CLNS 00/1702
CLEO 00-25

Evidence of New States Decaying into $\Xi_c'\pi$

CLEO Collaboration

(November 26, 2000)

Abstract

Using 13.7 fb^{-1} of data recorded by the CLEO detector at CESR, we report evidence for two new charmed baryons: one decaying into $\Xi_c^{0\prime}\pi^+$ with the subsequent decay $\Xi_c^{0\prime} \to \Xi_c^0\gamma$, and its isospin partner decaying into $\Xi_c^{+\prime}\pi^-$ followed by $\Xi_c^{+\prime} \to \Xi_c^+\gamma$. We measure the following mass differences for the two states: $M(\Xi_c^0\gamma\pi^+) - M(\Xi_c^0) = 318.2 \pm 1.3 \pm 2.9$ MeV, and $M(\Xi_c^+\gamma\pi^-) - M(\Xi_c^+) = 324.0 \pm 1.3 \pm 3.0$ MeV. We interpret these new states as the $J^P = \frac{1}{2}^-$ Ξ_{c1} particles, the charmed-strange analogs of the $\Lambda_{c1}^+(2593)$.

S. E. Csorna,[1] I. Danko,[1] K. W. McLean,[1] Z. Xu,[1] R. Godang,[2] G. Bonvicini,[3] D. Cinabro,[3] M. Dubrovin,[3] S. McGee,[3] G. J. Zhou,[3] A. Bornheim,[4] E. Lipeles,[4] S. P. Pappas,[4] M. Schmidtler,[4] A. Shapiro,[4] W. M. Sun,[4] A. J. Weinstein,[4] D. E. Jaffe,[5] G. Masek,[5] H. P. Paar,[5] D. M. Asner,[6] A. Eppich,[6] T. S. Hill,[6] R. J. Morrison,[6] R. A. Briere,[7] G. P. Chen,[7] T. Ferguson,[7] H. Vogel,[7] A. Gritsan,[8] J. P. Alexander,[9] R. Baker,[9] C. Bebek,[9] B. E. Berger,[9] K. Berkelman,[9] F. Blanc,[9] V. Boisvert,[9] D. G. Cassel,[9] P. S. Drell,[9] J. E. Duboscq,[9] K. M. Ecklund,[9] R. Ehrlich,[9] A. D. Foland,[9] P. Gaidarev,[9] R. S. Galik,[9] L. Gibbons,[9] B. Gittelman,[9] S. W. Gray,[9] D. L. Hartill,[9] B. K. Heltsley,[9] P. I. Hopman,[9] L. Hsu,[9] C. D. Jones,[9] J. Kandaswamy,[9] D. L. Kreinick,[9] M. Lohner,[9] A. Magerkurth,[9] T. O. Meyer,[9] N. B. Mistry,[9] E. Nordberg,[9] M. Palmer,[9] J. R. Patterson,[9] D. Peterson,[9] D. Riley,[9] A. Romano,[9] J. G. Thayer,[9] D. Urner,[9] B. Valant-Spaight,[9] G. Viehhauser,[9] A. Warburton,[9] P. Avery,[10] C. Prescott,[10] A. I. Rubiera,[10] H. Stoeck,[10] J. Yelton,[10] G. Brandenburg,[11] A. Ershov,[11] D. Y.-J. Kim,[11] R. Wilson,[11] T. Bergfeld,[12] B. I. Eisenstein,[12] J. Ernst,[12] G. E. Gladding,[12] G. D. Gollin,[12] R. M. Hans,[12] E. Johnson,[12] I. Karliner,[12] M. A. Marsh,[12] C. Plager,[12] C. Sedlack,[12] M. Selen,[12] J. J. Thaler,[12] J. Williams,[12] K. W. Edwards,[13] R. Janicek,[14] P. M. Patel,[14] A. J. Sadoff,[15] R. Ammar,[16] A. Bean,[16] D. Besson,[16] X. Zhao,[16] S. Anderson,[17] V. V. Frolov,[17] Y. Kubota,[17] S. J. Lee,[17] R. Mahapatra,[17] J. J. O'Neill,[17] R. Poling,[17] T. Riehle,[17] A. Smith,[17] C. J. Stepaniak,[17] J. Urheim,[17] S. Ahmed,[18] M. S. Alam,[18] S. B. Athar,[18] L. Jian,[18] L. Ling,[18] M. Saleem,[18] S. Timm,[18] F. Wappler,[18] A. Anastassov,[19] E. Eckhart,[19] K. K. Gan,[19] C. Gwon,[19] T. Hart,[19] K. Honscheid,[19] D. Hufnagel,[19] H. Kagan,[19] R. Kass,[19] T. K. Pedlar,[19] H. Schwarthoff,[19] J. B. Thayer,[19] E. von Toerne,[19] M. M. Zoeller,[19] S. J. Richichi,[20] H. Severini,[20] P. Skubic,[20] A. Undrus,[20] V. Savinov,[21] S. Chen,[22] J. Fast,[22] J. W. Hinson,[22] J. Lee,[22] D. H. Miller,[22] E. I. Shibata,[22] I. P. J. Shipsey,[22] V. Pavlunin,[22] D. Cronin-Hennessy,[23] A.L. Lyon,[23] E. H. Thorndike,[23] T. E. Coan,[24] V. Fadeyev,[24] Y. S. Gao,[24] Y. Maravin,[24] I. Narsky,[24] R. Stroynowski,[24] J. Ye,[24] T. Wlodek,[24] M. Artuso,[25] R. Ayad,[25] C. Boulahouache,[25] K. Bukin,[25] E. Dambasuren,[25] G. Majumder,[25] G. C. Moneti,[25] R. Mountain,[25] S. Schuh,[25] T. Skwarnicki,[25] S. Stone,[25] J.C. Wang,[25] A. Wolf,[25] J. Wu,[25] S. Kopp,[26] M. Kostin,[26] and A. H. Mahmood[27]

