Rapid Communications

Observation of excited Ω_c charmed baryons in e^+e^- collisions

J. Yelton,[7] I. Adachi,[13,9] H. Aihara,[74] S. Al Said,[67,32] D. M. Asner,[57] V. Aulchenko,[3,55] T. Aushev,[46] R. Ayad,[67] T. Aziz,[68] V. Babu,[68] A. M. Bakich,[66] V. Bansal,[57] E. Barberio,[44] P. Behera,[20] M. Berger,[64] V. Bhardwaj,[16] B. Bhuyan,[18] J. Biswal,[28] A. Bobrov,[3,55] A. Bozek,[52] M. Bračko,[42,28] T. E. Browder,[12] D. Červenkov,[4] P. Chang,[51] A. Chen,[49] B. G. Cheon,[11] K. Chilikin,[38,45] K. Cho,[33] S.-K. Choi,[10] Y. Choi,[65] S. Choudhury,[19] D. Cinabro,[79] T. Czank,[72] N. Dash,[17] S. Di Carlo,[79] Z. Doležal,[4] D. Dutta,[68] S. Eidelman,[3,55] J. E. Fast,[57] T. Ferber,[6] B. G. Fulsom,[57] R. Garg,[58] V. Gaur,[78] N. Gabyshev,[3,55] A. Garmash,[3,55] M. Gelb,[30] A. Giri,[19] P. Goldenzweig,[30] B. Golob,[39,28] D. Greenwald,[70] E. Guido,[26] J. Haba,[13,9] K. Hayasaka,[54] H. Hayashii,[48] M. T. Hedges,[12] W.-S. Hou,[51] K. Inami,[47] G. Inguglia,[6] A. Ishikawa,[72] R. Itoh,[13,9] M. Iwasaki,[56] Y. Iwasaki,[13] W. W. Jacobs,[21] H. B. Jeon,[36] Y. Jin,[74] T. Julius,[44] K. H. Kang,[36] G. Karyan,[6] Y. Kato,[47] T. Kawasaki,[54] H. Kichimi,[13] D. Y. Kim,[63] H. J. Kim,[36] J. B. Kim,[34] S. H. Kim,[11] K. Kinoshita,[5] P. Kodyš,[4] S. Korpar,[42,28] D. Kotchetkov,[12] P. Križan,[39,28] R. Kroeger,[24] P. Krokovny,[3,55] T. Kuhr,[40] R. Kulasiri,[31] T. Kumita,[76] A. Kuzmin,[3,55] Y.-J. Kwon,[80] J. S. Lange,[81] I. S. Lee,[11] S. C. Lee,[36] C. H. Li,[44] L. K. Li,[22] Y. Li,[78] L. Li Gioi,[43] D. Liventsev,[78,13] M. Lubej,[28] T. Luo,[59] M. Masuda,[73] D. Matvienko,[3,55] M. Merola,[25] H. Miyata,[54] R. Mizuk,[38,45,46] G. B. Mohanty,[68] H. K. Moon,[34] T. Mori,[47] R. Mussa,[26] E. Nakano,[56] M. Nakao,[13,9] T. Nanut,[28] K. J. Nath,[18] M. Nayak,[79,13] M. Niiyama,[35] N. K. Nisar,[59] S. Nishida,[13,9] S. Ogawa,[71] S. Okuno,[29] H. Ono,[53,54] P. Pakhlov,[38,45] G. Pakhlova,[38,46] B. Pal,[5] H. Park,[36] S. Paul,[70] I. Pavelkin,[46] T. K. Pedlar,[41] R. Pestotnik,[28] L. E. Piilonen,[78] V. Popov,[46] M. Ritter,[40] G. Russo,[25] Y. Sakai,[13,9] S. Sandilya,[5] V. Savinov,[59] O. Schneider,[37] G. Schnell,[1,15] C. Schwanda,[23] Y. Seino,[54] M. E. Sevior,[44] V. Shebalin,[3,55] C. P. Shen,[2] T.-A. Shibata,[75] N. Shimizu,[74] J.-G. Shiu,[51] B. Shwartz,[3,55] F. Simon,[43,69] J. B. Singh,[58] E. Solovieva,[38,46] M. Starič,[28] J. F. Strube,[57] M. Sumihama,[8] T. Sumiyoshi,[76] K. Suzuki,[64] M. Takizawa,[62,14,60] U. Tamponi,[26,77] K. Tanida,[27] F. Tenchini,[44] M. Uchida,[75] T. Uglov,[38,46] Y. Unno,[11] S. Uno,[13,9] Y. Usov,[3,55] G. Varner,[12] K. E. Varvell,[66] A. Vinokurova,[3,55] V. Vorobyev,[3,55] C. H. Wang,[50] M.-Z. Wang,[51] P. Wang,[22] X. L. Wang,[57,13] Y. Watanabe,[29] S. Watanuki,[72] E. Widmann,[64] E. Won,[34] H. Ye,[6] Y. Yusa,[54] S. Zakharov,[38] Z. P. Zhang,[61] V. Zhilich,[3,55] V. Zhulanov,[3,55] and A. Zupanc[39,28]

