Study of Electromagnetic Decays of Orbitally Excited $\Xi_c$ Baryons

J. Yelton,9 I. Adachi,19, 15 J. K. Ahn,44 H. Aihara,89 S. Al Said,82, 41 D. M. Asner,3 T. Aushev,21 R. Ayad,82 V. Babu,8 S. Bahinipati,26 P. Behera,29 C. Belelo,14 J. Bennett,54 V. Bhardwaj,25 B. Bhuyan,27 T. Bilka,5 J. Biswal,37 G. Bonvicini,94 A. Bozek,64 M. Bračko,51, 37 T. E. Browder,18 M. Campajola,34, 59 D. Červenkov,5 M.-C. Chang,10 P. Chang,63 V. Chekelian,52 A. Chen,61 B. G. Cheon,17 K. Chilikin,46 K. Cho,43 S.-J. Cho,96 S.-K. Choi,16 Y. Choi,60 S. Choudhury,58 D. Cinabro,94 S. Cunliffe,8 G. De Nardo,34, 59 F. Di Capua,34, 59 Z. Doležal,5 T. V. Dong,11 S. Eidelman,4, 67, 46 D. Epifanov,4, 67 T. Ferber,8 B. G. Fulsom,69 R. Garg,20 V. Gaur,93 N. Gabyshev,4, 67 A. Garmash,4, 67 A. Giri,28 P. Goldenzwieg,38 C. Hadjivasiliou,69 O. Hartbrich,18 K. Hayasaka,66 H. Hayashi,60 M. T. Hedges,18 M. Hernandez Villanueva,54 W.-S. Hou,63 C.-L. Hsu,81 T. Iijima,58, 57 K. Inami,57 G. Inguglia,32 A. Ishikawa,19, 15 R. Itoh,19, 15 M. Iwasaki,68 Y. Iwasaki,19 W. W. Jacobs,50 S. Jia,11 Y. Jia,89 C. W. Joo,39 K. K. Joo,6 A. B. Kaliyar,83 K. H. Kang,45 G. Karyan,8 Y. Kato,57 T. Kawasugi,42 H. Kichimi,19 C. Kiesling,52 B. H. Kim,76 D. Y. Kim,79 S. H. Kim,76 Y.-K. Kim,96 K. Kinoshita,7 P. Kodys,5 S. Korpar,51, 37 D. Kotchetkov,18 P. Križan,47, 37 R. Kroeger,54 P. Krokovny,4, 67 R. Kulacir,46 R. Kumar,73 K. Kumara,94 A. Kuzmin,4, 67 Y.-J. Kwon,96 K. Lalwani,50 J. S. Lange,12 J. S. Lange,45 P. Lewis,2 L. K. Li,7 Y. B. Li,71 L. Li Gioi,52 J. J. Libby,29 K. Lieret,48 Z. Lipptak,18 D. Liventsev,94 T. Luo,11 C. MacQueen,53 M. Masuda,88, 74 T. Matsuda,55 D. Matvienko,4, 67, 46 J. T. McNeil,9 M. Merola,34, 59 K. Miyabayashi,60 H. Miyata,66 R. Mizuk,46, 21 G. B. Mohanty,83 S. Mohanty,83, 92 T. J. Moon,76 T. Mor,57 M. Mrvar,32 R. Mussa,35 E. Nakano,68 M. Nakao,19, 15 Z. Natkaniec,64 A. Natochich,18 M. Nayak,85 N. K. Nisar,3 S. Nishida,19, 15 K. Ogawa,66 S. Ogawa,66 H. Ono,65, 66 Y. Onuki,89 P. Oskin,46 P. Pakhlov,46, 56 G. Pakhlova,21, 46 S. Pardi,34 H. Park,45 S.-H. Park,96 S. Patra,25 S. Paul,84, 52 T. K. Pedlar,49 R. Pestotnik,37 L. E. Piilonen,93 T. Podobnik,47, 37 V. Popov,21 E. Precice,22 M. T. Prim,38 M. Ritter,48 A. Rostomyan,8 N. Rout,29 G. Russo,59 D. Sawo,83 Y. Sakai,19, 15 S. Sandilya,7 L. Sanel,47, 37 T. Sanuki,87 V. Savinov,72 G. Schnell,1, 24 J. Schueller,18 C. Schwanda,32 Y. Seino,96 K. Senyo,85 M. E. Sevior,53 M. Shapkin,33 V. Shebalin,18 C. P. Shen,31 J.-G. Shiu,63 B. Shwartz,4, 67 J. B. Singh,79 A. Sokolov,33 E. Solovieva,46 M. Staric,37 Z. S. Stottler,93 J. F. Strube,69 M. Sumihama,13 K. Sumisawa,19, 15 T. Sumiyoshi,91 W. Tschirrle,2 M. Takizawa,77, 20 U. Tamponi,35 K. Tanida,36 F. Tenchini,8 M. Uchida,90 T. Uglow,46, 21 Y. Unno,17 S. Uno,19, 15 P. Urquijo,53 Y. Usov,46, 67 S. E. Vahsen,18 R. Van Tonger,2 G. Varner,18 A. Vinokurova,4, 67 V. Vorobyev,4, 67 E. Waheed,19 C. H. Wang,62 E. Wang,72 M.-Z. Wang,63 P. Wang,31 X. L. Wang,11 M. Watanabe,66 E. Won,44 X. Xu,78 B. D. Yabsley,81 W. Yan,75 S. B. Yang,44 H. Ye,8 J. H. Yin,44 Z. P. Zhang,75 V. Zhihich,4, 67 V. Zhukova,46 and V. Zhulanov,46, 67 (The Collaboration)