[1]Vanderbilt University, Nashville, Tennessee 37235
[2]Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
[3]Wayne State University, Detroit, Michigan 48202
[4]California Institute of Technology, Pasadena, California 91125
[5]University of California, San Diego, La Jolla, California 92093
[6]University of California, Santa Barbara, California 93106
[7]Carnegie Mellon University, Pittsburgh, Pennsylvania 15213
[8]University of Colorado, Boulder, Colorado 80309-0390
[9]Cornell University, Ithaca, New York 14853
[10]University of Florida, Gainesville, Florida 32611
[11]Harvard University, Cambridge, Massachusetts 02138
[12]University of Illinois, Urbana-Champaign, Illinois 61801
[13]Carleton University, Ottawa, Ontario, Canada K1S 5B6
and the Institute of Particle Physics, Canada
[14]McGill University, Montréal, Québec, Canada H3A 2T8

and the Institute of Particle Physics, Canada
[15]Ithaca College, Ithaca, New York 14850
[16]University of Kansas, Lawrence, Kansas 66045
[17]University of Minnesota, Minneapolis, Minnesota 55455
[18]State University of New York at Albany, Albany, New York 12222
[19]Ohio State University, Columbus, Ohio 43210
[20]University of Oklahoma, Norman, Oklahoma 73019
[21]University of Pittsburgh, Pittsburgh, Pennsylvania 15260
[22]Purdue University, West Lafayette, Indiana 47907
[23]University of Rochester, Rochester, New York 14627
[24]Southern Methodist University, Dallas, Texas 75275
[25]Syracuse University, Syracuse, New York 13244
[26]University of Texas, Austin, TX 78712
[27]University of Texas - Pan American, Edinburg, TX 78539

