Observation of $B^\pm \rightarrow \chi_{c1}\pi^\pm$ and Search for Direct CP Violation

R. Kumar, J. B. Singh, K. Abe, K. Abe, H. Aihara, D. Anipko, T. Asaka, T. Aziz, A. M. Bakich, V. Balagura, M. Barbero, A. Bay, I. Bedny, K. Belous, U. Bitenc, S. Blyth, A. Bozek, M. Bračko, T. E. Browder, M.-C. Chang, A. Chen, W. T. Chen, B. G. Cheon, R. Chistov, Y. Choi, J. Dalseno, M. Dash, A. Drutskoy, S. Eidelman, S. Fratina, N. Gabyushin, T. Gershon, G. Gokhroo, B. Golob, A. Gorisiek, H. Ha, J. Haba, T. Hara, K. Hayasaka, H. Hayashii, M. Hazumi, D. Heffernan, T. Hokune, Y. Hoshi, S. Hou, W.-S. Hou, T. Iijima, A. Imoto, K. Inami, R. Itoh, Y. Iwasaki, J. H. Kang, N. Katayama, H. Kawai, T. Kawasaki, H. R. Khan, H. Kichimi, K. Kimishita, P. Krovkov, C. C. Kuo, Y.-J. Kwon, G. Leder, S.-W. Lin, D. Liventsev, F. Mandi, D. Marlow, T. Matsumoto, A. Matyja, W. Mitaroff, M. Miyabayashi, H. Miyake, H. Miyata, Y. Miyazaki, R. Mizuk, G. R. Moloney, J. Mueller, E. Nakano, M. Nakao, S. Nishida, O. Nitoh, S. Noguchi, T. Oshima, T. Olabe, S. Okuno, S. L. Olsen, Y. Okui, H. Ozaki, G. Pakhlova, H. Palka, H. Park, K. S. Park, R. Pestotnik, L. E. Piilonen, Y. Sakai, T. Schietinger, M. Schneider, J. Schürmann, C. Schwanda, M. Schwartiz, R. Seidl, M. Shapkin, H. Shibuya, B. Shwartz, V. Sidorov, A. Sokolov, A. Somov, N. Soni, M. Starie, H. Stoeck, S. Suzuki, T. Takasaki, M. Tanaka, G. N. Taylor, Y. Teramoto, X. C. Tian, T. Tsuchimori, K. Trabelsi, T. Tsuboyama, T. Tsukamoto, S. Uehara, T. Uglow, K. Ueno, S. Uno, Y. Usov, G. Varner, S. Villa, C. C. Wang, H. Wang, M.-Z. Wang, Y. Watanabe, E. Won, Q. L. Xie, A. Yamaguchi, Y. Yamashita, M. Yamauchi, C. C. Zhang, L. M. Zhang, Z. P. Zhang, A. Zupanc

(The Belle Collaboration)

1Budker Institute of Nuclear Physics, Novosibirsk
2Chiba University, Chiba
3Chonnam National University, Kwangju
4University of Cincinnati, Cincinnati, Ohio 45221
5University of Hawaii, Honolulu, Hawaii 96822
6High Energy Accelerator Research Organization (KEK), Tsukuba
7University of Illinois at Urbana-Champaign, Urbana, Illinois 61801
8Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
9Institute of High Energy Physics, Vienna
10Institute of High Energy Physics, Protvino
11Institute for Theoretical and Experimental Physics, Moscow
12J. Stefan Institute, Ljubljana
13Kanagawa University, Yokohama
14Korea University, Seoul
15Kyungpook National University, Taegu
16Swiss Federal Institute of Technology of Lausanne, EPFL, Lausanne
17University of Ljubljana, Ljubljana
18University of Maribor, Maribor
19University of Melbourne, Victoria
20Nagoya University, Nagoya
21Nara Women’s University, Nara
22National Central University, Chung-li
23National United University, Miaoli
24Department of Physics, National Taiwan University, Taipei
25H. Niewodniczanski Institute of Nuclear Physics, Krakow
26Nippon Dental University, Niigata
27Niigata University, Niigata
28Osaka City University, Osaka
29Osaka University, Osaka
30Panjab University, Chandigarh
31Peking University, Beijing
32University of Pittsburgh, Pittsburgh, Pennsylvania 15260
33Princeton University, Princeton, New Jersey 08544
34RIKEN BNL Research Center, Upton, New York 11973
35Saga University, Saga
36University of Science and Technology of China, Hefei
37Sungkyunkwan University, Suwon
38University of Sydney, Sydney NSW