(Belle Collaboration)

[1]*University of the Basque Country UPV/EHU, 48080 Bilbao*
[2]*Beihang University, Beijing 100191*
[3]*Budker Institute of Nuclear Physics SB RAS, Novosibirsk 630090*
[4]*Faculty of Mathematics and Physics, Charles University, 121 16 Prague*
[5]*University of Cincinnati, Cincinnati, Ohio 45221*
[6]*Deutsches Elektronen–Synchrotron, 22607 Hamburg*
[7]*University of Florida, Gainesville, Florida 32611*
[8]*Gifu University, Gifu 501-1193*
[9]*SOKENDAI (The Graduate University for Advanced Studies), Hayama 240-0193*
[10]*Gyeongsang National University, Chinju 660-701*
[11]*Hanyang University, Seoul 133-791*
[12]*University of Hawaii, Honolulu, Hawaii 96822*
[13]*High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801*
[14]*J-PARC Branch, KEK Theory Center, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801*
[15]*IKERBASQUE, Basque Foundation for Science, 48013 Bilbao*
[16]*Indian Institute of Science Education and Research Mohali, SAS Nagar, 140306*
[17]*Indian Institute of Technology Bhubaneswar, Satya Nagar 751007*
[18]*Indian Institute of Technology Guwahati, Assam 781039*
[19]*Indian Institute of Technology Hyderabad, Telangana 502285*
[20]*Indian Institute of Technology Madras, Chennai 600036*
[21]*Indiana University, Bloomington, Indiana 47408*
[22]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049*
[23]*Institute of High Energy Physics, Vienna 1050*
[24]*University of Mississippi, University, Mississippi 38677*
[25]*INFN—Sezione di Napoli, 80126 Napoli*
[26]*INFN—Sezione di Torino, 10125 Torino*
[27]*Advanced Science Research Center, Japan Atomic Energy Agency, Naka 319-1195*
[28]*J. Stefan Institute, 1000 Ljubljana*
[29]*Kanagawa University, Yokohama 221-8686*