The Ξ_c states consist of a combination of a charm quark, a strange quark and an up or down quark. Each angular momentum configuration of these quarks exists as an isospin pair. The ground states, the Ξ_c^0 and Ξ_c^+, have $J^P = \frac{1}{2}^+$ and no orbital angular momentum, and like the Λ_c^+ have a wave-function that is anti-symmetric under interchange of the lighter quark flavors or spins. They are the only members of the group that decay weakly, and over the past decade their masses, lifetimes, and many of their decay modes have been measured. In 1995 and 1996, CLEO found evidence for a pair of excited states [1] that were interpreted as the $J^P = \frac{3}{2}^+$ Ξ_c^* states, and one of these observations has since been confirmed [2]. In 1999, CLEO discovered [3] the Ξ_c' states, which like the ground states have $J^P = \frac{1}{2}^+$, but have a wave-function that is symmetric under interchange of the two light quark spins or flavors, and are the charmed-strange analogs of the Σ_c. The lowest lying states with orbital angular momentum are expected to be a pair of isodoublets, with the two lighter quarks in a spin-0 configuration, and one unit of orbital angular momentum between this di-quark and the charm quark. This unit of angular momentum combines with the charm quark spin to give $J^P = \frac{3}{2}^-$ and $J^P = \frac{1}{2}^-$ states. These states are denoted the Ξ_{c1} states, where the numerical subscript refers to the light quark angular momentum, and they are the analogs of the $\Lambda_{c1}^+(2630)$ and $\Lambda_{c1}^+(2593)$, respectively. In 1999, CLEO reported the discovery [4] of an isospin pair of states decaying into $\Xi_c^*\pi$ with a mass about 348 MeV above the ground states, which were identified as the $J^P = \frac{3}{2}^-$ Ξ_{c1} states. Here, using data from the CLEO II and CLEO II.V detector configurations, we present the first evidence of two peaks corresponding to particles decaying to $\Xi_c'\pi$. This is the expected decay mode of the $J^P = \frac{1}{2}^-$ Ξ_{c1} states. That fact, in addition to our measured masses, lead us to identify our peaks with these particles.

The data presented here were taken by the CLEO detector operating at the Cornell Electron Storage Ring. The sample used in this analysis corresponds to an integrated luminosity of 13.7 fb^{-1} from data taken on the $\Upsilon(4S)$ resonance and in the continuum at energies just below the $\Upsilon(4S)$. Of this data, $4.7 fb^{-1}$ was taken with the CLEO II configuration [5] and the remainder with the CLEO II.V configuration [6] which includes a silicon vertex detector in its charged particle measurement system. We detected charged tracks with a cylindrical drift chamber system inside a solenoidal magnet. Photons were detected using an electromagnetic calorimeter consisting of 7800 cesium iodide crystals.

We first obtain large samples of reconstructed Ξ_c^+ and Ξ_c^0 particles using their decays into Λ, Ξ^-, Ω^- and Ξ^0 hyperons as well as kaons, pions and protons[1]. The analysis chain for reconstructing these particles is very similar to that presented in our previous publications [1,3,4]. We fitted the invariant mass distributions for each decay mode to a sum of a Gaussian signal function and a second order polynomial background. Ξ_c candidates were defined as those combinations within 2σ of the known mass of the Ξ_c^+ or Ξ_c^0, where σ is the detector resolution for the detector configuration, calculated mode-by-mode by a GEANT-based [7] Monte Carlo simulation program. To illustrate the good statistics and signal-to-noise ratio of the Ξ_c signals, and to reduce the combinatorial background, we have placed a cut $x_p > 0.6$, where $x_p = p/p_{max}$, p is the momentum of the charmed baryon, $p_{max} = \sqrt{E_{beam}^2 - M^2}$, where

[1]Charge conjugate states are implied throughout.

M is the reconstructed Ξ_c mass. Table I details the number of signal and background events obtained from each decay mode. The x_p cut used to obtain the results in Table I was not used in the final analysis, as we prefer to apply an x_p cut only on the $\Xi_c'\pi$ combinations.