arXiv:hep-ex/0607008v2  22 Aug 2006
Decays of $B$-mesons to two-body final states including charmonium are expected to occur predominantly via the color-suppressed spectator diagram as shown in Fig. 1. The branching fraction for the $B^− \rightarrow \chi_{c1} K^{−}$ decay mode is well measured by Belle and BaBar \textsuperscript{2,3}. To produce this final state, the vector current $(W^+) \rightarrow c\bar{s}$ pair; the $c$-quark and spectator anti-quark hadronize into a kaon. If this theoretical description is correct, a corresponding Cabibbo-suppressed decay mode should exist, where the vector current couples to a $c\bar{d}$ pair. The $d$-quark and spectator anti-quark hadronize as a pion, which leads to a $B^− \rightarrow \chi_{c1} \pi^{−}$ decay. If the leading-order tree level diagram is the dominant contribution, the factorization picture implies that the branching fraction of $B^− \rightarrow \chi_{c1} \pi^{−}$ decay mode should be $\sim 5\%$ of that of the Cabibbo-allowed $B^− \rightarrow \chi_{c1} K^{−}$ decay mode \textsuperscript{4}. The Standard Model predicts that for $b \rightarrow c\bar{c}s$ decays, the tree and penguin contributions have a small relative weak phase. Therefore, negligible direct $CP$-violation is expected in $B^\pm \rightarrow \chi_{c1} K^{\pm}$ decay. In $b \rightarrow c\bar{c}d$ transitions, however, tree and penguin contributions have different phases and direct $CP$-violation may be as large as a few percent \textsuperscript{5,6}.

In this paper, we report the first observation of $B^− \rightarrow \chi_{c1} \pi^{−}$ decay. A measurement of the ratio of branching fractions $\mathcal{B}(B^− \rightarrow \chi_{c1} \pi^{−})/\mathcal{B}(B^− \rightarrow \chi_{c1} K^{−})$ and a search for direct $CP$-violation in $B^\pm \rightarrow \chi_{c1} \pi^{\pm}$ decays is also presented. We use a data sample containing $(386 \pm 5) \times 10^{6}$ $B\bar{B}$ events collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy $e^+e^−$ collider \textsuperscript{7}.

The Belle detector is a large solid-angle magnetic spectrometer located at the KEKB $e^+e^-$ storage rings, which collide 8.0 GeV electrons with 3.5 GeV positrons producing a center-of-mass (CM) energy of 10.58 GeV, the mass of the $\Upsilon(4S)$ resonance. Closest to the interaction point (IP) is a silicon vertex detector (SVD), surrounded by a 50-layer central drift chamber (CDC), an array of aerogel Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight (TOF) scintillation counters, and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals. These subdetectors are located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return yoke located outside the coil is instrumented to detect $K_L^0$ mesons and to identify muons. The detector is described in detail elsewhere \textsuperscript{8}. The data set consists of two subsets: the first $152 \times 10^{6}$ $B$-meson pairs were collected with a 2.0 cm radius beam-pipe and a 3-layer SVD, and the remaining $234 \times 10^{6}$ $B$-meson pairs with a 1.5 cm radius beam-pipe, a 4-layer SVD and a small-cell inner drift chamber \textsuperscript{9}.