[30]Institut für Experimentelle Kernphysik, Karlsruher Institut für Technologie, 76131 Karlsruhe
[31]Kennesaw State University, Kennesaw, Georgia 30144
[32]Department of Physics, Faculty of Science, King Abdulaziz University, Jeddah 21589
[33]Korea Institute of Science and Technology Information, Daejeon 305-806
[34]Korea University, Seoul 136-713
[35]Kyoto University, Kyoto 606-8502
[36]Kyungpook National University, Daegu 702-701
[37]École Polytechnique Fédérale de Lausanne (EPFL), Lausanne 1015
[38]P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow 119991
[39]Faculty of Mathematics and Physics, University of Ljubljana, 1000 Ljubljana
[40]Ludwig Maximilians University, 80539 Munich
[41]Luther College, Decorah, Iowa 52101
[42]University of Maribor, 2000 Maribor
[43]Max-Planck-Institut für Physik, 80805 München
[44]School of Physics, University of Melbourne, Victoria 3010
[45]Moscow Physical Engineering Institute, Moscow 115409
[46]Moscow Institute of Physics and Technology, Moscow Region 141700
[47]Graduate School of Science, Nagoya University, Nagoya 464-8602
[48]Nara Women's University, Nara 630-8506
[49]National Central University, Chung-li 32054
[50]National United University, Miao Li 36003
[51]Department of Physics, National Taiwan University, Taipei 10617
[52]H. Niewodniczanski Institute of Nuclear Physics, Krakow 31-342
[53]Nippon Dental University, Niigata 951-8580
[54]Niigata University, Niigata 950-2181
[55]Novosibirsk State University, Novosibirsk 630090
[56]Osaka City University, Osaka 558-8585
[57]Pacific Northwest National Laboratory, Richland, Washington 99352
[58]Panjab University, Chandigarh 160014
[59]University of Pittsburgh, Pittsburgh, Pennsylvania 15260
[60]Theoretical Research Division, Nishina Center, RIKEN, Saitama 351-0198
[61]University of Science and Technology of China, Hefei 230026
[62]Showa Pharmaceutical University, Tokyo 194-8543
[63]Soongsil University, Seoul 156-743
[64]Stefan Meyer Institute for Subatomic Physics, Vienna 1090
[65]Sungkyunkwan University, Suwon 440-746
[66]School of Physics, University of Sydney, New South Wales 2006
[67]Department of Physics, Faculty of Science, University of Tabuk, Tabuk 71451
[68]Tata Institute of Fundamental Research, Mumbai 400005
[69]Excellence Cluster Universe, Technische Universität München, 85748 Garching
[70]Department of Physics, Technische Universität München, 85748 Garching
[71]Toho University, Funabashi 274-8510
[72]Department of Physics, Tohoku University, Sendai 980-8578
[73]Earthquake Research Institute, University of Tokyo, Tokyo 113-0032
[74]Department of Physics, University of Tokyo, Tokyo 113-0033
[75]Tokyo Institute of Technology, Tokyo 152-8550
[76]Tokyo Metropolitan University, Tokyo 192-0397
[77]University of Torino, 10124 Torino
[78]Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
[79]Wayne State University, Detroit, Michigan 48202
[80]Yonsei University, Seoul 120-749
[81]Justus-Liebig-Universität Gießen, 35392 Gießen

(Received 21 November 2017; published 9 March 2018)

Using the entire Belle data sample of 980 fb^{-1} of e^+e^- collisions, we present the results of a study of excited Ω_c charmed baryons in the decay mode $\Xi_c^+K^-$. We show confirmation of four of the five narrow states reported by the LHCb Collaboration: the $\Omega_c(3000)$, $\Omega_c(3050)$, $\Omega_c(3066)$, and $\Omega_c(3090)$.

DOI: 10.1103/PhysRevD.97.051102

The Ω_c^0 [1] charmed baryon is a combination of css quarks. Charmed baryons can be treated as a heavy (c) quark and a light (in this case ss) diquark [2–4]. The ground state of Ω_c^0 can be considered as a spin-1 diquark in combination with the charm quark, as symmetry rules do not allow a spin-0 diquark. Thus, the ground-state Ω_c, although weakly decaying, has a quark structure analogous to the Σ_c and Ξ_c' rather than Λ_c and Ξ_c baryons. Until recently, the only excited state of the Ω_c^0 observed was the $J=\frac{3}{2}^+$ state known as the Ω_c^{*0} [5,6], which decays electromagnetically into the ground state. All excitations have restricted decay possibilities, because the decay $\Omega_c^{*0}\to\Omega_c^0\pi^0$ would violate isospin conservation. However, provided there is sufficient mass, strong decays into $\Xi_c\bar{K}$, $\Xi_c'\bar{K}$, and $\Xi_c^*\bar{K}$ are possible.

Recently, the LHCb collaboration announced the discovery of five narrow resonances in the final state $\Xi_c^+K^-$ [7]. In addition they showed a wide enhancement at the higher mass of 3.188 GeV/c^2, which may comprise more than one state. Here we present the results of an analysis of the same final state using data from the Belle experiment, and confirm many of the LHCb discoveries.

This analysis uses a data sample of e^+e^- annihilations recorded by the Belle detector [8] operating at the KEKB asymmetric-energy e^+e^- collider [9]. It corresponds to an integrated luminosity of 980 fb^{-1}. The majority of these data were taken with the accelerator energy tuned for production of the $\Upsilon(4S)$ resonance, as this is optimum for investigation of B decays. However, the excited charmed baryons in this analysis are produced in continuum charm production and are of higher momentum than those that are decay products of B mesons, so the data set used in this analysis also includes the Belle data taken at beam energies corresponding to the other Υ resonances and the nearby continuum ($e^+e^-\to q\bar{q}$, where $q\in\{u,d,s,c\}$).

