 0.85$).

We extract signal candidates in the global area $M_{\rm bc} > 5.20\ {\rm GeV}/c^2$ and $-0.3\ {\rm GeV} < \Delta E < +0.5\ {\rm GeV}$ by applying the above requirements and the vertex reconstruction algorithm in Ref. [16]. The selected candidates include not only signal events but also $B^0 \to K^+\pi^-$, $q\bar{q}$, and three-body B decay backgrounds. We estimate the signal and background yields with an unbinned extended maximum likelihood fit, making use of ΔE, $M_{\rm bc}$, and the kaon identification probability $x_\pm = \mathcal{L}_{K^\pm}/(\mathcal{L}_{K^\pm} + \mathcal{L}_{\pi^\pm})$ for the positively and negatively charged tracks of the candidates, where $\mathcal{L}_{\pi^\pm}$ ($\mathcal{L}_{K^\pm}$) is the likelihood value for the pion (kaon) hypotheses.

We use a sum of two bifurcated Gaussians and a single Gaussian to model the ΔE and $M_{\rm bc}$ shapes, respectively, for both $B^0 \to \pi^+\pi^-$ and $K^+\pi^-$. The probability density functions (PDF) as a function of $x_\pm$ for the signal and $B^0 \to K^+\pi^-$ decays are obtained from a large data sample of inclusive $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ decays. The yields of $B^0 \to K^+\pi^-$ events are parameterized as $n_{K^\pm\pi^\mp} = n_{K\pi}(1 \mp \mathcal{A}_{K\pi})/2$, where $\mathcal{A}_{K\pi} = -0.113 \pm 0.020$ [3] is the direct CP asymmetry in $B^0 \to K^+\pi^-$ decays. We fix the $\mathcal{A}_{K\pi}$ value and float the $B^0 \to K^+\pi^-$ yield $n_{K\pi}$ in the fit. For the signal and $B^0 \to K^+\pi^-$ events, we use MC-determined event fractions in each $\mathcal{R}$-r bin.

The ΔE ($M_{\rm bc}$) shape of the $q\bar{q}$ background is described by a second-order polynomial (an ARGUS function [17]). We use qr-dependent two-dimensional (x_+, x_-) PDFs for the $q\bar{q}$ background to take into account the correlation between positively and negatively charged tracks. These PDFs are determined from the sideband events.

For the three-body B decays, we employ a smoothed two-dimensional ΔE-$M_{\rm bc}$ histogram obtained from a MC sample. We use the same $x_\pm$ PDFs as those of the signal and $B^0 \to K^+\pi^-$ decays, with a ΔE-dependent kaon fraction determined from the MC sample.

By fitting to the data in the global area, we determine the yields of the signal and background components. Interpolating to the signal box, we obtain 1464 ± 65 $\pi^+\pi^-$, 4603 ± 105 $K^+\pi^-$, and 10764 ± 33 $q\bar{q}$ events, where the errors are statistical only. The contribution from three-body B decays is negligible in the signal box. From the signal yield and the detection efficiency (53.1%), we estimate the measured branching fraction to be $(5.2 \pm 0.2) \times 10^{-6}$, in agreement with the W.A. value [18]. Figure 1 shows the projection plots of ΔE, $M_{\rm bc}$, and $x_\pm$ for candidate events.

To determine $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$, we apply an unbinned maximum likelihood fit to the Δt distribution of the 16 831 candidates in the signal box. The signal distribution in Eq. (1) is modified to incorporate the effect of incorrect flavor assignment, using w_l and Δw_l. This distribution is then convolved with the proper time interval resolution function $R_{\rm sig}(\Delta t)$ [19]. The final signal PDF is given by

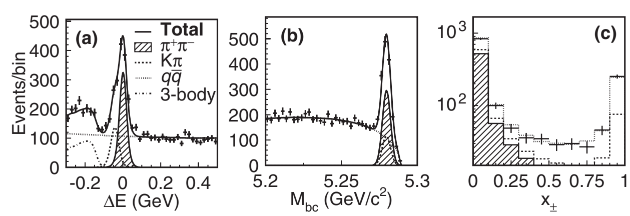

FIG. 1. (a) ΔE, (b) $M_{\rm bc}$, and (c) $x_\pm$ projection plots of the $B^0 \to \pi^+\pi^-$ candidates having $\mathcal{R} > 0.85$ in the signal box of (a) $M_{\rm bc}$ with $x_\pm < 0.4$, (b) ΔE with $x_\pm < 0.4$, and (c) $M_{\rm bc}$ with $0\ {\rm GeV} < \Delta E < 0.02$ GeV. Figure (c) is the sum of x_+ and x_- distributions.