Events with $B$-meson candidates are first selected by applying general hadronic event selection criteria. These include a requirement on charged tracks (at least three of them should originate from an event vertex consistent with the IP), a requirement on the reconstructed CM energy ($E_{CM} > 0.2\sqrt{s}$, where $\sqrt{s}$ is the total CM energy), a requirement on the longitudinal (z-direction) component of the reconstructed CM momentum with respect to the beam direction ($|p_z^{CM}| < 0.5\sqrt{s}/c$), and a requirement on the total ECL energy $(0.1\sqrt{s} < E_{ECL}^{CM} < 0.8\sqrt{s})$ with at least two energy clusters. To suppress continuum background, we reject events where the ratio of the second to zeroth Fox-Wolfram moments \textsuperscript{10} is greater than 0.5. To remove charged particle tracks that are poorly measured
or do not come from the interaction region, we require their origin to be within 0.5 cm of the IP in the radial direction, and 5 cm along the beam direction (z-direction).

We reconstruct the $\chi_{c1}$ state via the decay mode $\chi_{c1} \rightarrow J/\psi \ell^+ \ell^-$. We begin by reconstructing $J/\psi \rightarrow \ell^+ \ell^-$ candidates, where $\ell$ is a muon or electron. For muon tracks, identification is based on track penetration depth and the hit pattern in the KLM system. Electron tracks are identified by a combination of $E/p$ (where $E$ is the energy deposited in the ECL and $p$ is the momentum measured by the SVD and the CDC), and shower shape in the ECL. In order to recover the momentum measured by the SVD and the CDC, candidates are identified by a combination of $E/p$ and the hit pattern in the KLM system. Electron tracks, identification is based on track penetration depth $\ell$ candidates, where $\ell$ is a muon or electron. For muon tracks, identification is based on track penetration depth and the hit pattern in the KLM system. Electron tracks are identified by a combination of $E/p$ (where $E$ is the energy deposited in the ECL and $p$ is the momentum measured by the SVD and the CDC), and shower shape in the ECL. In order to recover the electron events in which one or both electrons radiate and shower shape in the ECL. In order to recover the momentum measured by the SVD and the CDC, are identified by a combination of $E/p$ and the hit pattern in the KLM system. Electron tracks, identification is based on track penetration depth $\ell$ candidates, where $\ell$ is a muon or electron. For muon tracks, identification is based on track penetration depth and the hit pattern in the KLM system. Electron tracks are identified by a combination of $E/p$ (where $E$ is the energy deposited in the ECL and $p$ is the momentum measured by the SVD and the CDC), and shower shape in the ECL. In order to recover the momentum measured by the SVD and the CDC, candidates are identified by a combination of $E/p$ and the hit pattern in the KLM system. Electron tracks, identification is based on track penetration depth $\ell$ candidates, where $\ell$ is a muon or electron. For muon tracks, identification is based on track penetration depth and the hit pattern in the KLM system. Electron tracks are identified by a combination of $E/p$ (where $E$ is the energy deposited in the ECL and $p$ is the momentum measured by the SVD and the CDC), and shower shape in the ECL. In order to recover the 

![Graph](image)

**FIG. 2:** The $\Delta M (M_{\ell^+\ell^-} - M_{\ell^+\ell^-})$ distribution for the $\chi_{c1}$ candidates. The arrows indicate the selected mass region. The enhancement just above the $\chi_{c1}$ mass region is due to the $\chi_{c2}$.

other photon in the event, satisfy $0.110 \text{ GeV/c}^2 \leq M_{\gamma\gamma} \leq 0.150 \text{ GeV/c}^2$. The $\chi_{c1}$ candidates are selected by requiring the mass difference $\Delta M = (M_{\ell^+\ell^-} - M_{\ell^+\ell^-})$ to lie between $0.370 \text{ GeV/c}^2$ and $0.438 \text{ GeV/c}^2$. The $\Delta M$ distribution is shown in Fig. 2. A mass-constrained fit is applied to all selected $\chi_{c1}$ candidates in order to improve the momentum resolution.

