

Search for $X(3872)$ and $X(3915)$ decay into $\chi_{c1}\pi^0$ in B decays at Belle

V. Bhardwaj,²² S. Jia,² I. Adachi,^{18,14} H. Aihara,⁸⁹ D. M. Asner,³ T. Aushev,⁵⁷ R. Ayad,⁸³ V. Babu,⁸⁴ I. Badhrees,^{83,37} S. Bahinipati,²³ V. Bansal,⁷⁰ P. Behera,²⁶ C. Beleño,¹³ M. Berger,⁸⁰ B. Bhuyan,²⁴ T. Bilka,⁵ J. Biswal,³⁴ A. Bobrov,^{4,68} A. Bondar,^{4,68} G. Bonvicini,⁹³ A. Bozek,⁶⁵ M. Bračko,^{51,34} T. E. Browder,¹⁷ M. Campajola,^{31,60} L. Cao,³⁵ D. Červenkov,⁵ P. Chang,⁶⁴ V. Chekelian,⁵² A. Chen,⁶² B. G. Cheon,¹⁶ K. Chilikin,⁴⁵ H. E. Cho,¹⁶ K. Cho,³⁹ S.-K. Choi,¹⁵ Y. Choi,⁸¹ S. Choudhury,²⁵ D. Cinabro,⁹³ S. Cunliffe,⁸ S. Di Carlo,⁴³ Z. Doležal,⁵ T. V. Dong,^{18,14} S. Eidelman,^{4,68,45} D. Epifanov,^{4,68} J. E. Fast,⁷⁰ T. Ferber,⁸ B. G. Fulsom,⁷⁰ R. Garg,⁷¹ V. Gaur,⁹² N. Gabyshev,^{4,68} A. Garmash,^{4,68} A. Giri,²⁵ P. Goldenzweig,³⁵ D. Greenwald,⁸⁵ O. Grzymkowska,⁶⁵ J. Haba,^{18,14} T. Hara,^{18,14} K. Hayasaka,⁶⁷ H. Hayashii,⁶¹ W.-S. Hou,⁶⁴ C.-L. Hsu,⁸² T. Iijima,^{59,58} K. Inami,⁵⁸ A. Ishikawa,⁸⁷ R. Itoh,^{18,14} M. Iwasaki,⁶⁹ Y. Iwasaki,¹⁸ W. W. Jacobs,²⁷ Y. Jin,⁸⁹ D. Joffe,³⁶ K. K. Joo,⁶ T. Julius,⁵³ A. B. Kaliyar,²⁶ G. Karyan,⁸ Y. Kato,⁵⁸ T. Kawasaki,³⁸ C. Kiesling,⁵² C. H. Kim,¹⁶ D. Y. Kim,⁷⁹ S. H. Kim,¹⁶ K. Kinoshita,⁷ P. Kodyš,⁵ S. Korpar,^{51,34} D. Kotchetkov,¹⁷ P. Križan,^{46,34} R. Kroeger,⁵⁴ P. Krokovny,^{4,68} T. Kuhr,⁴⁷ R. Kulasiri,³⁶ R. Kumar,⁷⁴ Y.-J. Kwon,⁹⁵ K. Lalwani,⁴⁹ J. S. Lange,¹¹ I. S. Lee,¹⁶ J. K. Lee,⁷⁷ J. Y. Lee,⁷⁷ S. C. Lee,⁴² L. K. Li,²⁸ Y. B. Li,⁷² L. Li Gioi,⁵² J. Libby,²⁶ D. Liventsev,^{92,18} P.-C. Lu,⁶⁴ J. MacNaughton,⁵⁵ C. MacQueen,⁵³ M. Masuda,⁸⁸ T. Matsuda,⁵⁵ D. Matvienko,^{4,68,45} M. Merola,^{31,60} K. Miyabayashi,⁶¹ R. Mizuk,^{45,56,57} G. B. Mohanty,⁸⁴ T. Mori,⁵⁸ R. Mussa,³² M. Nakao,^{18,14} K. J. Nath,²⁴ M. Nayak,^{93,18} M. Niiyama,⁴¹ N. K. Nisar,⁷³ S. Nishida,^{18,14} K. Nishimura,¹⁷ S. Ogawa,⁸⁶ H. Ono,^{66,67} Y. Onuki,⁸⁹ P. Pakhlov,^{45,56} G. Pakhlova,^{45,57} B. Pal,³ S. Pardi,³¹ H. Park,⁴² S.-H. Park,⁹⁵ S. Patra,²² S. Paul,⁸⁵ T. K. Pedlar,⁴⁸ R. Pestotnik,³⁴ L. E. Piilonen,⁹² V. Popov,^{45,57} E. Prencipe,²⁰ P. K. Resmi,²⁶ M. Ritter,⁴⁷ A. Rostomyan,⁸ G. Russo,³¹ Y. Sakai,^{18,14} M. Salehi,^{50,47} S. Sandilya,⁷ L. Santelj,¹⁸ T. Sanuki,⁸⁷ V. Savinov,⁷³ O. Schneider,⁴⁴ G. Schnell,^{1,21} C. Schwanda,²⁹ Y. Seino,⁶⁷ K. Senyo,⁹⁴ O. Seon,⁵⁸ M. E. Sevier,⁵³ C. P. Shen,² J.-G. Shiu,⁶⁴ B. Shwartz,^{4,68} F. Simon,⁵² A. Sokolov,³⁰ E. Solovieva,⁴⁵ M. Starič,³⁴ Z. S. Stottler,⁹² M. Sumihama,¹² T. Sumiyoshi,⁹¹ W. Sutcliffe,³⁵ M. Takizawa,^{78,19,75} U. Tamponi,³² K. Tanida,³³ F. Tenchini,⁸ K. Trabelsi,⁴³ M. Uchida,⁹⁰ S. Uehara,^{18,14} T. Uglov,^{45,57} S. Uno,^{18,14} P. Urquijo,⁵³ R. Van Tonder,³⁵ G. Varner,¹⁷ B. Wang,⁵² C. H. Wang,⁶³ M.-Z. Wang,⁶⁴ P. Wang,²⁸ X. L. Wang,¹⁰ M. Watanabe,⁶⁷ S. Watanuki,⁸⁷ E. Won,⁴⁰ S. B. Yang,⁴⁰ H. Ye,⁸ J. Yelton,⁹ J. H. Yin,²⁸ J. Zhang,²⁸ Z. P. Zhang,⁷⁶ V. Zhilich,^{4,68} V. Zhukova,⁴⁵ and V. Zhulanov^{4,68}