TABLE I. Ξ_c^0 and Ξ_c^+ Decay Mode Yields

Particle	Mode	Ξ_c Yield, $x_p > 0.6$	Background
Ξ_c^0			
	$\Xi^-\pi^+$	440	112
	$\Xi^-\pi^+\pi^-\pi^+$	106	133
	$\Xi^-\pi^+\pi^0$	357	377
	Ω^-K^+	59	12
	$\Xi^0\pi^+\pi^-$	196	202
	$\Lambda K^-\pi^+$	179	238
	ΛK_s^0	106	80
	Total	1443	1154
Ξ_c^+			
	$\Xi^0\pi^+$	84	168
	$\Xi^0\pi^+\pi^-\pi^+$	216	460
	$\Sigma^+K^-\pi^+$	83	62
	$\Xi^-\pi^+\pi^+$	668	200
	$\Xi^0\pi^+\pi^0$	345	650
	$\Lambda K_s^0\pi^+$	188	270
	$\Lambda K^-\pi^+\pi^+$	38	78
	Total	1622	1888

The Ξ_c candidates defined above were then combined with a photon, and the mass differences $M(\Xi_c^0\gamma) - M(\Xi_c^0)$ and $M(\Xi_c^+\gamma) - M(\Xi_c^+)$ were calculated. The transition photons were required to each have energy in excess of 100 MeV, to come from the part of the detector that had the best resolution ($|\cos\theta| < 0.7$, where θ is the polar angle), and to have an energy profile consistent with being that of an isolated photon. Any photon which, when combined with another photon, made a combination consistent with being a π^0, was rejected. Those combinations with calculated mass differences within 8 MeV ($\approx 2\sigma$) of the measured mass differences for the Ξ_c' particles [3], were retained for further analysis. As the Ξ_c' decays electromagnetically, its instrinsic width is negligible, and so the candidates were kinematically constrained to the Ξ_c' masses using the measured mass differences.

We then combine these Ξ_c' candidates with an appropriately charged track in the event and plot $M(\Xi_c'\pi) - M(\Xi_c)$ for each isospin state. Figure 1(a) shows $M(\Xi_c^{0\prime}\pi^+) - M(\Xi_c^0)$, and Figure 1(b) shows $M(\Xi_c^{+\prime}\pi^-) - M(\Xi_c^+)$, each with a requirement of $x_p > 0.7$ on the $\Xi_c^{+\prime}\pi^-$ combination. Given the kinematics of the decays, such a criterion corresponds roughly to $x_p > 0.6$ for the Ξ_c daughters. In both figures there is a peak at about 320 MeV, indicative of the decay of a Ξ_{c1}^+ (Figure 1a) and a Ξ_{c1}^0 (Figure 1b). We fit each of the two peaks to a sum of a Gaussian signal function of floating width, and a polynomial background function. For the $\Xi_c^{0\prime}\pi^+$ case, we find a signal of $18.4^{+5.6}_{-4.9}$ events, with a width of 5.6 ± 1.7 MeV. For the $\Xi_c^{+\prime}\pi^-$ case, we find an excess of $14.2^{+4.6}_{-3.9}$ events and a width of 3.9 ± 1.5 MeV. The

mass resolutions of the detector for these decays are found from our Monte Carlo simulation program to be about 1.2 MeV in the CLEO II.V data, and around 1.4 MeV in the CLEO II data. This indicates that the states have non-negligible intrinsic widths. We have also fit the plots to Breit-Wigner functions convolved with a double Gaussian resolution function using a maximum likelihood method and a bin width of 0.5 MeV. The results of this fit are, $M(\Xi_c^{0\prime}\pi^+) - M(\Xi_c^0) = 318.2 \pm 1.3$ MeV, and $\Gamma = 6.8^{+6.0}_{-4.8}$ MeV, for Figure 1a, and $M(\Xi_c^{+\prime}\pi^-) - M(\Xi_c^+) = 324.0 \pm 1.3$ MeV, and $\Gamma = 6.1^{+4.4}_{-2.8}$ MeV for Figure 1b. These fits that are superimposed on the data in Figure 1. The results for Γ are limited in their precision by the low statistics, but indicate that it is very likely that these states have an instrinsic width of the order of several MeV. However, we prefer to place 90% confidence level upper limits on the width of these states, $\Gamma(\Xi_{c1}^+) < 15$ MeV and $\Gamma(\Xi_{c1}^0) < 12$ MeV, dominated by the statistical uncertainty.

