Evidence for $B^0 \rightarrow \chi_{c1} \pi^0$ at Belle

R. Kumar, J. B. Singh, I. Adachi, H. Aihara, K. Arinstein, T. Aushev, T. Aziz, A. M. Bakich, V. Balagura, A. Bay, V. Bhardwaj, U. Bitenc, A. Bozek, M. Bračko, T. E. Browder, A. Chen, B. G. Cheon, R. Chistov, I.-S. Cho, Y. Choi, J. Dalseno, M. Dash, A. Drutskoy, W. Dunigel, S. Eidem, N. Gabyshev, P. Goldenzweig, B. Golob, H. Ha, J. Haba, K. Hayasaka, H. Hayashii, M. Hazumi, Y. Horii, Y. Hoshi, W.-S. Hou, Y. B. Hsiung, H. J. Hyun, T. Iijima, K. Inami, A. Ishikawa, H. Ishino, R. Itoh, M. Iwasaki, D. H. Kah, J. H. Kang, N. Katayama, H. Kawai, T. Kawasaki, H. Kichimi, S. K. Kim, Y. I. Kim, J. J. Kim, K. Kinoshita, S. Korpar, P. Križan, P. Krokovny, A. Kuzmin, Y.-J. Kwon, S.-H. Kyeong, J. S. Lange, J. S. Lee, M. J. Lee, A. Limosani, S.-W. Lin, D. Liventsev, R. Louvat, F. Mandl, A. Matyja, S. McOnie, T. Medvedeva, K. Miyabayashi, H. Miyake, H. Miyata, Y. Mizuk, T. Mori, I. Nakamura, E. Nakano, H. Nakazawa, S. Nishida, O. Nitoh, S. Ogawa, T. Ohshima, S. Okuno, H. Ozaki, P. Pakhlov, G. Pakhlova, C. W. Park, H. Park, H. K. Park, R. Pestotnik, L. E. Piilonen, H. Sahoo, Y. Sakai, O. Schneider, A. Sekiya, K. Senyo, M. Shapkin, J.-G. Shin, B. Shwartz, A. Somov, S. Stanič, M. Starić, T. Sumiyoshi, S. Suzuki, M. Tanaka, G. N. Taylor, Y. Teramoto, K. Trabelsi, S. Uehara, Y. Unno, S. Uno, Y. Usov, G. Varner, K. Vervink, C. C. Wang, C. H. Wang, M.-Z. Wang, P. Wang, Y. Watanabe, R. Wedd, E. Won, Y. Yamashita, C. C. Zhang, Z. P. Zhang, V. Zhulanov, T. Zivko, A. Zupanc, O. Zyukova (The Belle Collaboration)

1 Budker Institute of Nuclear Physics, Novosibirsk
2 Chiba University, Chiba
3 University of Cincinnati, Cincinnati, Ohio 45221
4 Justus-Liebig-Universität Gießen, Gießen
5 The Graduate University for Advanced Studies, Hayama
6 Hangang University, Seoul
7 University of Hawaii, Honolulu, Hawaii 96822
8 High Energy Accelerator Research Organization (KEK), Tsukuba
9 Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
10 Institute of High Energy Physics, Vienna
11 Institute of High Energy Physics, Protvino
12 Institute for Theoretical and Experimental Physics, Moscow
13 J. Stefan Institute, Ljubljana
14 Kansagawa University, Yokohama
15 Korea University, Seoul
16 Kyungpook National University, Taegu
17 École Polytechnique Fédérale de Lausanne (EPFL), Lausanne
18 Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana
19 University of Maribor, Maribor
20 University of Melbourne, School of Physics, Victoria 3010
21 Nagoya University, Nagoya
22 Nara Women’s University, Nara
23 National Central University, Chung-li
24 National United University, Miaoli
25 Department of Physics, National Taiwan University, Taipei
26 H. Niewodniczanski Institute of Nuclear Physics, Krakow
27 Nippon Dental University, Niigata
28 Niigata University, Niigata
29 University of Nova Gorica, Nova Gorica
30 Osaka City University, Osaka
31 Osaka University, Osaka
32 Panjab University, Chandigarh
33 Saga University, Saga
34 University of Science and Technology of China, Hefei
35 Seoul National University, Seoul
36 Sungkyunkwan University, Suwon
37 University of Sydney, Sydney, New South Wales
38 Tata Institute of Fundamental Research, Mumbai
39 Toho University, Funabashi
40 Tohoku Gakuin University, Tagajo
We present a measurement of the branching fraction for the Cabibbo- and color-suppressed \( B^0 \to \chi_c \pi^0 \) decay based on a data sample of \( 657 \times 10^6 \) \( B\bar{B} \) events collected at the \( \Upsilon(4S) \) resonance with the Belle detector at the KEKB asymmetric-energy \( e^+e^- \) collider. We observe a signal of \( 40 \pm 9 \) events with a significance of \( 4.7\sigma \) including systematic uncertainties. The measured branching fraction is \( \mathcal{B}(B^0 \to \chi_c \pi^0) = (1.12 \pm 0.25\text{(stat.)} \pm 0.12\text{(syst.)}) \times 10^{-5} \).

