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Study of electromagnetic decays of orbitally excited Ξ_c baryons

J. Yelton,[9] I. Adachi,[19,15] J. K. Ahn,[43] H. Aihara,[88] S. Al Said,[81,40] D. M. Asner,[3] T. Aushev,[21] R. Ayad,[81] V. Babu,[8] S. Bahinipati,[25] P. Behera,[28] C. Beleño,[14] J. Bennett,[53] V. Bhardwaj,[24] B. Bhuyan,[26] T. Bilka,[5] J. Biswal,[36] G. Bonvicini,[93] A. Bozek,[63] M. Bračko,[50,36] T. E. Browder,[18] M. Campajola,[33,58] D. Červenkov,[5] M.-C. Chang,[10] P. Chang,[62] V. Chekelian,[51] A. Chen,[60] B. G. Cheon,[17] K. Chilikin,[45] K. Cho,[42] S.-J. Cho,[95] S.-K. Choi,[16] Y. Choi,[79] S. Choudhury,[27] D. Cinabro,[93] S. Cunliffe,[8] G. De Nardo,[33,58] F. Di Capua,[33,58] Z. Doležal,[5] T. V. Dong,[11] S. Eidelman,[4,66,45] D. Epifanov,[4,66] T. Ferber,[8] B. G. Fulsom,[68] R. Garg,[69] V. Gaur,[92] N. Gabyshev,[4,66] A. Garmash,[4,66] A. Giri,[27] P. Goldenzweig,[37] C. Hadjivasiliou,[68] O. Hartbrich,[18] K. Hayasaka,[65] H. Hayashii,[59] M. T. Hedges,[18] M. Hernandez Villanueva,[53] W.-S. Hou,[62] C.-L. Hsu,[80] T. Iijima,[57,56] K. Inami,[56] G. Inguglia,[31] A. Ishikawa,[19,15] R. Itoh,[19,15] M. Iwasaki,[67] Y. Iwasaki,[19] W. W. Jacobs,[29] S. Jia,[11] Y. Jin,[88] C. W. Joo,[38] K. K. Joo,[6] A. B. Kaliyar,[82] K. H. Kang,[44] G. Karyan,[8] Y. Kato,[56] T. Kawasaki,[41] H. Kichimi,[19] C. Kiesling,[51] B. H. Kim,[75] D. Y. Kim,[78] S. H. Kim,[75] Y.-K. Kim,[95] K. Kinoshita,[7] P. Kodyš,[5] S. Korpar,[50,36] D. Kotchetkov,[18] P. Križan,[46,36] R. Kroeger,[53] P. Krokovny,[4,66] R. Kulasiri,[39] R. Kumar,[72] K. Kumara,[93] A. Kuzmin,[4,66] Y.-J. Kwon,[95] K. Lalwani,[49] J. S. Lange,[12] S. C. Lee,[44] P. Lewis,[2] L. K. Li,[7] Y. B. Li,[70] L. Li Gioi,[51] J. Libby,[28] K. Lieret,[47] Z. Liptak,[18,*] D. Liventsev,[93,19] T. Luo,[11] C. MacQueen,[52] M. Masuda,[87,73] T. Matsuda,[54] D. Matvienko,[4,66,45] J. T. McNeil,[9] M. Merola,[33,58] K. Miyabayashi,[59] H. Miyata,[65] R. Mizuk,[45,21] G. B. Mohanty,[82] S. Mohanty,[82,91] T. J. Moon,[75] T. Mori,[56] M. Mrvar,[31] R. Mussa,[34] E. Nakano,[67] M. Nakao,[19,15] Z. Natkaniec,[63] A. Natochii,[18] M. Nayak,[84] N. K. Nisar,[3] S. Nishida,[19,15] K. Ogawa,[65] S. Ogawa,[85] H. Ono,[64,65] Y. Onuki,[88] P. Oskin,[45] P. Pakhlov,[45,55] G. Pakhlova,[21,45] S. Pardi,[33] H. Park,[44] S.-H. Park,[95] S. Patra,[24] S. Paul,[83,51] T. K. Pedlar,[48] R. Pestotnik,[36] L. E. Piilonen,[92] T. Podobnik,[46,36] V. Popov,[21] E. Prencipe,[22] M. T. Prim,[37] M. Ritter,[47] A. Rostomyan,[8] N. Rout,[28] G. Russo,[58] D. Sahoo,[82] Y. Sakai,[19,15] S. Sandilya,[7] L. Santelj,[46,36] T. Sanuki,[86] V. Savinov,[71] G. Schnell,[1,23] J. Schueler,[18] C. Schwanda,[31] Y. Seino,[65] K. Senyo,[94] M. E. Sevior,[52] M. Shapkin,[32] V. Shebalin,[18] C. P. Shen,[11] J.-G. Shiu,[62] B. Shwartz,[4,66] J. B. Singh,[69] A. Sokolov,[32] E. Solovieva,[45] M. Starič,[36] Z. S. Stottler,[92] J. F. Strube,[68] M. Sumihama,[13] K. Sumisawa,[19,15] T. Sumiyoshi,[90] W. Sutcliffe,[2] M. Takizawa,[76,20] U. Tamponi,[34] K. Tanida,[35] F. Tenchini,[8] M. Uchida,[89] T. Uglov,[45,21] Y. Unno,[17] S. Uno,[19,15] P. Urquijo,[52] Y. Usov,[4,66] S. E. Vahsen,[18] R. Van Tonder,[2] G. Varner,[18] A. Vinokurova,[4,66] V. Vorobyev,[4,66,45] E. Waheed,[19] C. H. Wang,[61] E. Wang,[71] M.-Z. Wang,[62] P. Wang,[30] X. L. Wang,[11] M. Watanabe,[65] E. Won,[43] X. Xu,[77] B. D. Yabsley,[80] W. Yan,[74] S. B. Yang,[43] H. Ye,[8] J. H. Yin,[43] Z. P. Zhang,[74] V. Zhilich,[4,66] V. Zhukova,[45] and V. Zhulanov[4,66]