In order to check that all the Ξ_{c1} decays proceed via an intermediate Ξ_c', we remove the cuts on $M(\Xi_c\gamma) - M(\Xi_c)$, select combinations within 8 MeV of our established masses in $\Xi_c\gamma\pi$, and plot $M(\Xi_c\gamma) - M(\Xi_c)$. Each plot (Figures 2a and 2b) is fit to the sum of a fixed width Ξ_c' signal and a polynomial background function, and they show signals which are consistent in mass with our published results for the Ξ_c' pair [3]. It is clear that our data are consistent with all the $J^P = \frac{1}{2}^-$ Ξ_{c1} decays proceeding via an intermediate Ξ_c'.

When quoting our results as a mass difference with respect to a ground state, our systematic uncertainty is dominated by the uncertainty in the $M(\Xi_c') - M(\Xi_c)$ mass differences. Alternatively, we can quote the mass difference with respect to the Ξ_c' states, and we find $M(\Xi_c^{+\prime}\pi^-) - M(\Xi_c^{+\prime}) = 216.2 \pm 1.3 \pm 1.0$ MeV and $M(\Xi_c^{0\prime}\pi^+) - M(\Xi_c^{0\prime}) = 211.2 \pm 1.3 \pm 1.0$ MeV. The quoted systematic uncertainties include the spread in our results obtained with different fitting procedures and an estimate of the systematic uncertainty of our mass difference scale. These uncertainties are smaller than those in the $M(\Xi_c') - M(\Xi_c)$ mass differences, as the latter involve γ transitions which have poorer resolution and lower signal to noise ratio than charged particle transitions.

The decay patterns of the Ξ_{c1} states should be closely analogous to those of the Λ_{c1}^+. The preferred decay of the $J^P = \frac{1}{2}^-$ Ξ_{c1} should be to $\Xi_c'\pi$ because the spin-parity of the baryons allows this decay to proceed via an S-wave decay, whereas strong decays to Ξ_c^* would have to proceed via a D-wave. In Heavy Quark Effective Theory (HQET) [8], where the angular momentum and parity of the light di-quark degrees of freedom must be considered separately from those of the heavy quark, decays of the Ξ_{c1} directly to ground state Ξ_c baryons are not allowed. Thus we identify our two peaks as the $J^P = \frac{1}{2}^-$ Ξ_{c1}^0 and Ξ_{c1}^+. Combining our results found here with our previous results on the $J^P = \frac{3}{2}^-$ Ξ_{c1} states [4], and using world average values [10] for the isospin splitting of the ground state Ξ_c baryons, we find the splitting between the $J^P = \frac{3}{2}^-$ and $J^P = \frac{1}{2}^-$ of $24.9 \pm 1.8 \pm 3.2$ MeV in the charged case, and $28.7 \pm 1.6 \pm 4.0$ MeV for the neutral case. These are similar to the analogous splittings in the Λ_c^+ and charmed meson systems, [10] as expected from HQET.