1University of the Basque Country UPV/EHU, 48080 Bilbao
2University of Bonn, 53115 Bonn
3Brookhaven National Laboratory, Upton, New York 11973
4Budker Institute of Nuclear Physics SB RAS, Novosibirsk 630090
5Faculty of Mathematics and Physics, Charles University, 121 16 Prague
6Chonnam National University, Gwangju 61186
7University of Cincinnati, Cincinnati, Ohio 45221
8Deutsches Elektronen–Synchrontron, 22607 Hamburg
9University of Florida, Gainesville, Florida 32611
10Department of Physics, Fu Jen Catholic University, Taipei 24205
11Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) and Institute of Modern Physics, Fudan University, Shanghai 200443
12Justus-Liebig-Universität Gießen, 35392 Gießen
13Gifu University, Gifu 501-1193
14II. Physikalisches Institut, Georg-August-Universität Göttingen, 37073 Göttingen
15SOKENDAI (The Graduate University for Advanced Studies), Hayama 240-0193
16Gyeongsang National University, Jinju 52828
17Department of Physics and Institute of Natural Sciences, Hangang University, Seoul 04763
18University of Hawaii, Honolulu, Hawaii 96822
19High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801
20J-PARC Branch, KEK Theory Center, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801
21Higher School of Economics (HSE), Moscow 101000
22 Forschungszentrum Jülich, 52425 Jülich
23 Hiroshima Institute of Technology, Hiroshima 731-5193
24 IKERBASQUE, Basque Foundation for Science, 48013 Bilbao
25 Indian Institute of Science Education and Research Mohali, SAS Nagar, 140306
26 Indian Institute of Technology Bhubaneswar, Satya Nagar 751007
27 Indian Institute of Technology Guwahati, Assam 781039
28 Indian Institute of Technology Hyderabad, Telangana 502285
29 Indian Institute of Technology Madras, Chennai 600036
30 Indiana University, Bloomington, Indiana 47408
31 Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049
32 Institute of High Energy Physics, Vienna 1050
33 Institute for High Energy Physics, Protvino 142281
34 INFN - Sezione di Napoli, 80126 Napoli
35 INFN - Sezione di Torino, 10125 Torino
36 Advanced Science Research Center, Japan Atomic Energy Agency, Naka 319-1195
37 J. Stefan Institute, 1000 Ljubljana
38 Institut für Experimentelle Teilchenphysik, Karlsruher Institut für Technologie, 76131 Karlsruhe
39 Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Kashiwa 277-8583
40 Kennesaw State University, Kennesaw, Georgia 30144
41 Department of Physics, Faculty of Science, King Abdulaziz University, Jeddah 21589
42 Kitasato University, Sagamihara 252-0373
43 Korea Institute of Science and Technology Information, Daejeon 34141
44 Korea University, Seoul 02841
45 Kyungpook National University, Daegu 41566
46 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow 119991
47 Faculty of Mathematics and Physics, University of Ljubljana, 1000 Ljubljana
48 Ludwig Maximilians University, 80539 Munich
49 Luther College, Decorah, Iowa 52101
50 Malaviya National Institute of Technology Jaipur, Jaipur 302017
51 University of Maribor, 2000 Maribor
52 Max-Planck-Institut für Physik, 80805 München
53 School of Physics, University of Melbourne, Victoria 3010
54 University of Mississippi, University, Mississippi 38677
55 University of Miyazaki, Miyazaki 889-2192
56 Moscow Physical Engineering Institute, Moscow 115409
57 Graduate School of Science, Nagoya University, Nagoya 464-8602
58 Kobayashi-Maskawa Institute, Nagoya University, Nagoya 464-8602
59 Università di Napoli Federico II, 80126 Napoli
60 Nara Women’s University, Nara 630-8506
61 National Central University, Chung-li 32054
62 National United University, Miaoli 36003
63 Department of Physics, National Taiwan University, Taipei 10617
64 H. Niewodniczanski Institute of Nuclear Physics, Krakow 31-342
65 Nippon Dental University, Niigata 951-8580
66 Niigata University, Niigata 950-2181
67 Novosibirsk State University, Novosibirsk 630090
68 Osaka City University, Osaka 558-8585
69 Pacific Northwest National Laboratory, Richland, Washington 99352
70 Panjab University, Chandigarh 160014
71 Peking University, Beijing 100871
72 University of Pittsburgh, Pittsburgh, Pennsylvania 15260
73 Panjab Agricultural University, Ludhiana 141004
74 Research Center for Nuclear Physics, Osaka University, Osaka 567-0047
75 Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei 230026
76 Seoul National University, Seoul 08826
77 Showa Pharmaceutical University, Tokyo 194-8543
78 Soochow University, Suzhou 215006
79 Soongsil University, Seoul 06978
80 Sungkyunkwan University, Suwon 16419
81 School of Physics, University of Sydney, New South Wales 2006
82 Department of Physics, Faculty of Science, University of Tabuk, Tabuk 71451
83 Tata Institute of Fundamental Research, Mumbai 400005
84 Department of Physics, Technische Universität München, 85748 Garching
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 \(\Xi_c(2815)^0 \rightarrow \Xi_c^0\gamma\), and we measure:

\[
\frac{B(\Xi_c(2815)^0 \rightarrow \Xi_c^0\gamma)}{B(\Xi_c(2815)^0 \rightarrow \Xi_c(2645)^+\pi^- \rightarrow \Xi_c^0\pi^+\pi^-)} = 0.41 \pm 0.05 \pm 0.03.
\]

We also present evidence (3.8 standard deviations) for the similar decay of the \(\Xi_c(2790)^0\) and measure:

\[
\frac{B(\Xi_c(2790)^0 \rightarrow \Xi_c^0\gamma)}{B(\Xi_c(2790)^0 \rightarrow \Xi_c^0\pi^+ \rightarrow \Xi_c^0\pi^+\pi^-)} = 0.13 \pm 0.03 \pm 0.02.
\]

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:

\[
\frac{B(\Xi_c(2815)^+ \rightarrow \Xi_c(2645)^+\pi^- \rightarrow \Xi_c^0\pi^+\pi^-)}{B(\Xi_c(2790)^+ \rightarrow \Xi_c^0\pi^+ \rightarrow \Xi_c^0\pi^+\pi^-)} < 0.09, \quad \frac{B(\Xi_c(2815)^+ \rightarrow \Xi_c^0\gamma)}{B(\Xi_c(2790)^+ \rightarrow \Xi_c^0\gamma)} < 0.06.
\]

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.

The \(\Xi_c\) baryons comprise \(csu\) or \(csd\) quark combinations. Many excited states of these baryons have been observed and studied. In particular, a recent study 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. Such excitations are denoted \(\lambda\) 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 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.