PACS numbers: 13.25.Hw, 14.40.Gx, 14.40.Nd

The decay \( B^0 \to \chi_c \pi^0 \) is a \( b \to c\bar{c}d \) transition that proceeds at leading order through the color-suppressed tree diagram as shown in Fig. 1. If the tree diagram dominates, then the time-dependent \( CP \)-violating asymmetries in this decay mode are predicted to be the same as those measured in \( b \to c\bar{c}s \) decays, such as \( B^0 \to J/\psi K_S^0 \) \([4]\). A deviation of the \( CP \)-violating asymmetries in \( B^0 \to \chi_c \pi^0 \) from these expectations could indicate non-negligible contributions from a penguin amplitude or amplitudes from new physics. For a similar \( B \) decay mode, \( B^0 \to J/\psi \pi^0 \), the time-dependent \( CP \)-violation parameters have been measured by the Belle \([2]\) and BaBar \([3]\) collaborations. Comparison of the properties of \( B^0 \to J/\psi \pi^0 \) and \( B^0 \to \chi_c \pi^0 \) decays will also provide an opportunity to probe new physics that predicts different couplings to left-handed and right-handed particles \([4]\).

The \( B^0 \to \chi_c \pi^0 \) decay has not been observed so far. Confirming its existence is a very important step toward detailed studies of the \( b \to c\bar{c}d \) transition. The factorization approach \([5]\) and isospin symmetry imply that the branching fraction of the \( B^0 \to \chi_c \pi^0 \) decay mode should be one half of that for \( B^\pm \to \chi_c \pi^\pm \) \([6]\). Precise measurement of the branching fractions of these decays can also provide information related to the final state interactions in \( B \) decays.

In this paper, we report the first evidence of \( B^0 \to \chi_c \pi^0 \) using a data sample containing \( (657 \pm 9) \times 10^6 \) \( B\bar{B} \) events collected at the \( \Upsilon(4S) \) resonance with the Belle detector \([7]\) at the KEKB asymmetric-energy \( e^+e^- \) collider \([8]\). 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.

The Belle detector consists of a silicon vertex detector (SVD), which is 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 (KLM) located outside the coil is instrumented to detect \( K_L^0 \) mesons and to identify muons. The detector is described in detail elsewhere \([9]\). The data set used in this analysis 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 \( 505 \times 10^6 \) \( B \) meson pairs with a 1.5 cm radius beam pipe in a 4-layer SVD and a small-cell inner drift chamber \([8]\) \([10]\).

Events with \( B \) meson candidates are first selected by applying the following general selection criteria for hadronic events: at least three charged tracks are required to originate from an event vertex which is consistent with the interaction point (IP); the reconstructed CM energy should satisfy \( E_{CM} > 0.2\sqrt{s} \), where \( \sqrt{s} \) is the total CM energy; the component of momentum along the beam direction (\( z \)-direction) must be in the range \( p_{z,CM}^E < 0.5\sqrt{s}/c \); and the total ECL energy should consist of at least two energy clusters and satisfy \( 0.1\sqrt{s} < E_{ECL}^T < 0.8\sqrt{s} \). To suppress continuum background dominated by two-jet-like \( e^+e^- \to q\bar{q} \) annihilation \((q = u,d,s)\), we reject events where the ratio of the second to zeroth Fox-Wolfram moments \([11]\) \( R_2 \) is greater than 0.5. We find no contribution from continuum background after applying this cut on \( R_2 \). To remove tracks of charged particles that are poorly measured or do not originate from the interaction region, we require their origin to be within 0.5 cm of the IP in the radial direction, and 5 cm in \( z \)-direction.

We reconstruct \( J/\psi \) from pairs of \( e^+e^- \) or \( \mu^+\mu^- \) can-
the invariant mass calculation. The invariant mass win-

to suppress photons originating from π0 → γγ, we veto photons that, when combined with another photon in the event, satisfy 0.110 GeV/c^2 ≤ Mγγ ≤ 0.150 GeV/c^2. The χc1 candidates are selected by requiring the mass difference (∆M = M_{ℓ+ℓ−γ} - M_{ℓ+ℓ−}) to lie between 0.3 GeV/c^2 and 0.5 GeV/c^2. The ∆M distribution is shown in Fig. 2. A mass-constrained fit is applied to χc1 candidates in order to improve the momentum resolution.