We can also measure the isospin splitting between the new states. We find $M(\Xi_{c1}^0) - M(\Xi_{c1}^+) = 0.3 \pm 1.9 \pm 4.5$ MeV, where the quoted systematic uncertainties include the systematic uncertainties of our mass difference measurement, as well as the uncertainty in the mass difference of the ground states. Although the uncertainties are large, this supports the picture that the excited states of the Ξ_c have smaller isospin splittings than that of the

ground states. The $J^P = \frac{1}{2}$ Ξ_{c1} particles are the analogs of the $\Lambda_{c1}^+(2593)$. Although the latter decays with very little phase space, it has been measured to have an instrinsic width of a few MeV. It is not surprising, therefore, that the $J^P = \frac{1}{2}^-$ Ξ_{c1} pair, which have more phase space available for two-body decays, should also appear as wide peaks in our data.

In conclusion, we present evidence for the production of two new states. The first of these states decays into $\Xi_c^{0\prime}\pi^+$ with measured mass given by $M(\Xi_c^0\gamma\pi^+) - M(\Xi_c^0) = 318.2 \pm 1.3 \pm 2.9$ MeV. The second state decays into $\Xi_c^{+\prime}\pi^-$ with a mass given by $M(\Xi_c^+\gamma\pi^-) - M(\Xi_c^+) = 324.0 \pm 1.3 \pm 3.0$ MeV. Although we do not measure the spin or parity of these states, the observed decay modes, masses, and widths are all consistent with the new states being the $J^P = \frac{1}{2}^-$ Ξ_{c1}^+ and Ξ_{c1}^0 states, the charmed-strange analogs of the $\Lambda_{c1}^+(2593)$.

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. This work was supported by the National Science Foundation, the U.S. Department of Energy, the Research Corporation, the Natural Sciences and Engineering Research Council of Canada, the A.P. Sloan Foundation, the Swiss National Science Foundation, the Texas Advanced Research Program, and the Alexander von Humboldt Stiftung.

REFERENCES

[1] CLEO Collaboration, P. Avery *et al.*, Phys. Rev. Lett. **75**, 4364 (1995); L. Gibbons *et al.*, Phys. Rev. Lett. **77**, 811 (1996).

[2] E-687 Collaboration, P. Frabetti *et al.*, Phys. Lett. B **426**, 403 (1998).

[3] CLEO Collaboration, C. Jessop *et al.*, Phys. Rev. Lett. **82**, 492 (1999). The measurements are: $M(\Xi_c^{+\prime}) - M(\Xi_c^+) = 107.8 \pm 1.7 \pm 2.5$ MeV and $M(\Xi_c^{0\prime}) - M(\Xi_c^0) = 107.0 \pm 1.5 \pm 2.5$ MeV.

[4] CLEO Collaboration, J. Alexander *et al.*, Phys. Rev. Lett. **83**, 3390 (1999). The measurements are: $M(\Xi_{c1}^+) - M(\Xi_c^+) = 348.6 \pm 0.6 \pm 1.0$ MeV, and $M(\Xi_{c1}^0) - M(\Xi_c^0) = 347.2 \pm 0.7 \pm 2.0$ MeV.

[5] CLEO Collaboration, Y. Kubota *et al.*, Nucl. Instrum. and Meth. A **320**, 66 (1992).

[6] CLEO Collaboration, T. Hill *et al.*, Nucl. Instrum. and Meth. A **418**, 32 (1998).

[7] R. Brun *et al.*, GEANT 3.15, CERN Report No. DD/EE/84-1 (1987).

[8] N. Isgur and M. Wise, Phys. Rev. Lett. **66**, 1130 (1991).

[9] D. Pirjol and T-M. Yan, Phys. Rev. D **56**, 5483 (1997).

[10] The Particle Data Group, D. Groom *et al.*, Eur. Phys. J. C **15** 1, (2000). They calculate $M(\Xi_c^0) - M(\Xi_c^+) = 5.5 \pm 1.8$ MeV.