The Belle detector is a large-solid-angle spectrometer comprising six sub-detectors: the Silicon Vertex Detector (SVD), the 50-layer Central Drift Chamber (CDC), the Aerogel Cherenkov Counter (ACC), the Time-of-Flight scintillation counter (TOF), the electromagnetic calorimeter, and the K_L and muon detector. A superconducting solenoid produces a 1.5 T magnetic field throughout the first five of these sub-detectors. The detector is described in detail elsewhere [8]. Two inner detector configurations were used. The first comprised a 2.0 cm radius beam pipe and a 3-layer silicon vertex detector, and the second a 1.5 cm radius beam pipe and a 4-layer silicon detector and a small-cell inner drift chamber.

In 2016, Belle published [10] the results of an analysis of excited Ξ_c states decaying into $\Xi_c^{+/0}$ and a photon and/or pions. To do this, seven different Ξ_c^+ decay modes ($\Xi^-\pi^+\pi^+$, $\Lambda K^-\pi^+\pi^+$, $\Xi^0\pi^+$, $\Xi^0\pi^+\pi^-\pi^+$, $\Sigma^+K^-\pi^+$, $\Lambda K_S^0\pi^+$, and $\Sigma^0K_s^0\pi^+$) were reconstructed. The analysis presented here uses the identical reconstruction chains and the same selection criteria to reconstruct these same ground state Ξ_c^+ baryons. The Ξ_c^+ candidates are made by kinematically fitting the decay daughters to a common decay vertex. The position of the interaction point (IP) is not included in this vertex, as the small decay length associated with the Ξ_c^+ decays, though very short, is not completely negligible. The χ^2 of this vertex is required to be consistent with all the daughters having a common parent. Those combinations with a measured mass within 2 standard deviations of the nominal mass of the Ξ_c^+ [11] are then constrained to that mass and retained for further analysis. The resolution of the Ξ_c^+ signals depends on the decay mode and has a range of 3.2–15.0 MeV/c^2. In Fig. 1, we show the yield and signal-to-noise ratio of the reconstructed Ξ_c^+ candidates by plotting the "pull-mass", i.e., the difference in the reconstructed mass of the candidate and the nominal mass of the Ξ_c^+ divided by the resolution, for all the modes together. The candidates in this distribution have a requirement on the scaled momentum, $x_p=p^*c/\sqrt{s/4-M^2c^4}$ of $x_p>0.65$, where p^* is the momentum of the combination in the e^+e^- center-of-mass frame, s is the total center-of-mass energy squared, M is the invariant mass of the combination, and c is the speed of

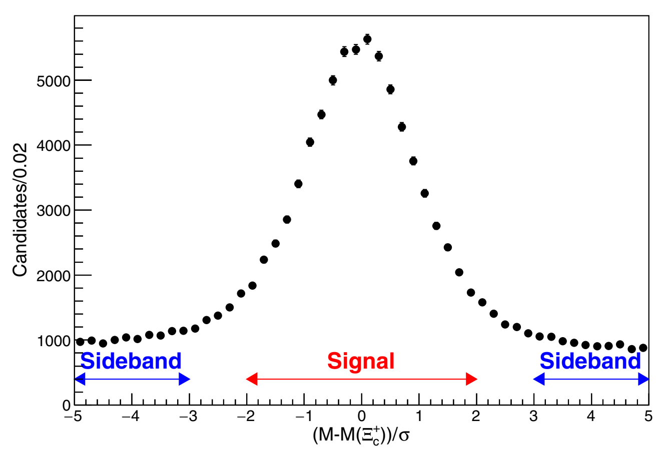

FIG. 1. The distribution of the "pull-mass", that is $(M_{\text{measured}}-M(\Xi_c^+))/\sigma$, for all reconstructed modes of Ξ_c^+ baryons. There is a requirement of $x_p>0.65$.

light. This requirement is not applied as part of the final analysis as we prefer to place an x_p cut requirement only on the $\Xi_c^+ K^-$ combinations; however, it serves to display the approximate signal-to-noise ratio of our reconstructed Ξ_c^+ baryons.

To investigate resonances decaying into $\Xi_c^+ K^-$, Ξ_c^+ candidates obtained as described above are combined with an appropriately charged kaon candidate not contributing to the reconstructed Ξ_c^+. The kaons used to make these combinations are identified using the same criteria as in the Ξ_c^+ reconstruction. That is, they are selected using the likelihood information from the tracking (SVD, CDC) and charged-hadron identification (CDC, ACC, TOF) systems into a combined likelihood, $\mathcal{L}(K{:}h) = \mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_h)$ where h is a proton or a pion, with requirements of $\mathcal{L}(K{:}p) > 0.6$ and $\mathcal{L}(K{:}\pi) > 0.6$. These requirements are approximately 93% efficient.