In general, the decays of excited charmed baryons proceed via strong interactions, with the only electromagnetic decays observed so far being \(\Xi_c^0 \rightarrow \Xi_c\gamma\) and \(\Omega_c(2770) \rightarrow \Omega_c\gamma\), 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) predicts a partial width of 263 keV/c\(^2\) for the decay \(\Xi_c(2790)^0 \rightarrow \Xi_c^0\gamma\) and 292 keV/c\(^2\) for \(\Xi_c(2815)^0 \rightarrow \Xi_c^0\gamma\), assuming that they are \(\lambda\) excitations. On the other hand, the analogous decays for the \(\Xi_c^+\) baryons are predicted to have very small partial widths. The same model predicts widths of less than 10 keV/c\(^2\) if the unit of orbital excitation is between the two light quarks (a “\(p\) excitation”). Other models make different predictions in particular, a treatment of the \(\Xi_c(2790)\) isodoublet as dynamically generated baryons predicts large partial widths for both charge states. These predictions are summarized in Table I.

In this paper, we present a search for the electromagnetic decays \(\Xi_c(2790,2815)^{+0} \rightarrow \Xi_c^{+0}\gamma\). The results are converted to branching ratios and, with certain assumptions, 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 was a large-solid-angle spectrometer operating at the KEKB asymmetric-energy \(e^+e^-\) collider, 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

* now at Hiroshima University
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 \( \Xi^c \) baryons, we first reconstruct a large sample of ground-state \( \Xi^0_c \) and \( \Xi^+_c \) baryons with good signal-to-noise ratio. To obtain large statistics, we use ten decay modes of the \( \Xi^0_c \), and seven of the \( \Xi^+_c \) ground states. 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 \( \Xi_c \) in the center-of-mass frame, \( p^* \), which is set as \( p^* > 2.25 \text{ GeV}/c \), a choice which is described below. To show the yield of the reconstructed \( \Xi^0_c \) and \( \Xi^+_c \) 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 \( \Xi^0_c \) and \( \Xi^+_c \), respectively [2], divided by the resolution (\( \sigma \)), which is found mode-by-mode and is \( \sim 5 \text{ MeV}/c^2 \). \( \Xi_c \) candidates are selected if they are within \( \pm 2\sigma \) of the nominal mass. For \( \Xi^+_c \), the number of selected candidates is 79k above a background of 61k, and for \( \Xi^0_c \) 142k signal candidates with a background of 154k.

To optimize the requirements specific to this analysis, a simulated data set is constructed using a combination of the decays under study and generic \( e^+e^- \) hadronic events. In addition to the \( p^* > 2.25 \text{ GeV}/c \) requirement on the \( \Xi_c \) 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 \times 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 \( \pi^0 \) 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 \( \pi^0 \) is larger than 0.5. These likelihoods are determined from Monte Carlo studies [10] and are a function of the energy of the other photon, its polar angle, and the mass 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 \( \Xi^+ \gamma \) invariant-mass distributions for the charged and neutral \( \Xi_c \) 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 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 \( \sim 6.5 \text{ MeV}/c^2 \), 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 \( \Xi_c(2815)^0 \rightarrow \Xi^0_c \gamma \) with 401 \pm 45 events and evidence for the decay \( \Xi_c(2790)^0 \rightarrow \Xi^0_c \gamma \) with 222 \pm 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,

![Pull mass distribution for the \( \Xi^0_c \) (upper data points), and \( \Xi^+_c \) (lower data points) candidates.](image-url)
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 Ξ_c(2815)^0 → Ξ^0γ and Ξ_c(2790)^0 → Ξ^0γ to be n_σ = 8.6 and 3.8, respectively.

To measure branching ratios

\[ R_{2815} = \frac{B(\Xi_c(2815)^{0/\pm} \to \Xi^{0/\pm} \gamma)}{B(\Xi_c(2815)^{0/\pm} \to \Xi^{0/\pm} \pi^+\pi^-)} \]

and \[ R_{2790} = \frac{B(\Xi_c(2790)^{0/\pm} \to \Xi^{0/\pm} \pi^+\pi^-)}{B(\Xi_c(2790)^{0/\pm} \to \Xi^{0/\pm} \gamma\pi^+\pi^-)} \]

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 \( p^* > 2.25 \text{ GeV}/c \). 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%) \[21\], uncertainties due to the modeling of the Chebychev polynomial used for the background function, as its reduced χ^2 is satisfactory, and this produces a more conservative limit.