$P^{q\ell}_{\pi\pi}(\Delta t) = (1 - f_{\rm ol})\mathcal{P}^{q\ell}_{\pi\pi}(\Delta t) \otimes R_{\rm sig}(\Delta t) + f_{\rm ol}\mathcal{P}_{\rm ol}(\Delta t)$, where the outlier PDF $\mathcal{P}_{\rm ol}(\Delta t)$ accommodates a small fraction $f_{\rm ol}$ of events having large Δt values. The Δt distribution for $B^0 \to K^+\pi^-$ is $\mathcal{P}^{q\ell}_{K^\pm\pi^\mp}(\Delta t) = (1/4\tau_{B^0}) \times e^{-|\Delta t|/\tau_{B^0}}[1 - q\Delta w_l \mp q(1-2w_l)\cos(\Delta m_d \Delta t)]$; the corresponding PDF $P^{q\ell}_{K^\pm\pi^\mp}(\Delta t)$ is constructed in the same manner as the signal PDF. The $q\bar{q}$ background distribution contains prompt and finite-lifetime components; it is convolved with a background resolution function modeled as a sum of two Gaussians and combined with the outlier PDF to give the $q\bar{q}$ background PDF $P_{q\bar{q}}(\Delta t)$. All the parameters of $P_{q\bar{q}}(\Delta t)$ are determined using sideband events.

We define a likelihood value for the i-th event, which lies in the ℓ-th bin of $\mathcal{R}$ *vs* r:

$$P_i = \sum_k n^\ell_k \mathcal{P}^{q(\ell)}_k(\vec{s}_i) P^{(q\ell)}_k(\Delta t_i). \qquad (2)$$

Here, n^ℓ_k is the fraction of component $k \in \{\pi^+\pi^-, K^+\pi^-, K^-\pi^+, q\bar{q}\}$ in $\mathcal{R}$-r bin ℓ; $\mathcal{P}^{q(\ell)}_k(\vec{s})$ is the event-by-event probability for component k as a function of $\vec{s} = (\Delta E, M_{\rm bc}, x_+, x_-)$; and $P^{(q\ell)}_k(\Delta t)$ is the event-by-event probability for component k and flavor tag q as a function of Δt. In the fit, $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ are the only free parameters and are determined by maximizing the likelihood function $\mathcal{L} = \prod_i P_i$.

The unbinned maximum likelihood fit yields $\mathcal{S}_{\pi\pi} = -0.61 \pm 0.10(\text{stat}) \pm 0.04(\text{syst})$ and $\mathcal{A}_{\pi\pi} = +0.55 \pm 0.08(\text{stat}) \pm 0.05(\text{syst})$. The correlation between $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ is $\rho = +0.15$. Figures 2(a) and 2(b) show the background subtracted Δt distributions of the signal events with $r > 0.5$ for $q = \pm 1$ and the asymmetry $\mathcal{A}_{CP}$ in each Δt bin, respectively, where $\mathcal{A}_{CP} = (N_+ - N_-)/(N_+ + N_-)$ and $N_{+(-)}$ is the number of signal events with $q = +1$ (-1) obtained by a fit in each Δt bin.

The main contributions to the systematic error come from the vertex reconstruction (± 0.03 for $\mathcal{S}_{\pi\pi}$ and ± 0.01 for $\mathcal{A}_{\pi\pi}$) and event fractions (± 0.01 for $\mathcal{S}_{\pi\pi}$ and ± 0.04 for $\mathcal{A}_{\pi\pi}$); the latter includes a conservative uncertainty for the possible $q\bar{q}$ background flavor asymmetry of ± 0.02. We include the effect of tag side interference [20] on $\mathcal{S}_{\pi\pi}$ (± 0.01) and $\mathcal{A}_{\pi\pi}$ (± 0.02). Other sources of systematic error for both $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ are the uncertainties in the wrong tag fraction (± 0.01), physics parameters τ_{B^0}, Δm_d, and $\mathcal{A}_{K\pi}$ (<0.01), resolution function (± 0.02), background Δt shape (<0.01), and fit bias (± 0.01). We add each contribution in quadrature to obtain the total systematic error.