(The Belle Collaboration)

¹University of the Basque Country UPV/EHU, 48080 Bilbao²Beihang University, Beijing 100191³Brookhaven National Laboratory, Upton, New York 11973⁴Budker Institute of Nuclear Physics SB RAS, Novosibirsk 630090⁵Faculty of Mathematics and Physics, Charles University, 121 16 Prague⁶Chonnam National University, Kwangju 660-701⁷University of Cincinnati, Cincinnati, Ohio 45221⁸Deutsches Elektronen-Synchrotron, 22607 Hamburg⁹University of Florida, Gainesville, Florida 32611¹⁰Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) and Institute of Modern Physics, Fudan University, Shanghai 200443¹¹Justus-Liebig-Universität Gießen, 35392 Gießen¹²Gifu University, Gifu 501-1193¹³II. Physikalisches Institut, Georg-August-Universität Göttingen, 37073 Göttingen¹⁴SOKENDAI (The Graduate University for Advanced Studies), Hayama 240-0193¹⁵Gyeongsang National University, Chinju 660-701¹⁶Hanyang University, Seoul 133-791¹⁷University of Hawaii, Honolulu, Hawaii 96822¹⁸High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801¹⁹J-PARC Branch, KEK Theory Center, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801²⁰Forschungszentrum Jülich, 52425 Jülich²¹IKERBASQUE, Basque Foundation for Science, 48013 Bilbao²²Indian Institute of Science Education and Research Mohali, SAS Nagar 140306²³Indian Institute of Technology Bhubaneswar, Satya Nagar 751007²⁴Indian Institute of Technology Guwahati, Assam 781039²⁵Indian Institute of Technology Hyderabad, Telangana 502285

- ²⁶Indian Institute of Technology Madras, Chennai 600036
- ²⁷Indiana University, Bloomington, Indiana 47408
- ²⁸Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049
- ²⁹Institute of High Energy Physics, Vienna 1050
- ³⁰Institute for High Energy Physics, Protvino 142281
- ³¹INFN—Sezione di Napoli, 80126 Napoli
- ³²INFN—Sezione di Torino, 10125 Torino
- ³³Advanced Science Research Center, Japan Atomic Energy Agency, Naka 319-1195
- ³⁴J. Stefan Institute, 1000 Ljubljana
- ³⁵Institut für Experimentelle Teilchenphysik, Karlsruher Institut für Technologie, 76131 Karlsruhe
- ³⁶Kennesaw State University, Kennesaw, Georgia 30144
- ³⁷King Abdulaziz City for Science and Technology, Riyadh 11442
- ³⁸Kitasato University, Sagami-hara 252-0373
- ³⁹Korea Institute of Science and Technology Information, Daejeon 305-806
- ⁴⁰Korea University, Seoul 136-713
- ⁴¹Kyoto University, Kyoto 606-8502
- ⁴²Kyungpook National University, Daegu 702-701
- ⁴³LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay 91898
- ⁴⁴École Polytechnique Fédérale de Lausanne (EPFL), Lausanne 1015
- ⁴⁵P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow 119991
- ⁴⁶Faculty of Mathematics and Physics, University of Ljubljana, 1000 Ljubljana
- ⁴⁷Ludwig Maximilians University, 80539 Munich
- ⁴⁸Luther College, Decorah, Iowa 52101
- ⁴⁹Malaviya National Institute of Technology Jaipur, Jaipur 302017
- ⁵⁰University of Malaya, 50603 Kuala Lumpur
- ⁵¹University of Maribor, 2000 Maribor
- ⁵²Max-Planck-Institut für Physik, 80805 München
- ⁵³School of Physics, University of Melbourne, Victoria 3010
- ⁵⁴University of Mississippi, University, Mississippi 38677
- ⁵⁵University of Miyazaki, Miyazaki 889-2192
- ⁵⁶Moscow Physical Engineering Institute, Moscow 115409
- ⁵⁷Moscow Institute of Physics and Technology, Moscow Region 141700
- ⁵⁸Graduate School of Science, Nagoya University, Nagoya 464-8602
- ⁵⁹Kobayashi-Maskawa Institute, Nagoya University, Nagoya 464-8602
- ⁶⁰Università di Napoli Federico II, 80055 Napoli
- ⁶¹Nara Women's University, Nara 630-8506
- ⁶²National Central University, Chung-li 32054
- ⁶³National United University, Miao Li 36003
- ⁶⁴Department of Physics, National Taiwan University, Taipei 10617
- ⁶⁵H. Niewodniczanski Institute of Nuclear Physics, Krakow 31-342
- ⁶⁶Nippon Dental University, Niigata 951-8580
- ⁶⁷Niigata University, Niigata 950-2181
- ⁶⁸Novosibirsk State University, Novosibirsk 630090
- ⁶⁹Osaka City University, Osaka 558-8585
- ⁷⁰Pacific Northwest National Laboratory, Richland, Washington 99352
- ⁷¹Panjab University, Chandigarh 160014
- ⁷²Peking University, Beijing 100871
- ⁷³University of Pittsburgh, Pittsburgh, Pennsylvania 15260
- ⁷⁴Punjab Agricultural University, Ludhiana 141004
- ⁷⁵Theoretical Research Division, Nishina Center, RIKEN, Saitama 351-0198
- ⁷⁶University of Science and Technology of China, Hefei 230026
- ⁷⁷Seoul National University, Seoul 151-742
- ⁷⁸Showa Pharmaceutical University, Tokyo 194-8543
- ⁷⁹Soongsil University, Seoul 156-743
- ⁸⁰Stefan Meyer Institute for Subatomic Physics, Vienna 1090
- ⁸¹Sungkyunkwan University, Suwon 440-746
- ⁸²School of Physics, University of Sydney, New South Wales 2006
- ⁸³Department of Physics, Faculty of Science, University of Tabuk, Tabuk 71451
- ⁸⁴Tata Institute of Fundamental Research, Mumbai 400005
- ⁸⁵Department of Physics, Technische Universität München, 85748 Garching