Charged pions and kaons are identified using energy loss measurements in the CDC, Cherenkov light yields in the ACC, and TOF information. The information from these detectors is combined to form a $\pi/K$ likelihood ratio, $R(\pi/K) = L_\pi/(L_\pi + L_K)$, where $L_\pi$ ($L_K$) is the likelihood that a pion (kaon) would produce the observed detector response. Charged tracks with $R(\pi/K) > 0.9$ are selected as charged pions, and tracks with $R(\pi/K) \leq 0.4$ are selected as charged kaons. The efficiency for pion (kaon) identification is 75.1% (86.1%) and the probability of kaon (pion) misidentification is 4.6% (10.5%) with the above criteria. We determine the selection criteria by optimizing the figure of merit, $S/\sqrt{(S+B)}$, where $S(B)$ is the number of signal (background) events in the signal region, with an assumed branching fraction that is 5% of that for $B^- \rightarrow \chi_{c1}K^-$. [11]

We reconstruct $B$-mesons by combining a $\chi_{c1}$ candidate with a charged pion or kaon. The energy difference, $\Delta E \equiv E_B^* - E_{\text{beam}}$, and the beam-constrained mass $M_{bc} \equiv \sqrt{E_{\text{beam}}^2 - p_B^2}$, are used to separate signal from background, where $E_{\text{beam}}$ is the run dependent beam energy, and $E_B^*$ and $p_B^*$ are the reconstructed energy and momentum, respectively, of the $B$-meson candidates in the CM frame. We accept candidates in the region $5.27 \text{ GeV/c}^2 \leq M_{bc} \leq 5.29 \text{ GeV/c}^2$ and $|\Delta E| < 0.2 (0.15) \text{ GeV}$ for the $B^- \rightarrow \chi_{c1}\pi^-(K^-)$ mode. When an event contains more than one $B$-meson candidate passing the above requirements (this occurs in $\sim 2.5\%$ of the candidate events), the candidate with $M_{bc}$ closest to the nominal $B^-$ mass [11] is selected.

We extract the signal yields by performing a binned maximum likelihood fit to the $\Delta E$ distribution of the selected candidates. For the $B^- \rightarrow \chi_{c1}K^-$ mode, we fit with a sum of two Gaussians for signal and a second-order polynomial for background. In the fit for the $B^- \rightarrow \chi_{c1}\pi^-$ mode, a background component exists due to misidentified $\chi_{c1}K^-$. This background has a peak at $\Delta E \sim -0.07 \text{ GeV}$ and is modeled by a sum of two bifurcated Gaussians. A third-order polynomial is used for the sum of all other backgrounds. We study backgrounds using a large sample of inclusive charmonium Monte Carlo (MC) events [12]. Except for the misidentified $B^- \rightarrow \chi_{c1}K^-$ background, no structure is observed in the $\Delta E$ distribution. However, the $M_{bc}$ distribution has a peaking component. Therefore, we use the $\Delta E$ distributions for the signal extraction. The scatter plot of $\Delta E$ versus $M_{bc}$ for $B^- \rightarrow \chi_{c1}\pi^-$ candidates is shown in Fig. 3, where the $M_{bc}$ requirement is loosened to $5.2 \text{ GeV/c}^2$.

All parameters of the fitting functions are floated in the fit of the $B^- \rightarrow \chi_{c1}K^-$ mode. For the $B^- \rightarrow \chi_{c1}\pi^-$
mode, the signal shape is fixed to that obtained from the $B^− \rightarrow \chi_{c1} K^−$ mode. The shape of misidentified $\chi_{c1} K^−$ background is initially determined from a MC sample, with a correction applied to account for the small difference between data and MC in the $B^− \rightarrow \chi_{c1} K^−$ sample. We obtain $1597 \pm 48$ and $55 \pm 10$ signal events for $B^− \rightarrow \chi_{c1} K^−$ and $B^− \rightarrow \chi_{c1} \pi^−$ modes, respectively. The $\Delta E$ distributions are shown in Figs. 4 and 5, together with the fit results. The number of misidentified $B^− \rightarrow \chi_{c1} K^−$ events obtained from the fit to Fig. 5 is $61 \pm 14$. This is consistent with the expectation from the observed $B^− \rightarrow \chi_{c1} K^−$ signal yield (Fig. 4) given the probability of misidentifying a kaon as a pion. The significance of the $B^− \rightarrow \chi_{c1} \pi^−$ signal is $6.3 \sigma$, where the significance is defined as $\sqrt{-2 \ln(\mathcal{L}_0/\mathcal{L}_{max})}$ and $\mathcal{L}_{max}$ ($\mathcal{L}_0$) denotes the likelihood value at the maximum (with the signal yield fixed at zero). We include the effect of systematic error in this calculation by subtracting a quadratic sum of the variations of the significance in smaller direction when each fixed parameter in the fit is changed by $\pm 1 \sigma$.