(The Belle Collaboration)

[1]*University of the Basque Country UPV/EHU, 48080 Bilbao*
[2]*University of Bonn, 53115 Bonn*
[3]*Brookhaven National Laboratory, Upton, New York 11973*
[4]*Budker Institute of Nuclear Physics SB RAS, Novosibirsk 630090*
[5]*Faculty of Mathematics and Physics, Charles University, 121 16 Prague*
[6]*Chonnam National University, Gwangju 61186*
[7]*University of Cincinnati, Cincinnati, Ohio 45221*
[8]*Deutsches Elektronen–Synchrotron, 22607 Hamburg*
[9]*University of Florida, Gainesville, Florida 32611*
[10]*Department of Physics, Fu Jen Catholic University, Taipei 24205*
[11]*Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) and Institute of Modern Physics, Fudan University, Shanghai 200443*
[12]*Justus-Liebig-Universität Gießen, 35392 Gießen*
[13]*Gifu University, Gifu 501-1193*
[14]*II. Physikalisches Institut, Georg-August-Universität Göttingen, 37073 Göttingen*
[15]*SOKENDAI (The Graduate University for Advanced Studies), Hayama 240-0193*
[16]*Gyeongsang National University, Jinju 52828*
[17]*Department of Physics and Institute of Natural Sciences, Hanyang University, Seoul 04763*
[18]*University of Hawaii, Honolulu, Hawaii 96822*
[19]*High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801*
[20]*J-PARC Branch, KEK Theory Center, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801*
[21]*Higher School of Economics (HSE), Moscow 101000*
[22]*Forschungszentrum Jülich, 52425 Jülich*
[23]*IKERBASQUE, Basque Foundation for Science, 48013 Bilbao*