⁸⁶Toho University, Funabashi 274-8510⁸⁷Department of Physics, Tohoku University, Sendai 980-8578⁸⁸Earthquake Research Institute, University of Tokyo, Tokyo 113-0032⁸⁹Department of Physics, University of Tokyo, Tokyo 113-0033⁹⁰Tokyo Institute of Technology, Tokyo 152-8550⁹¹Tokyo Metropolitan University, Tokyo 192-0397⁹²Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061⁹³Wayne State University, Detroit, Michigan 48202⁹⁴Yamagata University, Yamagata 990-8560⁹⁵Yonsei University, Seoul 120-749

(Received 15 April 2019; published 12 June 2019)

We report a search for $X(3872)$ and $X(3915)$ in $B^+ \rightarrow \chi_{c1}\pi^0 K^+$ decays. We set an upper limit of $\mathcal{B}(B^+ \rightarrow X(3872)K^+) \times \mathcal{B}(X(3872) \rightarrow \chi_{c1}\pi^0) < 8.1 \times 10^{-6}$ and $\mathcal{B}(B^+ \rightarrow X(3915)K^+) \times \mathcal{B}(X(3915) \rightarrow \chi_{c1}\pi^0) < 3.8 \times 10^{-5}$ at 90% confidence level. We also measure $\mathcal{B}(X(3872) \rightarrow \chi_{c1}\pi^0)/\mathcal{B}(X(3872) \rightarrow J/\psi\pi^+\pi^-) < 0.97$ at 90% confidence level. The results reported here are obtained from $772 \times 10^6 B\bar{B}$ events collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider.

DOI: [10.1103/PhysRevD.99.111101](https://doi.org/10.1103/PhysRevD.99.111101)

The $X(3872)$ state was observed for the first time by the Belle collaboration in 2003 via its decay to $J/\psi\pi^+\pi^-$ in the $B^+ \rightarrow J/\psi\pi^+\pi^-K^+$ decays [1]. Its mass (3871.69 ± 0.17) MeV/ c^2 , narrow width ($\Gamma < 1.2$ MeV) [2], and other properties suggest it to be a nonconventional $c\bar{c}$ state. The $X(3872)$ has also been seen in other decay modes: $D^0\bar{D}^{*0}$, $J/\psi\gamma$, $\psi(2S)\gamma$, and $J/\psi\pi^+\pi^-\pi^0$ [3–7]. Very recently, a new decay mode, $\chi_{c1}\pi^0$, was reported by BESIII [8] in $e^+e^- \rightarrow \chi_{c1}\pi^0\gamma$. According to their measurement, $R_{\chi_{c1}/\psi}^X \equiv \mathcal{B}(X(3872) \rightarrow \chi_{c1}\pi^0)/\mathcal{B}(X(3872) \rightarrow J/\psi\pi^+\pi^-) = 0.88_{-0.27}^{+0.33} \pm 0.10$, where the first uncertainty is statistical and the second is systematic. In comparison with conventional charmonium, this ratio seems to be large; e.g., $\mathcal{B}(\psi(2S) \rightarrow J/\psi\pi^0)/\mathcal{B}(\psi(2S) \rightarrow J/\psi\pi^+\pi^-) = 3.66 \times 10^{-3}$.

If the $X(3872)$ structure is dominated by a charmonium $\chi_{c1}(2P)$ component, we expect the branching fraction for the pionic transition, $X(3872) \rightarrow \chi_{c1}\pi^0$, to be very small due to isospin breaking by the light quark masses [9], significantly suppressed compared to that for $X(3872) \rightarrow \chi_{c1}\pi^+\pi^-$ ($R \approx 4.0\%$). The BESIII result disfavors the $\chi_{c1}(2P)$ interpretation of the $X(3872)$ and suggests instead a tetraquark or molecular state with a significant isovector part in its wave function, which results in an enhanced single-pion transition [9].

In the search for $X(3872) \rightarrow \chi_{c1}\pi^+\pi^-$ [10], the Belle Collaboration determined the branching fraction $\mathcal{B}(B^+ \rightarrow X(3872)K^+) \times \mathcal{B}(X(3872) \rightarrow \chi_{c1}\pi^+\pi^-)$ to be

less than 1.5×10^{-6} at 90% confidence level (C.L.). In addition, the Belle Collaboration observed $B^+ \rightarrow \chi_{c1}\pi^0 K^+$ and published the background-subtracted $sPlot$ [11] distribution for $M_{\chi_{c1}\pi^0}$, which showed no structure at the $X(3872)$ mass. We use a similar technique to provide a limit on $R_{\chi_{c1}/\psi}^X$.

The $X(3915)$ was first observed, via its decay to $J/\psi\omega$, by the Belle Collaboration in $B \rightarrow J/\psi\omega K$ decay [12]. The quantum numbers of $X(3915)$ were identified to be $J^{PC} = 0^{++}$ [13], suggesting it may be $\chi_{c0}(2P)$. If $X(3915)$ is $\chi_{c0}(2P)$, its width should be larger [14]. However, the measured width (20 ± 5 MeV/ c^2) [2] is significantly narrower than theoretical expectations (> 100 MeV/ c^2). The $J/\psi\omega$ is also expected to be suppressed by the Okubo-Zweig-Iizuka (OZI) rule in the $\chi_{c0}(2P)$ scenario [15]. A $J^{PC} = 2^{++}$ assignment is also consistent with our observation [16]. If $X(3915)$ is a nonconventional $c\bar{c}$ state, then one may expect the single pion transition to be enhanced in $X(3915)$ decays as compared to charmonium, where it is suppressed due to isotopic symmetry breaking.