We find 90% confidence level limits of 56 and 64 events for the decays Ξ_c(2815)^0 → Ξ^0γ and Ξ_c(2790)^0 → Ξ^0γ, respectively, 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 charm baryons. Our determination of the relative reconstruction efficiency of the \( \Xi^0 \) with respect to the \( \Xi^+_c \) 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 \( \Xi^0 \) and \( \Xi^+_c \) 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 Σ mesons. We estimate the systematic uncertainty associated with the equality assumption to be ±15%; this is larger than the asymmetry observed in the \( \Sigma^{0}_{c}/\Sigma^{0} \) system \[22\].

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 \( \Xi^+_c \) 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 \( \Xi_c(2815)^0 \to \Xi(2645)^0 \pi \to \Xi,\pi\pi \) we calculate, using Clebsch-Gordan coefficients and phase space, that the charged-pion decays account for (38 ± 4)% of the total rate of this decay chain, where the rest of the decays include π^0 transitions. The uncertainty in this number...
Yield is observed to be (13 baryon of requirement on the momentum of the ground-state charmed baryon. Taking into account the decays Ξ(2815)0 → Ξcγπ− → Ξcγπ−, the width of the electromagnetic decay is observed to be (13.6 ± 1.5 ± 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 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 \( \Gamma[Ξ(2815)^0 → Ξ′(2790)^0 γ] = 320 ± 45_{−80}^{+80} \text{keV}/c^2 \). For the decays of the Ξ(2815)+ we use similar arguments to find \( \Gamma[Ξ(2815)^+ → Ξ′(2790)^+ γ] < 80 \text{keV}/c^2 \).

For the Ξ(2815)0 we find that a similar calculation leads to \( (7.9 ± 2.0_{−2.3}^{+2.3})% \) of the total width being due to the electromagnetic decay, implying a partial width of \( \Gamma[Ξ(2815)^0 → Ξ′(2790)^0 γ] \sim 800 \text{keV}/c^2 \) with an uncertainty of around 40%. Similarly, for the decay Ξ(2815)+ → Ξcγπ−, for which no signal is found, the upper limit on the partial width is set at 350 keV/c².

The difference between the decays of the neutral and charged Ξ(2815) states is clear, and these results are in good agreement with the prediction that was based on an identification of the Ξ(2815) as \( λ \) orbital excitations of the ground-state baryons [14]. For the Ξ*(2790) decays, the data are much less precise. Still, the evidence for the decay of the neutral Ξ(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 orbitalley-excited charmed baryon, and measure the branching ratio \( B[Ξ(2815)^0 → Ξ′(2790)^0 γ] = 0.41 ± 0.05 ± 0.03 \). We also present evidence for the similar decay of the Ξ(2815)+ and measure \( B[Ξ(2815)^0 → Ξ′(2790)^0 γ] = 0.13 ± 0.03 ± 0.02 \). We find no evidence of the analogous decays of the Ξ(2815)+ and Ξ(2790)+ baryons. Using reasonable estimates of the unseen decays, we conclude that the partial widths of the electromagnetic decays of the Ξ(2815) and Ξ(2815)+ into the ground states are \( 320 ± 45_{−80}^{+80} \text{keV}/c^2 \) and \( ∼ 800 \text{keV}/c^2 \), respectively. The partial widths for the similar decays of the Ξ(2815)+ and Ξ(2790)+ are less than 80 keV/c² and less than 350 keV/c², respectively. These results are consistent with predictions based on the identification of the Ξ(2815) and Ξ(2790) baryons as orbital excitations of the Ξc baryons, where the unit of orbital excitation is between the heavy quark and the spin-0 light diquark system.

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 DP180102629, DP170102389, DP170102204, DP150103061, FT130100303; Austrian Science Fund (FWF); the National Natural Science Foundation of China under Contracts No. 11435013, No. 11475187, No. 11521505, No. 11575017, No. 11675166, 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 VolkswagenStifung; the Department of Science and Technology of India; the Istituto Nazionale di Fisica Nucleare of Italy; National Research Foundation (NRF) of Korea Grant Nos. 2016R1D1A1B02012900, 2018R1A2B3003643, 2018R1A2B3003643;
Throughout this paper, the inclusion of the charge-conjugate is implied.

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