[24]Indian Institute of Science Education and Research Mohali, SAS Nagar, 140306
[25]Indian Institute of Technology Bhubaneswar, Satya Nagar 751007
[26]Indian Institute of Technology Guwahati, Assam 781039
[27]Indian Institute of Technology Hyderabad, Telangana 502285
[28]Indian Institute of Technology Madras, Chennai 600036
[29]Indiana University, Bloomington, Indiana 47408
[30]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049
[31]Institute of High Energy Physics, Vienna 1050
[32]Institute for High Energy Physics, Protvino 142281
[33]INFN—Sezione di Napoli, 80126 Napoli
[34]INFN—Sezione di Torino, 10125 Torino
[35]Advanced Science Research Center, Japan Atomic Energy Agency, Naka 319-1195
[36]J. Stefan Institute, 1000 Ljubljana
[37]Institut für Experimentelle Teilchenphysik, Karlsruher Institut für Technologie, 76131 Karlsruhe
[38]Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Kashiwa 277-8583
[39]Kennesaw State University, Kennesaw, Georgia 30144
[40]Department of Physics, Faculty of Science, King Abdulaziz University, Jeddah 21589
[41]Kitasato University, Sagamihara 252-0373
[42]Korea Institute of Science and Technology Information, Daejeon 34141
[43]Korea University, Seoul 02841
[44]Kyungpook National University, Daegu 41566
[45]P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow 119991
[46]Faculty of Mathematics and Physics, University of Ljubljana, 1000 Ljubljana
[47]Ludwig Maximilians University, 80539 Munich
[48]Luther College, Decorah, Iowa 52101
[49]Malaviya National Institute of Technology Jaipur, Jaipur 302017
[50]University of Maribor, 2000 Maribor
[51]Max-Planck-Institut für Physik, 80805 München
[52]School of Physics, University of Melbourne, Victoria 3010
[53]University of Mississippi, University, Mississippi 38677
[54]University of Miyazaki, Miyazaki 889-2192
[55]Moscow Physical Engineering Institute, Moscow 115409
[56]Graduate School of Science, Nagoya University, Nagoya 464-8602
[57]Kobayashi-Maskawa Institute, Nagoya University, Nagoya 464-8602
[58]Università di Napoli Federico II, 80126 Napoli
[59]Nara Women's University, Nara 630-8506
[60]National Central University, Chung-li 32054
[61]National United University, Miao Li 36003
[62]Department of Physics, National Taiwan University, Taipei 10617
[63]H. Niewodniczanski Institute of Nuclear Physics, Krakow 31-342
[64]Nippon Dental University, Niigata 951-8580
[65]Niigata University, Niigata 950-2181
[66]Novosibirsk State University, Novosibirsk 630090
[67]Osaka City University, Osaka 558-8585
[68]Pacific Northwest National Laboratory, Richland, Washington 99352
[69]Panjab University, Chandigarh 160014
[70]Peking University, Beijing 100871
[71]University of Pittsburgh, Pittsburgh, Pennsylvania 15260
[72]Punjab Agricultural University, Ludhiana 141004
[73]Research Center for Nuclear Physics, Osaka University, Osaka 567-0047
[74]Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei 230026
[75]Seoul National University, Seoul 08826
[76]Showa Pharmaceutical University, Tokyo 194-8543
[77]Soochow University, Suzhou 215006
[78]Soongsil University, Seoul 06978
[79]Sungkyunkwan University, Suwon 16419
[80]School of Physics, University of Sydney, New South Wales 2006
[81]Department of Physics, Faculty of Science, University of Tabuk, Tabuk 71451

[82]*Tata Institute of Fundamental Research, Mumbai 400005*
[83]*Department of Physics, Technische Universität München, 85748 Garching*
[84]*School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978*
[85]*Toho University, Funabashi 274-8510*
[86]*Department of Physics, Tohoku University, Sendai 980-8578*
[87]*Earthquake Research Institute, University of Tokyo, Tokyo 113-0032*
[88]*Department of Physics, University of Tokyo, Tokyo 113-0033*
[89]*Tokyo Institute of Technology, Tokyo 152-8550*
[90]*Tokyo Metropolitan University, Tokyo 192-0397*
[91]*Utkal University, Bhubaneswar 751004*
[92]*Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061*
[93]*Wayne State University, Detroit, Michigan 48202*
[94]*Yamagata University, Yamagata 990-8560*
[95]*Yonsei University, Seoul 03722*

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Using 980 fb^{-1} of data collected with the Belle detector operating at the KEKB asymmetric-energy e^+e^- collider, we report a study of the electromagnetic decays of excited charmed baryons $\Xi_c(2790)$ and $\Xi_c(2815)$. A clear signal (8.6 standard deviations) is observed for $\Xi_c(2815)^0 \to \Xi_c^0\gamma$, and we measure: $\frac{\mathcal{B}[\Xi_c(2815)^0 \to \Xi_c^0\gamma]}{\mathcal{B}[\Xi_c(2815)^0 \to \Xi_c(2645)^+\pi^- \to \Xi_c^0\pi^+\pi^-]} = 0.41 \pm 0.05 \pm 0.03$. We also present evidence (3.8 standard deviations) for the similar decay of the $\Xi_c(2790)^0$ and measure: $\frac{\mathcal{B}[\Xi_c(2790)^0 \to \Xi_c^0\gamma]}{\mathcal{B}[\Xi_c(2790)^0 \to \Xi_c'^+\pi^- \to \Xi_c^+\gamma\pi^-]} = 0.13 \pm 0.03 \pm 0.02$. The first quoted uncertainties are statistical and the second systematic. We find no hint of the analogous decays of the $\Xi_c(2815)^+$ and $\Xi_c(2790)^+$ baryons and set upper limits at the 90% confidence level of: $\frac{\mathcal{B}[\Xi_c(2815)^+ \to \Xi_c^+\gamma]}{\mathcal{B}[\Xi_c(2815)^+ \to \Xi_c(2645)^0\pi^+ \to \Xi_c^+\pi^-\pi^+]} < 0.09$, and $\frac{\mathcal{B}[\Xi_c(2790)^+ \to \Xi_c^+\gamma]}{\mathcal{B}[\Xi_c(2790)^+ \to \Xi_c'^0\pi^+ \to \Xi_c^0\gamma\pi^+]} < 0.06$. Approximate values of the partial widths of the decays are extracted, which can be used to discriminate between models of the underlying quark structure of these excited states.