In the study reported here, we reproduce the previous result for $B^+ \rightarrow \chi_{c1}\pi^0 K^+$ [10,17], search for the intermediate states X [X denotes $X(3872)$ and $X(3915)$], and measure the product branching fraction $\mathcal{B}(B^+ \rightarrow XK^+) \times \mathcal{B}(X \rightarrow \chi_{c1}\pi^0)$.

We use a sample of $772 \times 10^6 B\bar{B}$ events collected with the Belle detector [18] at the KEKB asymmetric-energy e^+e^- collider, operating at the $\Upsilon(4S)$ resonance [19]. The Belle detector is a large-solid-angle spectrometer, which includes a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of 8736 CsI(Tl) crystals located inside

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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 identify muons. The detector is described in detail elsewhere [18]. Two inner detector configurations were used. A first sample of 152×10^6 $B\bar{B}$ events was collected with a 2.0-cm-radius beam pipe and a 3-layer SVD, and the remaining 620×10^6 $B\bar{B}$ pairs were collected with a 1.5-cm-radius beam pipe, a 4-layer SVD and a modified CDC [20].

We use EVTGEN [21] with QED final-state radiation by PHOTOS [22] for the generation of Monte Carlo (MC) simulation events. GEANT3-based [23] MC simulation is used to model the response of the detector and determine the efficiency of the signal reconstruction. Signal MC is used to estimate the efficiency and selection criteria for reconstructing $B^+ \rightarrow X(\rightarrow \chi_{c1} \pi^0) K^+$ decay.

We reconstruct the $B^+ \rightarrow \chi_{c1} \pi^0 K^+$ decay mode with the same selection criteria as those used in the previous analysis [10]. To suppress continuum background, we require the ratio of the second to the zeroth Fox-Wolfram moment [24] to be less than 0.5. Charged tracks are required to originate from the vicinity of the interaction point (IP): the distance of closest approach to the IP is required to be within 3.5 cm along the beam direction and within 1.0 cm in the plane transverse to the beam direction. An ECL cluster is treated as a photon candidate if it is isolated from the extrapolated charged tracks, and its energy in the lab frame is greater than 100 MeV. We reject a photon candidate if the ratio of energy deposited in the central 3×3 square of cells to that deposited in the enclosing 5×5 square of cells in its ECL cluster is less than 0.85. This helps to reduce photon candidates originating from neutral hadrons.

The J/ψ meson is reconstructed via its decay to $\ell^+ \ell^-$ ($\ell = e$ or μ) and selected by the invariant mass of the $\ell^+ \ell^-$ pair ($M_{\ell\ell}$). For the dimuon mode, $M_{\ell\ell}$ is the invariant mass $M_{\mu^+ \mu^-}$; for the dielectron mode, the four-momenta of all photons within 50 mrad cone of the original e^+ or e^- direction are absorbed into the $M_{\ell\ell} \equiv M_{e^+ e^- (\gamma)}$ to reduce the radiative tail. The reconstructed invariant mass of the J/ψ candidates is required to satisfy $2.95 \text{ GeV}/c^2 < M_{e^+ e^- (\gamma)} < 3.13 \text{ GeV}/c^2$ or $3.03 \text{ GeV}/c^2 < M_{\mu^+ \mu^-} < 3.13 \text{ GeV}/c^2$. For the selected J/ψ candidates, a vertex-constrained fit is applied to the charged tracks and then a mass-constrained fit is performed to improve the momentum resolution. The χ_{c1} candidates are reconstructed by combining a J/ψ candidate with a photon. To reduce background from $\pi^0 \rightarrow \gamma\gamma$, a likelihood function is employed to distinguish isolated photons from π^0 daughters using the invariant mass of the photon pair, photon energy in the laboratory frame and the polar angle with respect to the beam direction in the laboratory frame [25]. We combine the candidate photon with any other photon and then reject both photons of a pair whose π^0 likelihood is larger than 0.8. For further analysis,

we keep the χ_{c1} candidates with a reconstructed invariant mass satisfying $3.467 \text{ GeV}/c^2 < M_{J/\psi\gamma} < 3.535 \text{ GeV}/c^2$, which corresponds to $[-4.5\sigma, +2.8\sigma]$ about the nominal mass of the χ_{c1} [2], where σ is the χ_{c1} mass resolution from the fit to the MC simulated $J/\psi\gamma$ mass distribution. To improve the momentum resolution a mass-constrained fit is applied to the selected χ_{c1} candidates.

Particle identification is performed using specific ionization information from the CDC, time measurements from the TOF, and the light yield measured in the ACC. Charged kaons and pions are identified using the K likelihood ratio, $R_K = \mathcal{L}_K / (\mathcal{L}_K + \mathcal{L}_\pi)$, where \mathcal{L}_K and \mathcal{L}_π are likelihood values for the kaon and pion hypotheses [26]. Kaon tracks are correctly identified with an efficiency of 89.4%, whereas the probability of misidentifying a pion as a kaon is 10.1% for $B^+ \rightarrow X(3872)(\rightarrow \chi_{c1} \pi^0) K^+$.

Photon pairs are kept as π^0 candidates whose invariant mass lies in the range $120 \text{ MeV}/c^2 < M_{\gamma\gamma} < 150 \text{ MeV}/c^2$ ($\pm 3\sigma$ about the nominal mass of π^0). To reduce combinatorial background, the $\pi^0 \rightarrow \gamma\gamma$ candidates are also required to have an energy balance parameter $|E_1 - E_2| / (E_1 + E_2)$ smaller than 0.8, where E_1 (E_2) is the energy of the first (second) daughter photon in the laboratory frame. For each selected π^0 candidate, a mass-constrained fit is performed to improve its momentum resolution.