To optimize the mass resolution, a vertex constraint of the particles is made with the IP included. All decay modes of the Ξ_c^+ are considered together. We then place a requirement of $x_p > 0.75$ on the $\Xi_c^+ K^-$ combination. This requirement is typical for studies of orbitally excited charmed baryons as they are known to be produced with much higher average momenta than the combinatorial background.

Figure 2(a) shows the invariant mass distribution of the $\Xi_c^+ K^-$ combinations in the mass range of interest, which starts at the kinematic threshold. A fit is made to this spectrum, comprising six signal functions and a background threshold function of the form $A\sqrt{\Delta M} + B\Delta M$, where ΔM is the mass difference from threshold, and A and B are free parameters. Each of the signal functions is a Voigtian function (a Breit-Wigner function convolved with a Gaussian resolution). The masses and intrinsic widths of all six are fixed to the values found by LHCb [7]. The resolutions are obtained from Monte Carlo simulation, and vary from 0.72 MeV/c^2 for the lowest-mass peak to 1.96 MeV/c^2 for the high-mass wide resonance. We use an unbinned likelihoood fit. Figure 2(b) shows the same distribution for wrong-sign, i.e., $\Xi_c^+ K^+$ combinations. The

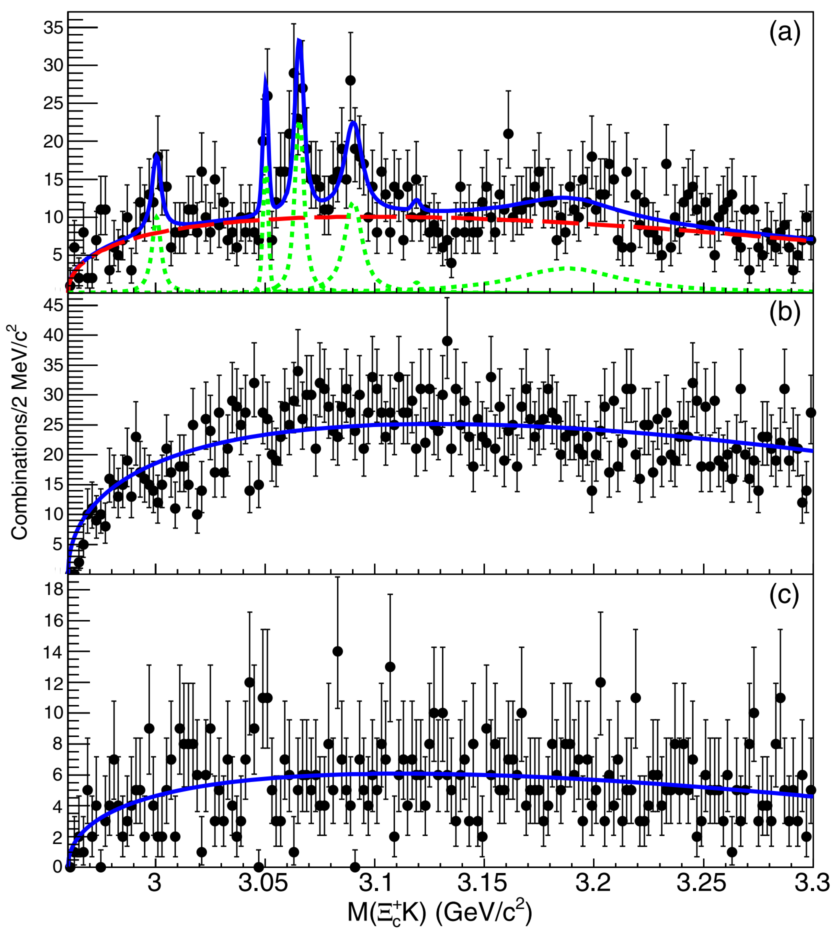

FIG. 2. (a) The $\Xi_c^+ K^-$ invariant mass distribution. The fit shown by the solid line is the sum of a threshold function (dashed line) and six Voigtian (Breit-Wigner convolved with Gaussian resolution) functions, with fixed masses, intrinsic widths and resolutions (dotted lines). (b) A threshold function fit to the $\Xi_c^+ K^+$ (wrong-sign) invariant mass distribution. (c) A threshold function fit to the invariant mass distribution for sidebands to the Ξ_c^+ candidates in combination with K^- candidates.