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The Ξ_c baryons comprise csu or csd quark combinations [1]. Many excited states of these baryons have been observed and studied [2]. In particular, a recent study [3] reported measurements of the masses and widths of the $\Xi_c(2790)^{+/0}$ and $\Xi_c(2815)^{+/0}$ states. In the picture of a charmed baryon comprising a heavy (c) quark and a light (su or sd) diquark, these states are typically interpreted as $L = 1$ orbital excitations of the ground states where the unit of angular momentum is between the charm quark and a spin-0 light diquark system [4–8]. Such excitations are denoted λ excitations. In this model, the $\Xi_c(2790)$ is the $J^P = \frac{1}{2}^-$ state and the $\Xi_c(2815)$ the $J^P = \frac{3}{2}^-$ state, and the particles recently observed at higher masses by LHCb [9] are part of the expected family of corresponding states with a spin-1 diquark. These identifications are not made by direct measurement of the spin and parity of the states, rather by inspection of their mass spectra and observed decay modes; clearly other interpretations are possible [10].

In general, the decays of excited charmed baryons proceed via strong interactions, with the only electromagnetic decays observed so far being $\Xi_c' \to \Xi_c\gamma$ [3,11] and $\Omega_c(2770) \to \Omega_c\gamma$ [12,13], since for these transitions the mass difference is not sufficient for a strong decay. However, some predictions for the partial widths of photon transitions indicate that they could be observable. In particular, one theoretical treatment by Wang, Yao, Zhong, and Zhao (WYZZ) [14] predicts a partial width of $263\ \mathrm{keV}/c^2$ for the decay $\Xi_c(2790)^0 \to \Xi_c^0\gamma$ and $292\ \mathrm{keV}/c^2$ for $\Xi_c(2815)^0 \to \Xi_c^0\gamma$, assuming that they are λ excitations. On the other hand, the analogous decays for the Ξ_c^+ baryons are predicted to have very small partial widths. The same model predicts widths of $< 10\ \mathrm{keV}/c^2$ if the unit of orbital excitation is between the two light quarks (a "ρ excitation"). Other models make different predictions [15]; in particular, a treatment of the $\Xi_c(2790)$ isodoublet as dynamically generated baryons predicts large partial widths for both charge states [16]. These predictions are summarized in Table I.

In this paper, we present a search for the electromagnetic decays $\Xi_c(2790, 2815)^{+/0} \to \Xi_c^{+/0}\gamma$. The results are converted to branching ratios and, with certain assumptions,

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[*] Now at Hiroshima University.

TABLE I. Theoretical predictions of the partial widths in keV/c^2 for the $\Xi_c(2790)$ and $\Xi_c(2815)$. There are three predictions from WYZZ [14] as they model one λ and two ρ excitation states for each overall J^P. The experimental measurements of the total widths are also listed.

Mode	WYZZ [14]			IKLR [15]	GJR [16]	Actual total width [3]
	λ excitation	ρ excitation	ρ excitation	λ excitation	dynamically generated states	
$\Xi_c(2790)^+ \to \Xi_c^+\gamma$	4.65	1.39	0.79	…	246	$8900 \pm 600 \pm 800$
$\Xi_c(2790)^0 \to \Xi_c^0\gamma$	263	5.57	3.00	…	117	$10000 \pm 700 \pm 800$
$\Xi_c(2815)^+ \to \Xi_c^+\gamma$	2.8	1.88	2.81	190 ± 5	…	$2430 \pm 200 \pm 170$
$\Xi_c(2815)^0 \to \Xi_c^0\gamma$	292	7.50	11.2	497 ± 14	…	$2540 \pm 180 \pm 170$

to estimates of the partial widths for these decays. These estimates can then be compared to the theoretical models and thus probe the inner structure of these heavy baryons.