To identify the B meson, two kinematic variables are used: the beam-energy-constrained mass M_{bc} and the energy difference ΔE . The former is defined as $\sqrt{E_{\text{beam}}^2/c^2 - (\sum_i \vec{p}_i)^2/c^2}$ and the latter as $\sum_i E_i - E_{\text{beam}}$, where E_{beam} is the beam energy and \vec{p}_i and E_i are the momentum and energy of the i th daughter particle in the center-of-mass (CM) frame; the summation is over all final-state particles used to reconstruct the B candidate. We reject candidates having M_{bc} less than $5.27 \text{ GeV}/c^2$ or $|\Delta E| > 120 \text{ MeV}$. After the reconstruction, an average of 1.24 B candidates per event is found. When there are multiple B candidates in one event, we retain only the candidate with the lowest χ^2 value defined as:

$$\chi^2 = \chi_V^2 + \chi_{\pi^0}^2 + \left(\frac{M_{\chi_{cJ}} - m_{\chi_{cJ}}}{\sigma_{\chi_{cJ}}} \right)^2 + \left(\frac{M_{bc} - m_B}{\sigma_{M_{bc}}} \right)^2,$$

where χ_V^2 is the reduced χ^2 returned by the vertex fit of all charged tracks, $\chi_{\pi^0}^2$ is the reduced χ^2 for the π^0 mass-constrained fit, $M_{\chi_{cJ}}$ is the reconstructed mass of χ_{cJ} , and $m_{\chi_{cJ}}$ and m_B are the nominal masses of the χ_{cJ} and B mesons, respectively. This method has 95% efficiency for selecting the true candidate.

We extract the signal yield from an unbinned extended maximum likelihood (UML) fit to the ΔE distribution. The signal probability density function (PDF) is modeled by a sum of a Gaussian function and a logarithmic Gaussian function [27]. The mean and width of the core Gaussian with larger fraction are floated and the remaining

parameters of tail distribution are fixed from studies of MC simulation.

To study the background from events with a J/ψ , we use MC-simulated $B \rightarrow J/\psi X$ sample corresponding to 100 times the integrated luminosity of the data sample. Possible peaking backgrounds from the feed-across of $B^+ \rightarrow \chi_{c2}\pi^0 K^+$ are found in the ΔE distribution around -50 MeV, which are due to the mass-constrained fit to $\chi_{c1} \rightarrow J/\psi\gamma$ candidates; we estimate that only five such events are expected in real data. Thus, we fix this peaking background contribution in the fit. The PDF for the peaking background is modeled by an asymmetric Gaussian distribution for which the parameters are fixed according to MC simulation after MC/data correction (using the signal events whose mean and sigma of the core Gaussian are floated).

The rest of the background is combinatorial and modeled by using a first-order Chebyshev polynomial. The fit to the ΔE distribution for $B^+ \rightarrow \chi_{c1}\pi^0 K^+$ is shown in Fig. 1(a). We obtain 806 ± 69 signal events for the $B^+ \rightarrow \chi_{c1}\pi^0 K^+$ decay mode, which is consistent with our previous study [10]. In order to improve the resolution on the invariant mass of the combined χ_{c1} and π^0 candidates ($M_{\chi_{c1}\pi^0}$), we scale the energy and momentum of the π^0 , such that ΔE is equal to zero while the M_{π^0} is kept constant to its already mass-constrained value. This corrects for the incomplete energy measurement of the π^0 detection. The corrected four-momentum of the π^0 is then used to improve the invariant mass $M_{\chi_{c1}\pi^0}$ and $M_{K^+\pi^0}$.

To search for the X , we examined the background-subtracted $M_{\chi_{c1}\pi^0}$ distribution produced with the $sPlot$ technique [28] for the range $(3.75 \text{ GeV}/c^2 < M_{\chi_{c1}\pi^0} < 4.05 \text{ GeV}/c^2)$ as shown in Fig. 1(b). Figure 1(c) shows the $M_{K^+\pi^0}$ $sPlot$ distribution in the range of interest $(3.75 \text{ GeV}/c^2 < M_{\chi_{c1}\pi^0} < 4.05 \text{ GeV}/c^2)$, where most events come from the K^* decays.

In order to extract the X signal yield, we use the $M_{\chi_{c1}\pi^0}$ distribution within the signal-enhanced window of

$-30 \text{ MeV} < \Delta E < 20 \text{ MeV}$ for $B^+ \rightarrow (\chi_{c1}\pi^0)K^+$ candidates. We veto events from $B^+ \rightarrow \chi_{c1}K^{*+}$ decay by rejecting events with $791.8 \text{ MeV}/c^2 < M(K^+\pi^0) < 991.8 \text{ MeV}/c^2$. This requirement reduces the background by 32% with a signal efficiency of 84%. We extract the signal by performing a 1D UML fit to the $M_{\chi_{c1}\pi^0}$ distribution. The signal PDFs for both $X(3872)$ and $X(3915)$ are modeled by the sum of two Gaussians. All the PDF parameters are fixed from the MC simulation after a MC/data correction estimated from the $B^+ \rightarrow \psi(2S)(\rightarrow\chi_{c1}\gamma)K^+$ sample is applied [29] (the mean and sigma of the core Gaussian were fixed after scaling, while the tail parameters were fixed from signal MC).

The efficiency (ϵ) is estimated to be 5.35% and 5.37% for $B^+ \rightarrow X(3872)(\rightarrow\chi_{c1}\pi^0)K^+$ and $B^+ \rightarrow X(3915)(\rightarrow\chi_{c1}\pi^0)K^+$ using the MC simulations, respectively. This efficiency has been calibrated by the difference between MC simulation and data, as described later. A fit to the data shown in Fig. 2 results in a signal yield of 2.7 ± 5.5 (42 ± 14) events having significance of 0.3σ (2.3σ) for the $B^+ \rightarrow X(3872)(\rightarrow\chi_{c1}\pi^0)K^+$ ($B^+ \rightarrow X(3915)(\rightarrow\chi_{c1}\pi^0)K^+$) decay mode. The systematic uncertainty (explained later) has been included in the significance calculation.

With the absence of any significant signal, we estimate an upper limit (U.L.) at 90% C.L. We apply a frequentist method that uses ensembles of pseudoexperiments. For a given signal yield, sets of signal and background events are generated according to their PDFs and fits are performed. The C.L. is determined from the fraction of samples that give a yield larger than that of data. We estimate the branching fraction according to the formula $\mathcal{B} = Y^{\text{U.L.}} / (\epsilon \times \mathcal{B}_s \times N_{B\bar{B}})$; here $Y^{\text{U.L.}}$ is the estimated U.L. yield at 90% C.L., ϵ is the reconstruction efficiency, \mathcal{B}_s is the product of secondary branching fraction taken from Ref. [2], and $N_{B\bar{B}}$ is the number of $B\bar{B}$ mesons in the data sample. Equal production of neutral and charged B meson pairs in the $\Upsilon(4S)$ decay is assumed. For this assumption, an uncertainty of 1.2% is added to the total systematics.