We reconstruct B mesons by combining a χc1 candidate with a neutral pion. The energy difference, ∆E ≡ E^∗_B - E^∗_beam, and the mass difference (∆M = M_{ℓ+ℓ−γ} - M_{ℓ+ℓ−}) are used to separate signal from background, where E^∗_beam and E^∗_B are the run-dependent beam energy and reconstructed energy of the B meson candidates in the CM frame, respectively. For the selected B^0 candidates, the beam-constrained mass, M_{bc} = √(E^∗_beam - p^2_B), where p_B is the reconstructed momentum of the B meson candidates in the CM frame, is required to be 5.27 GeV/c^2 < M_{bc} < 5.29 GeV/c^2. We retain B^0 candidates with 0.3 GeV/c^2 < ∆M < 0.5 GeV/c^2 and −0.2 GeV < ∆E < 0.2 GeV for the final analysis. The selection criteria are determined by optimizing the figure of merit, S/√(S + B), where S (B) is the number of signal (background) events in the signal region (−0.09 GeV < ∆E < 0.05 GeV and 0.380 GeV/c^2 < ∆M < 0.435 GeV/c^2). We assume the signal branching fraction is half of that for B^± → χc1π^±.

The backgrounds are dominated by the B^±B^− events with a J/ψ in the final state, where the J/ψ is produced either directly from B decay or from the χc1 → J/ψγ decay chain. We study these background processes using a large Monte Carlo (MC) sample [12] corresponding to 3.86×10^{10} generic B^±B^− decays that includes all known B → J/ψX processes and those where B decays into higher charmonium states (χc1, χc2 or ψ) that subsequently produce J/ψ in the final state. The dominant contribution comes from B^0 → J/ψK^0_S(→ π^0π^0), B^0 → J/ψK^∗±(892), B^± → J/ψK^0(892), B^0 → χc1K^±(→ π^0π^0), and a few other exclusive B → J/ψ(χc1) + X decay modes. To suppress neutral pions from K^0_S(→ π^0π^0) decays, we veto π^0’s that, when combined with another π^0 in the event, satisfy 0.469 GeV/c^2 < M_{π^0π^0} < 0.526 GeV/c^2. The K^0_S veto reduces the background by 16.2% with a signal loss of 4.2%. We further reduce the B → J/ψK^0_S(→ π^0π^0) background by requiring cosθ_hel > −0.88, where θ_hel is the angle between the direction opposite to the B momentum and the γ direction in the χc1 rest frame. After this requirement, we find that there is no peaking background in the ΔE signal region. The background from B → χc1 + X decay modes, such as B^0 → χc1K^0_S(→ π^0π^0), B^+ → χc1K^*, B^± → χc1π^± and B^0 → ψ(2S)(→ χc1γ)π^0, forms a peak in the ΔM signal region (called peaking background), while all other components are flat in ΔM (called combinatorial background). The background from B → χc2 + X decay modes is negligibly small and ignored.

The signal yield is extracted by maximizing a two-
parameters and the number of combinatorial background are floated. The shapes of combinatorial backgrounds are fixed from MC and those for the exponential function are found to be $0.380 \text{ GeV/c}^2 < \Delta M < 0.435 \text{ GeV/c}^2$ and (b) the projections in $\Delta M$ for events satisfying $-0.09 \text{ GeV} < \Delta E < 0.05 \text{ GeV}$. The solid curve represents the overall fit, dashed curve represents the sum of peaking and combinatorial background, and dotted curve only combinatorial background component.

The signal PDF is modeled using a Crystal Ball (CB) lineshape function [14] for $\Delta E$ and a CB lineshape function for $\Delta M$ whose shape parameters are determined from a signal MC sample. To take into account a small difference between data and MC, the shapes of the $\Delta E$ and $\Delta M$ distributions are corrected according to calibration constants obtained from the $B^+ \rightarrow J/\psi K^{*+} (K^{*+} \rightarrow K^+ \pi^0)$ and $B^- \rightarrow \chi_{c1} K^-$ samples, respectively. In the reconstruction of $B^+ \rightarrow J/\psi K^{*+}$ events, we require the momentum of the $\pi^0$ to be greater than 0.75 GeV/c. This requirement results in a $\Delta E$ distribution similar to that for the signal events. The calibration constants for the mean and width of $\Delta E$ ($\Delta M$) are found to be $-6.23 \pm 0.97$ MeV ($-1.16 \pm 0.46$ MeV) and $1.37 \pm 0.07$ (1.12 $\pm 0.05$), respectively.