The Belle detector [17] was a large-solid-angle spectrometer operating at the KEKB asymmetric-energy e^+e^- collider [18], comprising six subdetectors: the tracking system composed of the silicon vertex detector and the 50-layer central drift chamber, the aerogel Cherenkov counter, the time-of-flight scintillation counter, the electromagnetic calorimeter, and the K_L^0 and muon detector. A superconducting solenoid produced a 1.5 T magnetic field throughout the first five of these subdetectors. Two inner detector configurations were used. The first consisted of a 3-layer silicon vertex detector and a 2.0 cm radius beampipe, and the second of a 4-layer silicon detector and a small-cell inner drift chamber around a 1.5 cm radius beampipe.

In order to study Ξ_c baryons, we first reconstruct a large sample of ground-state Ξ_c^0 and Ξ_c^+ baryons with good signal-to-noise ratio. To obtain large statistics, we use ten decay modes of the Ξ_c^0, and seven of the Ξ_c^+ ground states, as used in Ref. [3]. The decays are reconstructed from combinations of charged particles measured using the tracking system, and neutral particles measured in the electromagnetic calorimeter. The decays of long-lived mesons and hyperons are measured using secondary and tertiary vertex reconstruction. Each mode has specific requirements on its decay products designed to suppress combinatorial backgrounds, and we follow the selection criteria described in detail in our previous publication [3], except for the requirement on the momentum of the Ξ_c in the center-of-mass frame, p^*, which is set as $p^* > 2.25$ GeV/c, a choice which is described below. To show the yield of the reconstructed Ξ_c^0 and Ξ_c^+ baryons, we present in Fig. 1 the distributions of "pull mass" i.e., the difference between the measured and nominal mass (2470.91 MeV/c^2 and 2467.93 MeV/c^2 for the Ξ_c^0 and Ξ_c^+, respectively [2]), divided by the resolution (σ), which is found mode-by-mode and is $\sim$5 MeV/c^2. Ξ_c candidates are selected if they are within $\pm 2\sigma$ of the nominal mass. For Ξ_c^+, the number of selected candidates is 79 k above a background of 61 k, and for Ξ_c^0 142 k signal candidates with a background of 154 k.

To optimize the requirements specific to this analysis, a simulated data set is constructed using the combination of the decays under study and generic e^+e^- hadronic events. In addition to the $p^* > 2.25$ GeV/c requirement on the Ξ_c momentum, the following three selection criteria are determined by maximizing the signal significance in the sample. First, the photon energy is required to be greater than 550 MeV. Second, the sum of the energy deposited in the central nine cells of a 5×5 cell photon cluster is required to be at least 94% of the total energy of the cluster. Third, to discriminate against photons that are π^0 daughters, each photon is combined with each other photon candidate in the event and the pair is rejected if the likelihood of it being part of a π^0 is larger than 0.5. These likelihoods are determined from Monte Carlo (MC) studies [19] and are a function of the energy of the other photon, its polar angle, and the mass

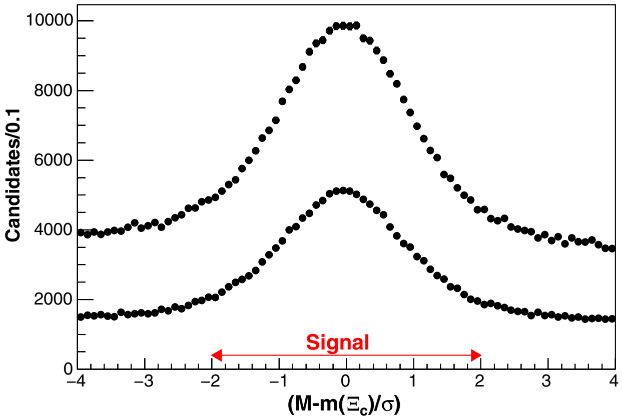

FIG. 1. Pull mass distribution for the Ξ_c^0 (upper data points), and Ξ_c^+ (lower data points) candidates.