TABLE I. Yields of the six resonances, and comparison of the mass measurements to the LHCb values. In rows 4 and 5, the units are MeV/c^2. None of the mass measurements include the uncertainty in the ground-state Ξ_c^+ which is common to both experiments.

Ω_c Excited state	3000	3050	3066	3090	3119	3188
Yield	37.7 ± 11.0	28.2 ± 7.7	81.7 ± 13.9	86.6 ± 17.4	3.6 ± 6.9	135.2 ± 43.0
Significance	3.9σ	4.6σ	7.2σ	5.7σ	0.4σ	2.4σ
LHCb mass	$3000.4 \pm 0.2 \pm 0.1$	$3050.2 \pm 0.1 \pm 0.1$	$3065.5 \pm 0.1 \pm 0.3$	$3090.2 \pm 0.3 \pm 0.5$	$3119 \pm 0.3 \pm 0.9$	$3188 \pm 5 \pm 13$
Belle mass (with fixed Γ)	$3000.7 \pm 1.0 \pm 0.2$	$3050.2 \pm 0.4 \pm 0.2$	$3064.9 \pm 0.6 \pm 0.2$	$3089.3 \pm 1.2 \pm 0.2$	⋯	$3199 \pm 9 \pm 4$

background function, with floating values of A and B, fits well to this distribution. Figure 2(c) shows the same distribution using Ξ_c^+ candidates with reconstructed masses between three and five standard deviations from the canonical mass. Again, this sideband distribution shows no significant peaks, and the background function, with floating values of A and B, fits the distribution well.

Table I shows the yield for each of the five narrow resonances and the wide enhancement reported by LHCb. The significance of each signal is calculated by excluding that one peak from the fit, finding the change in the log-likelihood ($\Delta[\log(L)]$), and expressing the significance in terms of standard deviation using the formula $n_\sigma = \sqrt{2\Delta[\log(L)]}$. Systematic uncertainties are included by calculating the significances using a series of different fits and choosing the lowest resultant significance value. The differences in the fits considered are the use of different masses and widths within the uncertainties of the LHCb result, allowing the presence or not of an extra $C\Delta M^2$ term in the threshold function, changing the functions fitting the peaks from Voigtian functions to s-wave relativistic Breit-Wigner functions convolved with the resolution functions, and lastly adding or not extra functions representing possible feed-down from $\Omega_c(3066)$, $\Omega_c(3080)$ and $\Omega_c(3119)$ decays to $\Xi_c'^+ K^-$ as seen by LHCb, with shapes found by Monte Carlo simulation, and floating yields.

It is clear that these data unambiguously confirm the existence of the $\Omega_c(3066)$ and $\Omega_c(3090)$. Signals of reasonable significance are seen for the $\Omega_c(3000)$ and the $\Omega_c(3050)$, but no signal is apparent for the $\Omega_c(3119)$. We note that, for the four narrow signals seen, we find the ratio of yields with respect to LHCb to be ≈ 0.036. If this were also to hold for the $\Omega_c(3119)$, we would expect an $\Omega_c(3119)$ signal yield of ≈ 17, whereas we find 3.6 ± 6.9. Thus our nonobservation of this particle is not in disagreement with LHCb. There is an excess in the Belle data around 3.188 GeV/c^2, which may (as was the case in the LHCb data) be due to one or more particles.

We can measure the masses of the five confirmed signals, by fitting the same distribution without constraining the masses. In all cases, the masses we find are consistent with the LHCb values, as shown in Table I. The systematic uncertainty in the reconstruction of these masses is smaller than the statistical uncertainties. The uncertainty due to the knowledge of the momentum scale is less than 0.05 MeV/c^2, which is small compared with the other uncertainties. The systematic uncertainties in Table I are dominated by the variations of the measured masses when fitting with different values of the intrinsic widths as defined by the uncertainties in the LHCb measurements, and the use of different—yet reasonable—background functions in the fit as was done when calculating the significances of the signals. In addition to the uncertainties shown in Table I, there is an important systematic uncertainty of $(+0.3, -0.4)$ MeV/c^2 common to the Belle and LHCb mass measurements, due to the mass measurement of the ground state Ξ_c^+ [11].