The branching fraction for the $B^− \rightarrow \chi_{c1} \pi^−$ decay mode is calculated by dividing the observed signal yield by the reconstruction efficiency, the number of $B\bar{B}$ events in the data sample, and the daughter branching fractions. We determine the reconstruction efficiency (17.3%) from signal MC events, where the correction for difference between data and MC has been applied for the pion identification requirement (0.90±0.01) and the $\Delta M$ requirement (0.97±0.03). The correction factor for the $\Delta M$ requirement is determined from the $B^− \rightarrow \chi_{c1} K^−$ sample and is estimated by taking the ratio of yields from data and MC for tight (0.370 GeV/$c^2 < \Delta M < 0.438$ GeV/$c^2$) and loose (0.3 GeV/$c^2 < \Delta M < 0.5$ GeV/$c^2$) $\Delta M$ windows. We use the daughter branching fractions published in Particle Data Book 2004 [11]. Equal production of neutral and charged $B$-meson pairs in $\Upsilon$(4S) decay is assumed. The resulting branching fraction is

$$B(B^\pm \rightarrow \chi_{c1} \pi^\pm) = (2.2 \pm 0.4 \pm 0.3) \times 10^{-5}, \quad (1)$$

where the first error is statistical and the second is systematic. We obtain the branching fraction for the $B^− \rightarrow \chi_{c1} K^−$ decay mode by similar procedures. The result, $(51.4 \pm 1.5) \times 10^{-5}$, (error is statistical only) is consistent with the previous measurements [2, 3]. The ratio of branching fractions is

$$\frac{B(B^− \rightarrow \chi_{c1} K^−)}{B(B^\pm \rightarrow \chi_{c1} \pi^\pm)} = (4.3 \pm 0.8 \pm 0.3)\%, \quad (2)$$

which is consistent with expectations from the factorization model [4].

The systematic uncertainties are summarized in Table I. Since the shape used for the signal is fixed in the

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**FIG. 3:** The scatter plot of $\Delta E$ versus $M_{bc}$ for $B^\pm \rightarrow \chi_{c1} \pi^\pm$ candidates, where the two vertical lines indicate the $M_{bc}$ region used for signal extraction.

**FIG. 4:** The $\Delta E$ distribution for the $B^\pm \rightarrow \chi_{c1} K^\pm$ decay mode. The solid and dashed curves show the total fit and the polynomial background component of the fit, respectively.

**FIG. 5:** The $\Delta E$ distribution for the $B^\pm \rightarrow \chi_{c1} \pi^\pm$ decay mode. The signal peak is seen around zero. The peak at $-0.07$ GeV is from $B^\pm \rightarrow \chi_{c1} K^\pm$ decay. The solid and dashed curves show the total fit and the polynomial background component of the fit, respectively.
fit to Fig. 5, we repeat the fit, varying each fixed shape parameter by the \( \pm 1 \sigma \) uncertainty in our determination of it from external samples (Fig. 4 and MC). The systematic uncertainty on the signal yield is then calculated by taking the quadratic sum of the deviations in the signal yield from the nominal value. We checked for possible bias in the fitting using a MC sample; no significant bias was found. The systematic uncertainty assigned to the yield is 5.9\%. The uncertainty on the tracking efficiency is estimated to be 1.0\% per track, while that due to lepton identification is 2.0\% per lepton, and 1.0\% (1.3\%) per pion (kaon) identification (PID). We assign an uncertainty of 2.0\% for the \( \gamma \) detection efficiency. The systematic uncertainty due to the \( \Delta M \) requirement is 3.0\%. The uncertainty in yield extraction is 5.9\%. The uncertainty on the tracking efficiency is 3.0\%.