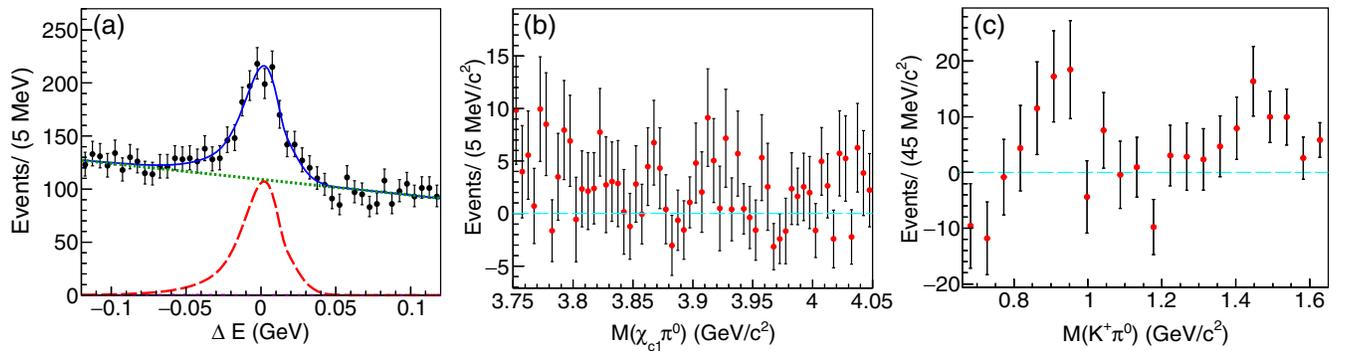


FIG. 1. (a) The ΔE distribution for the $B^0 \rightarrow \chi_{c1}\pi^0 K^+$ decay mode for the whole $M_{\chi_{c1}\pi^0}$ range. The curves show the signal (red dashed), the peaking background (magenta double dotted-dashed) and the background component (green dotted for combinatorial) as well as the overall fit (blue solid). Background-subtracted $sPlot$ (b) $M_{\chi_{c1}\pi^0}$ and (c) $M_{K^+\pi^0}$ distributions (in $3.75 \text{ GeV}/c^2 < M_{\chi_{c1}\pi^0} < 4.05 \text{ GeV}/c^2$ signal window) for the $B^+ \rightarrow \chi_{c1}\pi^0 K^+$ decay mode. Points with error bar represent the data.

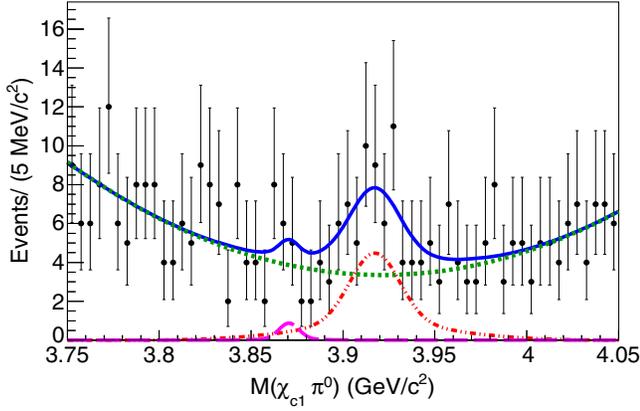


FIG. 2. 1D UML fit to the $M_{\chi_{c1}\pi^0}$ distribution in the $-30 \text{ MeV} < \Delta E < 20 \text{ MeV}$ signal region for the $B^+ \rightarrow (\chi_{c1}\pi^0)K^+$ decay mode. The curves show the $B^+ \rightarrow X(3872)(\rightarrow\chi_{c1}\pi^0)K^+$ signal (magenta dashed), $B^+ \rightarrow X(3915)(\rightarrow\chi_{c1}\pi^0)K^+$ signal (red double dotted-dashed), and the background component (green dotted for combinatorial) as well as the overall fit (blue solid). Points with error bar represent the data.

We estimate the U.L. on the product of branching fractions $\mathcal{B}(B^+ \rightarrow X(3872)K^+) \times \mathcal{B}(X(3872) \rightarrow \chi_{c1}\pi^0)$ directly from the above MC pseudoexperiment samples. The limit includes the systematic uncertainties from efficiency, particle identification, and signal extraction method into the yield obtained by smearing the assumed values by their uncertainties. Along with that we also smear the $N_{B\bar{B}}$ and secondary branching fraction by adding their systematic uncertainties as a fluctuation of the value used to calculate the branching fraction. Using the MC pseudoexperiment samples we estimate the U.L. (90% C.L.) on the product branching fraction as:

$$\begin{aligned} \mathcal{B}(B^+ \rightarrow X(3872)K^+) \times \mathcal{B}(X(3872) \rightarrow \chi_{c1}\pi^0) &< 8.1 \times 10^{-6} \\ \mathcal{B}(B^+ \rightarrow X(3915)K^+) \times \mathcal{B}(X(3915) \rightarrow \chi_{c1}\pi^0) &< 3.8 \times 10^{-5}. \end{aligned}$$