To validate our CP-violating parameter measurement, we check the measurement of $\mathcal{A}_{\pi\pi}$ using a time-integrated fit, and obtain $\mathcal{A}_{\pi\pi} = +0.56 \pm 0.10$, consistent with the time-dependent fit results. An unbinned extended maximum likelihood fit to the $q = +1$ ($q = -1$) subset with $\mathcal{R} > 0.85$ and $r > 0.5$ yields 280 ± 20 (169 ± 16) $\pi^+\pi^-$ signal events, in agreement with the measured $\mathcal{A}_{\pi\pi}$ value taking into account the dilution due to the wrong tag fractions and $B^0\bar{B}^0$ mixing. We also check the

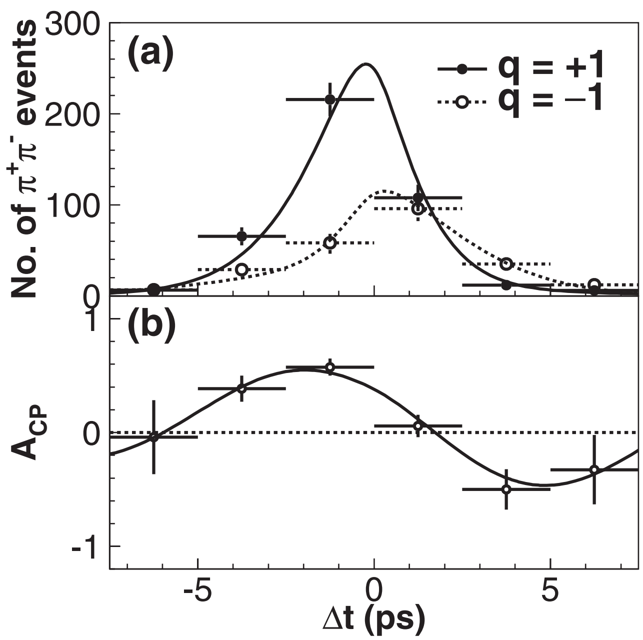

FIG. 2. (a) Δt distributions of $B^0 \to \pi^+\pi^-$ signal events with $r > 0.5$ after background subtraction for $q = +1$ (solid line) and $q = -1$ (dashed line), and (b) asymmetry $\mathcal{A}_{CP}$ plot. The curves are projections of the fit result. The difference in the heights of the $q = +1$ and $q = -1$ components in (a) is due to direct CP violation.

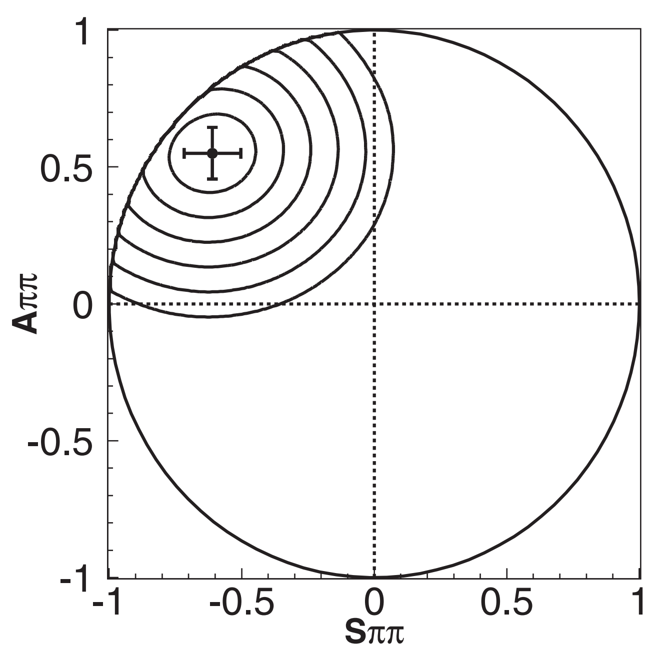

FIG. 3. Confidence regions for $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$. The curves show the contour for $1 - \text{C.L.} = 3.17 \times 10^{-1}$ (1σ), 4.55×10^{-2} (2σ), 2.70×10^{-3} (3σ), 6.33×10^{-5} (4σ), 5.73×10^{-7} (5σ), and 1.97×10^{-9} (6σ) from inside to outside. The point with error bars is the $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ measurement.