The peaking background shape is modeled using a CB lineshape function in $\Delta M$ and an exponential function in $\Delta E$. The shape parameters of the CB lineshape function are fixed from MC and those for the exponential function are floated. The shapes of combinatorial backgrounds are modeled by a first-order polynomial function for $\Delta E$ and a second-order polynomial function for $\Delta M$. The shape parameters and the number of combinatorial background events are allowed to float in the fit.

The $\Delta E$ and $\Delta M$ distributions along with the projections of the fit are shown in Fig. 4. The fit yields a signal of $40 \pm 9 B^0 \rightarrow \chi_{c1} \pi^0$ candidates. The number of peaking background events is $14 \pm 7$, which is in good agreement with MC expectations of 14.

The significance of the $B^0 \rightarrow \chi_{c1} \pi^0$ signal is $4.7 \sigma$, defined as $\sqrt{-2 \ln (L_0/L_{\text{max}})}$ and $L_{\text{max}}$ ($L_0$) denotes the maximum likelihood value (the value obtained from the fit when signal yield fixed to zero). We include the effect of systematic uncertainties by subtracting the 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 ($B$) for the $B^0 \rightarrow \chi_{c1} \pi^0$.
The systematic uncertainties are summarized in Table I. The systematic uncertainty on the signal yield is calculated by varying each shape parameter fixed in the fit by ±1σ, and then taking the quadratic sum of the deviations from the nominal value. We have checked for possible bias in the fitting using a MC sample; no significant bias was found. The systematic uncertainty assigned to the signal yield is 4.5%. The uncertainty on the tracking efficiency is estimated to be 1.0% per track, while that due to lepton identification is 3.9%. We also assign an uncertainty of 4.1% for π0 → γγ reconstruction, and an uncertainty of 2.0% for the γ detection efficiency; these are correlated and added linearly (6.1%). The systematic uncertainty due to the χc1 → J/ψ branching fractions is 5.5%. The total systematic error is the sum of all the above uncertainties in quadrature.

In summary, we report the first evidence of $B^0 \rightarrow \chi_{c1}\pi^0$ with $(657 \pm 9) \times 10^6 B\bar{B}$ events. The observed signal yield is 40 ± 9 with a significance of 4.7σ including systematic uncertainty. The measured branching fraction is $B(B^0 \rightarrow \chi_{c1}\pi^0) = (1.12 \pm 0.25 \pm 0.12) \times 10^{-5}$, which is consistent with the factorization model.

We thank the KEKB group for excellent operation of the accelerator, the KEK cryogenics group for efficient solenoid operations, and the KEK computer group for efficient detector response. We acknowledge support from MEXT and JSPS (Japan); ARC and DEST (Australia); NSFC (China); DST (India); MOEHRD, KOSEF and KRF (Korea); KBN (Poland); MES and RFAE (Russia); ARRS (Slovenia); SNSF (Switzerland); NSC and MOE (Taiwan); and DOE (USA).

### TABLE I: Summary of systematic errors on branching fraction.

| Source                            | Uncertainty (%) |
|-----------------------------------|-----------------|
| Yield uncertainty                 | 4.5             |
| Tracking                          | 2.0             |
| Lepton identification             | 3.9             |
| γ and π0 detection                | 6.1             |
| π0 veto                           | 1.6             |
| MC statistics                     | 2.3             |
| Nμμ                              | 1.4             |
| Secondary branching fractions     | 5.5             |
| Total                             | 10.8            |

The decay mode is calculated as follows:

$$\mathcal{B} = \frac{N_{\text{sig}}}{\epsilon \times N_{\text{MC}} \times B_{\text{sec}}}$$  

(2)

where $N_{\text{sig}}$ is the observed signal yield, $\epsilon (N_{\text{MC}})$ is the reconstruction efficiency (number of $B$ mesons in the data sample), and $B_{\text{sec}}$ is the product of $B(\chi_{c1} \rightarrow J/\psi\gamma)$, $B(J/\psi \rightarrow \ell\ell)$ and $B(\pi^0 \rightarrow \gamma\gamma)$. The reconstruction efficiency is determined from a signal MC sample. After a small correction for the muon identification requirement the efficiency is found to be 13.0%. We use the daughter branching fractions published in Ref. [12]. Equal production of neutral and charged $B$ meson pairs in Υ(4S) decay is assumed. The resulting branching fraction is

$$B(B^0 \rightarrow \chi_{c1}\pi^0) = (1.12 \pm 0.25 \pm 0.12) \times 10^{-5},$$  

(3)

where the first error is statistical and the second is systematic.

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