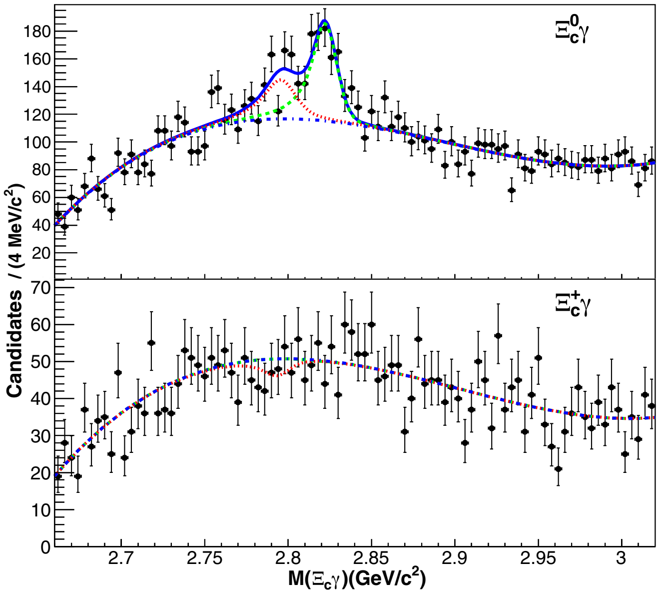

FIG. 2. The $\Xi_c\gamma$ mass distributions for (upper) Ξ_c^0 and (lower) Ξ_c^+. The fits are described in the text. In addition to the total fitted yields, the fitted $\Xi_c(2815)$ signal components (dotted lines, green) and $\Xi_c(2790)$ components (dashed lines, red) are shown stacked above the combinatorial background (dot-dashed lines, blue).

of the two-photon system. This last requirement retains 87% of the signal according to Monte Carlo studies, while eliminating 42% of the background.

Figure 2 shows the $\Xi_c\gamma$ invariant-mass distributions for the charged and neutral Ξ_c baryons. We fit a sum of a polynomial and two signal functions to the distributions using a binned maximum-likelihood fit with fine mass bins. In each case, the signal is a Breit-Wigner function convolved with a "Crystal Ball" function [20] to represent the detector resolution. The parameters of the latter function are found with a GEANT-based MC simulation [21] to model the response of the detector. The photon energies in the simulation are corrected to take into account the data-MC difference of resolution based on studies of mass resolution in the decays $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, and $D^{*0} \to D^0\gamma$ [22,23]. The masses and widths of the four particles under consideration have been precisely measured in our previous analysis [3] and are thus fixed to the values reported. The width of the resolution functions are $\sim 6.5\ \mathrm{MeV}/c^2$ with an estimated systematic uncertainty of 3%, so in each distribution the two signal functions overlap. In each case a third-order polynomial is used to describe the combinatorial background. There is a clear signal for the decay $\Xi_c(2815)^0 \to \Xi_c^0\gamma$ with 401 ± 45 events and evidence for the decay $\Xi_c(2790)^0 \to \Xi_c^0\gamma$ with 222 ± 55 events. The statistical significance of each signal is calculated by excluding the respective peak from the fit and finding the change in the log-likelihood ($\Delta[\ln L]$). The significance is expressed in terms of standard deviations, n_σ, using the formula $n_\sigma = \sqrt{2\Delta[\ln L]}$. For the decays $\Xi_c(2815)^0 \to \Xi_c^0\gamma$ and $\Xi_c(2790)^0 \to \Xi_c^0\gamma$ we find $n_\sigma =$ 9.7 and 4.0, respectively. No signals are present in the $\Xi_c^+\gamma$ mass distribution, and the fit yields are 0 ± 25 and -32 ± 31 decays of $\Xi_c(2815)^+$ and $\Xi_c(2790)^+$ baryons, respectively. In order to find upper-limit signal yields from these decays, we use a second-order polynomial as the background function, as its reduced χ^2 is satisfactory, and this produces a more conservative limit. We calculate the upper limits by integrating the likelihood functions obtained from the fits, and then finding the yield values for which the integrals contain 90% of the total integral of positive yields. (That is, we set a Bayesian upper limit using a uniform prior on the yield). We find 90% confidence level limits of 56 and 64 events for the decays of the $\Xi_c^+(2815)$ and $\Xi_c^+(2790)$, respectively.

The masses and widths of the excited Ξ_c states are very well known and their uncertainties have negligible effect on these yields. For the two significant signals, the largest systematic uncertainty is due to uncertainties in the background shape, evaluated by noting the change in the yield found when increasing the order of the Chebychev polynomial used for the background function (5%); decreasing the order of the polynomial produces an unsatisfactory fit result and so is not used. Taking into account this systematic uncertainty, we find the significances of the signals for $\Xi_c(2815)^0 \to \Xi_c^0\gamma$ and $\Xi_c^0(2790) \to \Xi^0\gamma$ to be $n_\sigma = 8.6$ and 3.8, respectively.