direct CP asymmetry in $B^0 \to K^+\pi^-$ events by floating $\mathcal{A}_{K\pi}$ in the time-dependent fit, and we obtain a value consistent with the W.A. [3] and the same ρ value as from the nominal fit. The fit is applied to various data subsets: a subset containing events with positive (negative) ΔE in which the $B^0 \to K^+\pi^-$ contamination is suppressed (enriched), where $\mathcal{A}_{\pi\pi} = +0.60 \pm 0.11$ ($+0.51 \pm 0.12$), events with $\mathcal{R} > 0.85$ ($\mathcal{R} < 0.85$) where the $q\bar{q}$ background fraction is suppressed (enriched), events with $x_{\pm} < 0.4$ where the signal fraction is enhanced, and events in one of the six r bins having different wrong tag fractions. All fits to the subsets yield CP asymmetries consistent with the overall fit result. No sizable asymmetry is found in a fit to sideband events.

We determine the statistical significance of our measurement using a frequentist approach [21], taking into account both statistical and systematic uncertainties. Figure 3 shows the resulting two-dimensional confidence regions in the $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ plane. The case of no direct CP violation, $\mathcal{A}_{\pi\pi} = 0$, is ruled out at a confidence level (C.L.) of $1 - 4 \times 10^{-8}$, equivalent to a 5.5σ significance for one-dimensional Gaussian errors. We also observe mixing-induced CP violation with a significance greater than 5.3σ for any $\mathcal{A}_{\pi\pi}$ value.

To constrain ϕ_2, we use the isospin relations [8] with our measured values of $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$, the W.A. branching ratios of $B^0 \to \pi^+\pi^-$ (5.2 ± 0.2 in units of 10^{-6}), $\pi^0\pi^0$ (1.31 ± 0.21) and $B^+ \to \pi^+\pi^0$ (5.7 ± 0.4), and the W.A. direct CP-asymmetry for $B^0 \to \pi^0\pi^0$ (0.36 ± 0.33) [18]. We follow the statistical method of Ref. [11] assuming Gaussian distributions. Figure 4 shows the difference 1-C.L. plotted for a range of ϕ_2 values. We find four different solutions consistent with our measurement. For the solution consistent with the expectation from other CKM measurements, $(100^{+5}_{-7})°$ [11], we find $\phi_2 = (97 \pm 11)°$. We exclude the ϕ_2 range $11° < \phi_2 < 79°$ at the 95% confidence level.

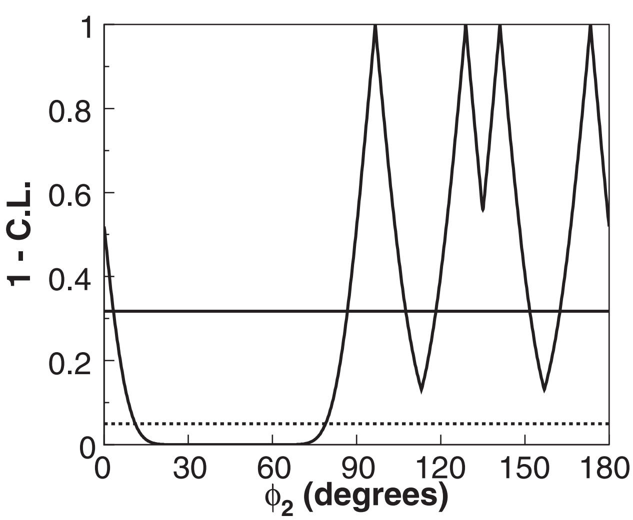

FIG. 4. Difference 1-C.L. plotted for a range of ϕ_2 values obtained with an isospin analysis using Belle measurements of $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$, and the W.A. values for the direct CP asymmetry in $B^0 \to \pi^0\pi^0$ decays and branching fractions for the $B \to \pi\pi$ modes. The solid and dashed lines indicate C.L. = 68.3% and 95%, respectively.