To measure the $R_{\chi_{c1}/\psi}^X$, we use the previous Belle measurement of $\mathcal{B}(B^+ \rightarrow X(3872)K^+) \times \mathcal{B}(X(3872) \rightarrow J/\psi\pi^+\pi^-) = (8.63 \pm 0.82(\text{stat}) \pm 0.52(\text{syst})) \times 10^{-6}$ [30]. Some of the systematic uncertainties cancel, such as lepton identification, $\mathcal{B}(J/\psi \rightarrow \ell\ell)$, some tracking systematics, and kaon identification. The U.L. on $R_{\chi_{c1}/\psi}^X$ is estimated in the same manner as that on $\mathcal{B}(B^+ \rightarrow X(3872)K^+) \times \mathcal{B}(X(3872) \rightarrow \chi_{c1}\pi^0)$. We remove the cancelled systematic uncertainties and smear the pseudoexperiments with the remaining ones. We further smear $\mathcal{B}(B^+ \rightarrow X(3872)K^+) \times \mathcal{B}(X(3872) \rightarrow J/\psi\pi^+\pi^-)$ by its statistical uncertainty and uncanceled systematic uncertainties. For each toy sample, $R_{\chi_{c1}/\psi}^X$ is estimated for the generated $R_{\chi_{c1}/\psi}^X$. The C.L. value is then determined from the fraction of samples of pseudoexperiments having $R_{\chi_{c1}/\psi}^X$ larger than the central

TABLE I. Summary of the systematics uncertainties for the $\mathcal{B}(B^+ \rightarrow XK^+) \times \mathcal{B}(X \rightarrow \chi_{c1}\pi^0)$ and $R_{\chi_{c1}/\psi}^X$.

Source	\mathcal{B} (%)		$R_{\chi_{c1}/\psi}^X$ (%)
	$X(3915)$	$X(3872)$	
Lepton identification	2.3	2.2	...
Kaon identification	1.0	1.0	...
Efficiency	0.5	0.5	2.2
$B\bar{B}$ pairs	1.4	1.4	...
B production	1.2	1.2	...
Tracking	1.1	1.1	0.7
γ identification	2.0	2.0	2.0
π^0 veto	1.2	1.2	1.2
π^0 reconstruction	2.2	2.2	2.2
Signal extraction	+16.1 -19.5	+37.0 -44.4	+37.1 -44.5
Secondary \mathcal{B}	3.0	3.0	2.9
Total	+17.0 -20.2	+37.4 -44.7	+37.4 -44.8

value of data. We estimate the U.L. to be $R_{\chi_{c1}/\psi}^X < 0.97$ at 90% C.L.

Table I summarizes systematic uncertainties for the measured product branching fraction $\mathcal{B}(B^+ \rightarrow XK^+) \times \mathcal{B}(X \rightarrow \chi_{c1}\pi^0)$ and the ratio $R_{\chi_{c1}/\psi}^X$. A correction for the small difference in the signal detection efficiency between MC and data is applied for the lepton identification requirements, which are determined from $e^+e^- \rightarrow e^+e^-\ell^+\ell^-$ and $J/\psi \rightarrow \ell^+\ell^-$ ($\ell = e$ or μ) samples. Dedicated $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$ samples are used to estimate the kaon (pion) identification efficiency correction. The uncertainty on the efficiency due to limited MC statistics is 0.5%, and the uncertainty on the number of $B\bar{B}$ pairs is 1.4%. The uncertainty on the track finding efficiency is found to be 0.35% per track by comparing data and MC for $D^* \rightarrow D^0\pi$ decay, where $D^0 \rightarrow K_S^0\pi^+\pi^-$ and $K_S^0 \rightarrow \pi^+\pi^-$. The uncertainty on the photon identification is estimated to be 2.0% from a sample of radiative Bhabha events. The systematic uncertainty associated with the difference of the π^0 veto between data and MC is estimated to be 1.2% from a study of the $B^+ \rightarrow \chi_{c1}(\rightarrow J/\psi\gamma)K^+$ sample. For π^0 reconstruction, the efficiency correction and systematic uncertainty are estimated from a sample of $\tau^- \rightarrow \pi^-\pi^0\nu_\tau$ decays. The errors on the PDF shapes are obtained by varying all fixed parameters by $\pm 1\sigma$ and taking the change in the yield as the systematic uncertainty. The largest uncertainty in the PDF parameterization for $X(3872)$ [$X(3915)$] is 30% ($^{+15}_{-17}\%$) from fixing the mass (width) of the $X(3872)$ [$X(3915)$] to the value reported in Ref. [2]. In order to estimate the uncertainty coming from the background shape, we used a third-order polynomial and took the difference as the uncertainty. Further, we also used large fitting range and added the difference in quadrature to the uncertainty coming from signal extraction

procedure. The uncertainties due to the secondary branching fractions are also taken into account. Assuming all the sources are independent we add them in quadrature to obtain the total systematic uncertainties.

To summarize, in our searches for $X(3872)$ and $X(3915)$ decaying to $\chi_{c1}\pi^0$, we did not find a significant signal. We obtained 2.7 ± 5.5 (42 ± 14) events, with a signal significance of 0.3σ (2.3σ) for the $B^+ \rightarrow X(3872)(\rightarrow \chi_{c1}\pi^0)K^+$ ($B^+ \rightarrow X(3915)(\rightarrow \chi_{c1}\pi^0)K^+$) decay mode. We determine an U.L. on the product branching fractions $\mathcal{B}(B^+ \rightarrow X(3872)K^+) \times \mathcal{B}(X(3872) \rightarrow \chi_{c1}\pi^0) < 8.1 \times 10^{-6}$ and $\mathcal{B}(B^+ \rightarrow X(3915)K^+) \times \mathcal{B}(X(3915) \rightarrow \chi_{c1}\pi^0) < 3.8 \times 10^{-5}$ at 90% C.L. The null result for our search is compatible with the interpretation of $X(3872)$ as an admixture state of a $D^0\bar{D}^{*0}$ molecule and a $\chi_{c1}(2P)$ charmonium state [9]. One can further estimate $R_{\chi_{c1}/\psi}^X < 0.97$ at 90% C.L. Our U.L. does not contradict the BESIII result [8]. This information can be used to constrain the tetraquark/molecular component of the X states.