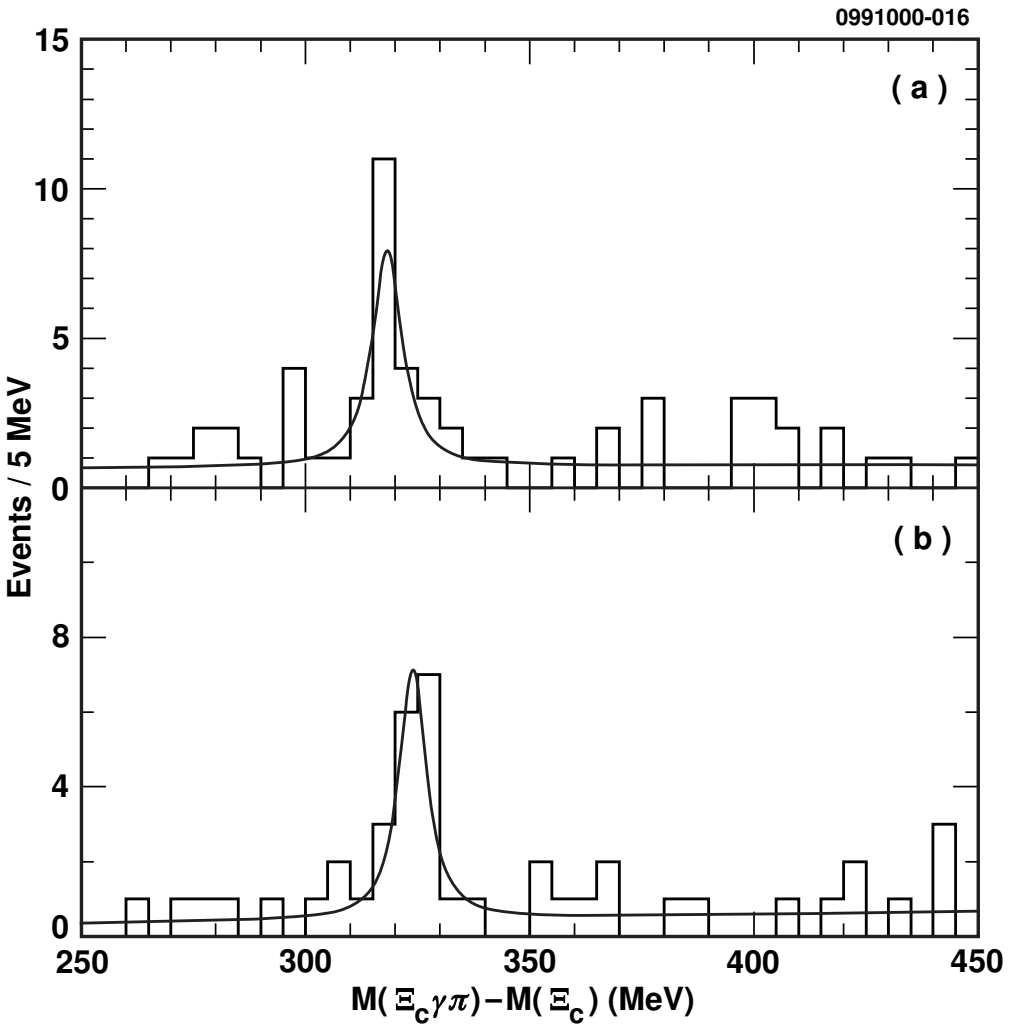

FIG. 1. Mass differences a) $M(\Xi_c^0\gamma\pi^+) - M(\Xi_c^0)$ and b) $M(\Xi_c^+\gamma\pi^-) - M(\Xi_c^+)$. Each plot shows a distinct peak. Note that the Ξ_c' mass has been fixed in these plots, so that we could equivalently show $M(\Xi_c'\pi) - M(\Xi_c)$ as this would just be a translation of the horizontal axis. The fits are described in the text.