To measure branching ratios

$$R_{2815} = \frac{\mathcal{B}[\Xi_c(2815)^{+/0} \to \Xi_c^{+/0}\gamma]}{\mathcal{B}[\Xi_c(2815)^{+/0} \to \Xi_c(2645)^{0/+}\pi^{+/-} \to \Xi_c^{+/0}\pi^+\pi^-]} \quad \text{and} \quad R_{2790} = \frac{\mathcal{B}[\Xi_c(2790)^{+/0} \to \Xi_c^{+/0}\gamma]}{\mathcal{B}[\Xi_c(2790)^{+/0} \to \Xi_c'^{0/+}\pi^{+/-} \to \Xi_c^{0/+}\gamma\pi^{+/-}]},$$

we reconstruct the normalization modes following the technique presented in the previous Belle paper [3], but using the momentum requirement on the daughter Ξ_c baryons of $p^* > 2.25\ \mathrm{GeV}/c$. The invariant-mass distributions for the normalization modes are shown in Fig. 3, and the yields for the signals listed in Table II. For the measurement of R_{2815}, the largest systematic uncertainty is due to the signal-yield extraction of the electromagnetic decays as detailed above. In addition, there are small contributions due to the efficiency estimation of the photon (3%) [22], uncertainties due to the modeling of the relative contributions of the different submodes (3%), the resolution

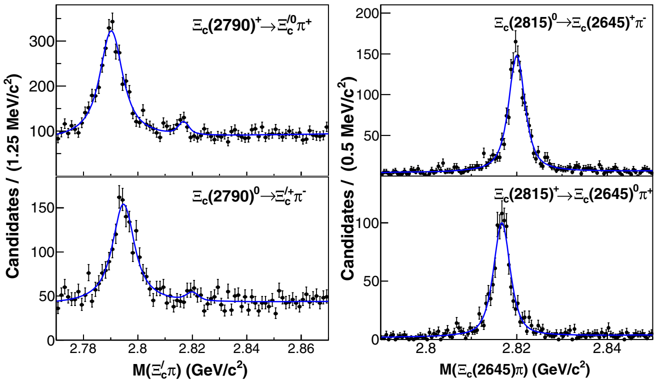

FIG. 3. The signals used as normalization modes in the analysis.

of the $\Xi_c\gamma$ mass distribution (2%), the uncertainty in the tracking efficiency (2%), the fitting of the normalization mode (1%), and uncertainties due to the Monte Carlo statistics used to evaluate efficiencies (1%). For the neutral mode, we find a value of $R_{2815} = 0.41 \pm 0.05 \pm 0.03$. For the charged mode, where no signal is observed, we set a limit at 90% confidence level of $R_{2815} < 0.09$.

The calculation of the R_{2790} branching ratios has the complication that the signal and normalization modes involve decays into different ground-state charmed baryons. Our determination of the relative reconstruction efficiency of the Ξ_c^0 with respect to the Ξ_c^+ depends on the relative production rate of the two states in the Belle dataset, which is not well known. We make the assumption that the production of Ξ_c^0 and Ξ_c^+ with $p^* > 2.25$ GeV$/c$ is equal, which would be the case with exact isospin symmetry between the u and d quarks. Deviations from this equality can occur if the probability of creating an su or an sd diquark in the fragmentation process is different. In addition, the decays from excited particles will not exactly preserve isospin symmetry because of the isospin mass splitting of several MeV$/c^2$ that has been measured in Ξ_c ground states and some excited states [2], and also is present in π mesons. We estimate the systematic uncertainty associated with the equality assumption to be ±15%; this is larger than the asymmetry observed in the Σ_c^{++}/Σ_c^0 system [24].

TABLE II. Yields of the normalization modes found from fits to the distributions shown in Fig. 3. In all cases, there is a requirement on the momentum of the ground-state charmed baryon of $p^* > 2.25$ GeV$/c$.

Decay	Yield
$\Xi_c(2790)^+ \to \Xi_c'^0\pi^+ \to \Xi_c^0\gamma\pi^+$	2591 ± 140
$\Xi_c(2790)^0 \to \Xi_c'^+\pi^- \to \Xi_c^+\gamma\pi^-$	1231 ± 87
$\Xi_c(2815)^0 \to \Xi_c(2645)^+\pi^- \to \Xi_c^0\pi^+\pi^-$	1646 ± 50
$\Xi_c(2815)^+ \to \Xi_c(2645)^0\pi^+ \to \Xi_c^+\pi^-\pi^+$	1121 ± 40

We find $R_{2790} = 0.13 \pm 0.03 \pm 0.02$ for the decay of the $\Xi_c(2790)^0$. For the decay of the Ξ_c^+ we set a limit at 90% confidence level of $R_{2790} < 0.06$.