ACKNOWLEDGMENTS

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 Pacific Northwest National Laboratory (PNNL) Environmental Molecular Sciences Laboratory (EMSL) computing group for strong computing support; and the National Institute of Informatics, and Science Information NETwork 5 (SINET5) for valuable network support. We acknowledge support from the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan, the Japan Society for the Promotion of Science (JSPS), and the Tau-Lepton Physics Research Center of Nagoya University; the Australian Research Council

including Grants No. DP180102629, No. DP170102389, No. DP170102204, No. DP150103061, and No. FT130100303; Austrian Science Fund (FWF); the National Natural Science Foundation of China under Contracts No. 11435013, No. 11475187, No. 11521505, No. 11575017, No. 11675166, and No. 11705209; Key Research Program of Frontier Sciences, Chinese Academy of Sciences (CAS), Grant No. QYZDJ-SSW-SLH011; the CAS Center for Excellence in Particle Physics (CCEPP); the Shanghai Pujiang Program under Grant No. 18PJ1401000; the Ministry of Education, Youth and Sports of the Czech Republic under Contract No. LTT17020; the Carl Zeiss Foundation, the Deutsche Forschungsgemeinschaft, the Excellence Cluster Universe, and the VolkswagenStiftung; the Department of Science and Technology of India; the Istituto Nazionale di Fisica Nucleare of Italy; National Research Foundation (NRF) of Korea Grants No. 2015H1A2A1033649, No. 2016R1D1A1B01010135, No. 2016K1A3A7A09005 603, No. 2016R1D1A1B02012900, No. 2018R1A2B3003 643, No. 2018R1A6A1A06024970, and No. 2018R1D1 A1B07047294; Radiation Science Research Institute, Foreign Large-size Research Facility Application Supporting project, the Global Science Experimental Data Hub Center of the Korea Institute of Science and Technology Information and KREONET/GLORIAD; the Polish Ministry of Science and Higher Education and the National Science Center; the Grant of the Russian Federation Government, Agreement No. 14.W03.31.0026; the Slovenian Research Agency; Ikerbasque, Basque Foundation for Science, Spain; the Swiss National Science Foundation; the Ministry of Education and the Ministry of Science and Technology of Taiwan; and the United States Department of Energy and the National Science Foundation.

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- [1] S.-K. Choi *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **91**, 262001 (2003).
 - [2] M. Tanabashi *et al.* (Particle Data Group), *Phys. Rev. D* **98**, 030001 (2018).
 - [3] T. Aushev *et al.* (Belle Collaboration), *Phys. Rev. D* **81**, 031103(R) (2010).
 - [4] B. Aubert *et al.* (BABAR Collaboration), *Phys. Rev. Lett.* **102**, 132001 (2009).
 - [5] V. Bhardwaj *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **107**, 091803 (2011).
 - [6] R. Aaij *et al.* (LHCb Collaboration), *Nucl. Phys.* **B886**, 665 (2014).
 - [7] P. del Amo Sanchez *et al.* (BABAR Collaboration), *Phys. Rev. D* **82**, 011101(R) (2010).
 - [8] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev. Lett.* **122**, 202001 (2019).
 - [9] S. Dubynskiy and M. B. Voloshin, *Phys. Rev. D* **77**, 014013 (2008).
 - [10] V. Bhardwaj *et al.* (Belle Collaboration), *Phys. Rev. D* **93**, 052016 (2016).
 - [11] M. Pivk and F. R. Le Diberder, *Nucl. Instrum. Methods Phys. Res., Sect. A* **555**, 356 (2005).
 - [12] S.-K. Choi *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **94**, 182002 (2005).
 - [13] J. P. Lees *et al.* (BABAR Collaboration), *Phys. Rev. D* **86**, 072002 (2012).
 - [14] F. K. Guo and Ulf-G. Meissner, *Phys. Rev. D* **86**, 091501(R) (2012).
 - [15] S. L. Olsen, *Phys. Rev. D* **91**, 057501 (2015).
 - [16] Z. Y. Zhou, Z. Xiao, and H. Q. Zhou, *Phys. Rev. Lett.* **115**, 022001 (2015).

- [17] Charge-conjugate decays are included unless explicitly stated otherwise.
- [18] A. Abashian *et al.* (Belle Collaboration), *Nucl. Instrum. Methods Phys. Res., Sect. A* **479**, 117 (2002); also see detector section in J. Brodzicka *et al.*, *Prog. Theor. Exp. Phys.* **2012**, 04D001 (2012).
- [19] S. Kurokawa and E. Kikutani, *Nucl. Instrum. Methods Phys. Res., Sect. A* **499**, 1 (2003), and other papers included in this Volume; T. Abe *et al.*, *Prog. Theor. Exp. Phys.* **2013**, 03A001 (2013) and following articles up to 03A011.
- [20] Z. Natkaniec *et al.* (Belle SVD2 Group), *Nucl. Instrum. Methods Phys. Res., Sect. A* **560**, 1 (2006).
- [21] D. J. Lange, *Nucl. Instrum. Methods Phys. Res., Sect. A* **462**, 152 (2001).
- [22] E. Barberio and Z. Waş, *Comput. Phys. Commun.* **79**, 291 (1994).
- [23] R. Brun *et al.*, GEANT3.21, Report No. CERN-DD-EE-84-01, 1984.
- [24] G. C. Fox and S. Wolfram, *Phys. Rev. Lett.* **41**, 1581 (1978).
- [25] P. Koppenburg *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **93**, 061803 (2004).
- [26] E. Nakano, *Nucl. Instrum. Methods Phys. Res., Sect. A* **494**, 402 (2002).
- [27] The logarithmic Gaussian is parameterized as: $f(x) = N_0/c(x) \times \exp\{-\ln[(e-x)/(e-x_p)]\}^2/(2\sigma_0^2)$ where $e = \sigma/a + x_p$, $c(x) = \sqrt{2\pi}\sigma_0(e-x)$ and $\sigma_0 = (\ln(a\sqrt{2\ln 2} + \sqrt{1+2a^2\ln 2})/\sqrt{2\ln 2})$. Here, N_0 is the normalization, σ is the standard deviation, x_p is the mean and a is the asymmetry.
- [28] M. Pivk and F.R. Le Diberder, *Nucl. Instrum. Methods, Phys. Res. Sect. A* **555**, 356 (2005).
- [29] V. Bhardwaj *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **111**, 032001 (2013).
- [30] S.-K. Choi *et al.* (Belle Collaboration), *Phys. Rev. D* **84**, 052004 (2011).