In summary, using a data sample containing $535 \times 10^6 B\bar{B}$ pairs, we measure the CP-violating parameters in $B^0 \to \pi^+\pi^-$ decays: $\mathcal{S}_{\pi\pi} = -0.61 \pm 0.10(\text{stat}) \pm 0.04(\text{syst})$ and $\mathcal{A}_{\pi\pi} = +0.55 \pm 0.08(\text{stat}) \pm 0.05(\text{syst})$. We report the first observation of direct CP violation with 5.5σ significance. Our results as well as the evidence for direct CP violation in $B^0 \to K^+\pi^-$ decays [22] rule out superweak models, i.e., extensions of the SM in which all CP violation occurs through $\Delta B = 2$ processes [23]. The measured $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ values in this Letter are consistent with those reported in Ref. [4], and supersede Belle's earlier evidence for direct CP violation. Among the four ϕ_2 solutions, the $\pm 1\sigma$ range for the ϕ_2 solution consistent with the SM is more restrictive than that from measurements of $B \to \rho\pi$ [9] and $B \to \rho\rho$ decays [10].

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 and FAAE (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] A. B. Carter and A. I. Sanda, Phys. Rev. Lett. **45**, 952 (1980); A. B. Carter and A. I. Sanda, Phys. Rev. D **23**, 1567 (1981); I. I. Bigi and A. I. Sanda, Nucl. Phys. **193**, 85 (1981); M. Gronau, Phys. Rev. Lett. **63**, 1451 (1989).
[3] W.-M. Yao *et al.*, J. Phys. G **33**, 1 (2006).
[4] K. Abe *et al.* (Belle Collaboration), Phys. Rev. Lett. **95**, 101801 (2005).
[5] B. Aubert *et al.* (*BABAR* Collab.), arXiv:hep-ex/0703016 [Phys. Rev. Lett. (to be published)].
[6] Throughout this Letter, the inclusion of the charge conjugate decay mode is implied unless otherwise stated.
[7] Another naming convention, α ($= \phi_2$), is also used in the literature.
[8] M. Gronau and D. London, Phys. Rev. Lett. **65**, 3381 (1990).
[9] A. Kusaka *et al.* (Belle Collaboration), arXiv:hep-ex/0701015 [Phys. Rev. Lett. (to be published)]; B. Aubert *et al.* (*BABAR* Collaboration), arXiv:hep-ex/0703008 [Phys. Rev. D. (to be published)].
[10] K. Abe *et al.* (Belle Collaboration), arXiv:hep-ex/0702009; A. Somov *et al.* (Belle Collaboration), Phys. Rev. Lett. **96**, 171801 (2006); B. Aubert *et al.* (*BABAR* Collaboration), arXiv:hep-ex/0607098; B. Aubert *et al.* (*BABAR* Collab.), Phys. Rev. Lett. **95**, 041805 (2005).

[11] J. Charles *et al.*, Eur. Phys. J. C **41**, 1 (2005); http://ckmfitter.in2p3.fr.
[12] M. Bona *et al.*, J. High Energy Phys. 07 (2005) 028; http://utfit.roma1.infn.it.
[13] A. Abashian *et al.* (Belle Collaboration), Nucl. Instrum. & Meth. in Phys. Res. A **479**, 117 (2002); Z. Natkaniec *et al.* (Belle SVD2 Group), Nucl. Instrum. & Meth. in Phys. Res. A **560**, 1 (2006).
[14] S. Kurokawa and E. Kikutani, Nucl. Instrum. & Meth. in Phys. Res. A **499**, 1 (2003), and other papers included in this volume.
[15] H. Kakuno *et al.*, Nucl. Instrum. & Meth. in Phys. Res. A **533**, 516 (2004).
[16] K.-F. Chen *et al.* (Belle Collaboration), Phys. Rev. D **72**, 012004 (2005).
[17] H. Albrecht *et al.* (ARGUS Collaboration), Phys. Lett. B **241**, 278 (1990).
[18] Heavy Flavor Averaging Group, ‘‘Summer 2006,’’ http://www.slac.stanford.edu/xorg/hfag.
[19] H. Tajima *et al.*, Nucl. Instrum. & Meth. in Phys. Res. A **533**, 370 (2004).
[20] O. Long, M. Baak, R. N. Cahn, and D. Kirkby, Phys. Rev. D **68**, 034010 (2003).
[21] G. J. Feldman and R. D. Cousins, Phys. Rev. D **57**, 3873 (1998).
[22] Y. Chao *et al.* (Belle Collaboration), Phys. Rev. Lett. **93**, 191802 (2004); B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **93**, 131801 (2004).
[23] L. Wolfenstein, Phys. Rev. Lett. **13**, 562 (1964).