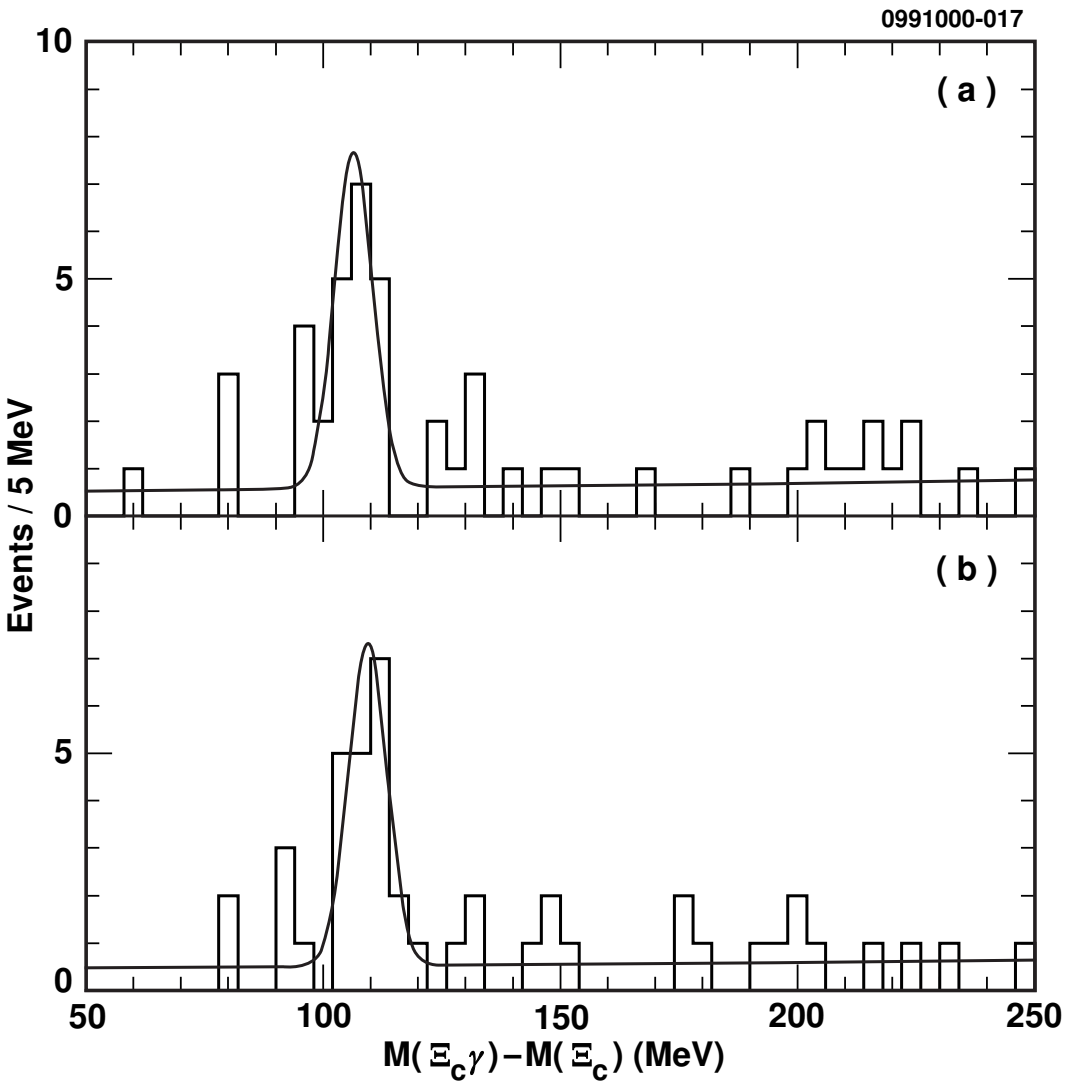

FIG. 2. Mass differences a) $M(\Xi_c^0\gamma) - M(\Xi_c^0)$, and b) $M(\Xi_c^+\gamma) - M(\Xi_c^+)$ for events in the Ξ_{c1} mass windows. The fits are described in the text.