Five states, each with one unit of orbital angular momentum between the diquark and the charm quark, are naturally predicted by the heavy-quark–light-diquark model of baryons [2]. Since the LHCb observation, there have been several theoretical interpretations of the five narrow states found [12–16], either in terms of these five states or by other configurations of the quarks. The wide state at higher mass appears to fit the pattern of wide states at around 500 MeV/c^2 above the ground-state charmed baryons (the $\Lambda_c^+(2765)$ and $\Xi_c^{+/0}(2970)$). A possible explanation is that they are the radial excitations of the ground state, with $J^P = \frac{1}{2}^+$.

To conclude, of the five narrow resonances observed in the $\Xi_c^+ K^-$ mass spectrum by LHCb, we strongly confirm the $\Omega_c(3066)$ and $\Omega_c(3090)$ with very similar parameters and confirm two more—the $\Omega_c(3000)$ and $\Omega_c(3050)$—with less significance, but cannot confirm the $\Omega_c(3119)$. In addition, we present indications that there is wide excess, consistent with that found by LHCb, at higher mass.

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, the National Institute of Informatics, and the PNNL/EMSL computing group for valuable computing and SINET5 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; Austrian Science Fund under Grant No. P 26794-N20; the National Natural Science Foundation of China under Contracts No. 10575109, No. 10775142, No. 10875115, No. 11175187, No. 11475187, No. 11521505 and No. 11575017; the Chinese Academy of Science Center for Excellence in Particle Physics; 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. 2014R1A2A2A01005286, No. 2015R1A2A2A01003280, No. 2015H1A2A1033649, No. 2016R1D1A1B01010135, No. 2016K1A3A7A09005603, No. 2016R1D1A1B02012900; Radiation Science Research Institute, Foreign Large-size Research Facility Application Supporting project and the Global Science Experimental Data Hub Center of the Korea Institute of Science and Technology Information; the Polish Ministry of Science and Higher Education and the National Science Center; the Ministry of Education and Science of the Russian Federation and the Russian Foundation for Basic Research; the Slovenian Research Agency; Ikerbasque, Basque Foundation for Science and MINECO (Juan de la Cierva), Spain; the Swiss National Science Foundation; the Ministry of Education and the Ministry of Science and Technology of Taiwan; and the U.S. Department of Energy and the National Science Foundation.

[1] Throughout this paper, the inclusion of the charge-conjugate mode decay is implied unless stated otherwise.

[2] D. Lichtenberg, Nuovo Cimento Soc. Ital. Fis. **28A**, 563 (1975).

[3] D. Ebert, R. Faustov, and V. Galkin, Phys. Rev. D **84**, 014025 (2011).

[4] B. Chen, K.-W. Wei, and A. Zhang, Eur. Phys. J. A **51**, 82 (2015).

[5] B. Aubert *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **97**, 232001 (2006).

[6] E. Solovieva *et al.* (Belle Collaboration), Phys. Lett. B **672**, 1 (2009).

[7] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **118**, 182001 (2017).

[8] A. Abashian *et al.* (Belle Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 117 (2002); see also detector section in J. Brodzicka *et al.*, Prog. Theor. Exp. Phys. **2012**, 4D001 (2012).

[9] S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods Phys. Res., Sect. A **499**, 1 (2003), and other papers included in this volume.

[10] J. Yelton *et al.* (Belle Collaboration), Phys. Rev. D **94**, 052011 (2016).

[11] C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C **40**, 100001 (2016). We use the "OUR FIT" values of $M(\Xi_c^+) = 2467.93^{+0.28}_{-0.40}$ MeV/c^2, and $M(\Xi_c^0) = 2470.85^{+0.28}_{-0.40}$ MeV/c^2.

[12] M. Karliner and J. Rosner, Phys. Rev. D **95**, 114012 (2017).

[13] K.-L. Wang, L.-Y. Xiao, X.-H. Zhong, and Q. Zhao, Phys. Rev. D **95**, 116010 (2017).

[14] W. Wang, Phys. Rev. D **96**, 014024 (2017).

[15] H. Y. Cheng and C.-W. Chiang, Phys. Rev. D **95**, 094018 (2017).

[16] Z.-G. Wang, Eur. Phys. J. C **77**, 325 (2017).