We cannot directly measure the partial widths of the decay modes under consideration. However, we can use our branching ratio measurements, together with the already measured total widths [3], to make estimates of the partial widths which can then be compared with theory. For the case of $\Xi_c(2815) \to \Xi_c(2645)\pi \to \Xi_c\pi\pi$ we calculate, using Clebsch-Gordan coefficients and phase space, that the charged-pion decays account for $(38 \pm 4)\%$ of the total rate of this decay chain, where the rest of the decays include π^0 transitions. The uncertainty in this number takes into account the mass and width uncertainties of the excited states, and is an estimate as none of the π^0 transitions have been observed and isospin is not an exact symmetry. Taking into account the decays $\Xi_c(2815) \to \Xi_c'\pi$ measured previously [3], the width of the electromagnetic decay is observed to be $(13.6 \pm 1.5 \pm 1.7)\%$ of the total width, where the first uncertainty is statistical, and the second is systematic. There is an additional possibility that other decays exist that we do not detect. These include possible single-pion decays from the orbitally excited states to the ground state, double-pion decays that do not go through an intermediate resonance, and transitions that involve electromagnetic decays to or from intermediate states. None of these are expected to be large, and we can estimate that they will produce a reduction of the calculated partial width of no more than 20%. Based on these considerations, we estimate a partial width of $\Gamma[\Xi_c(2815)^0 \to \Xi_c^0\gamma] = 320 \pm 45^{+45}_{-80}$ keV$/c^2$. For the decays of the $\Xi_c(2815)^+$ we use similar arguments to find $\Gamma[\Xi_c(2815)^+ \to \Xi_c^+\gamma] < 80$ keV$/c^2$.

For the $\Xi_c(2790)^0$ we find that a similar calculation leads to $(7.9 \pm 2.0^{+1.7}_{-2.3})\%$ of the total width being due to the electromagnetic decay, implying a partial width of $\Gamma[\Xi_c(2790)^0 \to \Xi_c^0\gamma] \sim 800$ keV$/c^2$ with an uncertainty of around 40%. Similarly, for the decay $\Xi_c(2790)^+ \to \Xi_c^+\gamma$, for which no signal is found, the upper limit on the partial width is set at 350 keV$/c^2$.

The difference between the decays of the neutral and charged $\Xi_c(2815)$ states is clear, and these results are in good agreement with the prediction that was based on an identification of the $\Xi_c(2815)$ as λ orbital excitations of the ground-state baryons [14]. For the $\Xi_c(2790)$ decays, the data are much less precise. Still, the evidence for the decay of the neutral $\Xi_c(2790)$ and the absence of evidence for its isospin partner is consistent with these predictions.

To conclude, we report the first observation of an electromagnetic decay of an orbitally excited charmed baryon, and measure the branching ratio $\frac{\mathcal{B}[\Xi_c(2815)^0 \to \Xi_c^0\gamma]}{\mathcal{B}[\Xi_c(2815)^0 \to \Xi_c(2645)^+\pi^- \to \Xi_c^0\pi^+\pi^-]} = 0.41 \pm 0.05 \pm 0.03$. We also present evidence for the similar decay of the $\Xi_c^0(2790)$ and measure $\frac{\mathcal{B}[\Xi_c(2790)^0 \to \Xi_c^0\gamma]}{\mathcal{B}[\Xi_c(2790)^0 \to \Xi_c'^+\pi^- \to \Xi_c^+\gamma\pi^-]} = 0.13 \pm 0.03 \pm 0.02$.

We find no evidence of the analogous decays of the $\Xi_c(2815)^+$ and $\Xi_c(2790)^+$ baryons. Using reasonable estimates of the unseen decays, we conclude that the partial widths of the electromagnetic decays of the $\Xi_c(2815)^0$ and $\Xi_c(2790)^0$ into the ground states are $320 \pm 45^{+45}_{-80}$ keV$/c^2$ and ~800 keV$/c^2$, respectively. The partial widths for the similar decays of the $\Xi_c(2815)^+$ and $\Xi_c(2790)^+$ are less than 80 keV$/c^2$ and less than 350 keV$/c^2$, respectively. These results are consistent with predictions based on the identification of the $\Xi_c(2815)$ and $\Xi_c(2790)$ baryons as orbital excitations of the Ξ_c baryons, where the unit of orbital excitation is between the heavy quark and the spin-0 light diquark system.

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