Many of the systematic errors cancel for the ratio of branching fractions; contributions come from only the uncertainty in the \( B^- \rightarrow \chi_{c1}\pi^- \) yield, PID (1.0\% for \( B^- \rightarrow \chi_{c1}K^- \)), and MC statistics (1.0\% for \( B^- \rightarrow \chi_{c1}K^- \)).

The \( CP \)-violating charge asymmetry \( A_i \) is defined as

\[
A_i = \frac{N_i^- - N_i^+}{N_i^- + N_i^+}; \quad i = \pi, K.
\]

(3)

Here, \( N_i^- \) and \( N_i^+ \) are the signal yields for negative and positive \( B \)-meson decays and are measured separately by using the method described above. For the \( B^- \rightarrow \chi_{c1}\pi^- \) mode, the polynomial background shape is fixed to that obtained for the branching fraction measurement.

The measured charge asymmetries for the \( B^{\pm} \rightarrow \chi_{c1}\pi^\mp(K\pm) \) decay modes are listed in Table II. No significant asymmetries are seen in either decay modes. The systematic errors on \( A_\pi \) (\( A_K \)) include: uncertainty in yield extraction, 0.007; possible difference between \( B^- \) and \( B^+ \) signal shape parameters, 0.002 (0.001); possible charge asymmetry in pion (kaon) identification efficiency 0.014 (0.011); and possible detector bias 0.016, which is estimated from the charge asymmetry of the \( B^\pm \rightarrow J/\psi K^\pm \) decay sample without a PID requirement.

In summary, we report the first observation of \( B^- \rightarrow \chi_{c1}\pi^- \) decay with \( 386 \times 10^6 B\bar{B} \) events. The observed signal yield is \( 55 \pm 10 \) with a significance of \( 6.3 \sigma \) including systematic uncertainty. The measured branching fraction is \( B(B^- \rightarrow \chi_{c1}\pi^-) = (2.2 \pm 0.4 \pm 0.3) \times 10^{-5} \). The ratio \( B(B^- \rightarrow \chi_{c1}\pi^-)/B(B^- \rightarrow \chi_{c1}K^-) = (4.3 \pm 0.8 \pm 0.3)\% \), which is consistent with the Standard Model prediction. While the accuracy of \( A_K \) is improved from the previous measurement [3], no significant \( CP \)-violating charge asymmetries are observed in either \( B^\pm \rightarrow \chi_{c1}\pi^\pm \) or \( B^\pm \rightarrow \chi_{c1}K^\pm \) decay modes.

We thank the KEKB group for the excellent operation of the accelerator, the KEK cryogenics group for the efficient operation of the solenoid, and the KEK computer group and the National Institute of Informatics for valuable computing and Super-SINET network support. We acknowledge support from the Ministry of Education, Culture, Sports, Science, and Technology of Japan and the Japan Society for the Promotion of Science; the Australian Research Council and the Australian Department of Education, Science and Training; the National Science Foundation of China and the Knowledge Innovation Program of the Chinese Academy of Sciences under contract No. 10575109 and IHEP-U-503; the Department of Science and Technology of India; the BK21 program of the Ministry of Education of Korea, the CHEP SRC program and Basic Research program (grant No. R01-2005-000-10089-0) of the Korea Science and Engineering Foundation, and the Pure Basic Research Group program of the Korea Research Foundation; the Polish State Committee for Scientific Research; the Ministry of Science and Technology of the Russian Federation; the Slovenian Research Agency; the Swiss National Science Foundation; the National Science Council and the Ministry of Education of Taiwan; and the U.S. Department of Energy.

[1] Charge-conjugate modes are included throughout this paper unless stated otherwise.

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