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Evidence of New States Decaying into $\Xi_c^* \pi$

CLEO Collaboration

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Abstract

Using data recorded by the CLEO II detector at CESR, we report evidence for two new charmed baryons, one decaying into $\Xi_c^+ \pi^+ \pi^-$ via an intermediate Ξ_c^{*0}, and its isospin partner decaying into $\Xi_c^0 \pi^+ \pi^-$ via an intermediate Ξ_c^{*+}. We measure the mass differences of the two states to be $M(\Xi_c^+ \pi^+ \pi^-) - M(\Xi_c^+) = 348.6 \pm 0.6 \pm 1.0$ MeV, and $M(\Xi_c^0 \pi^+ \pi^-) - M(\Xi_c^0) = 347.2 \pm 0.7 \pm 2.0$ MeV. We interpret these new states as the $J^P = \frac{3}{2}^-$ Ξ_{c1} particles, the charmed-strange analogues of the $\Lambda_{c1}^+(2625)$.

J. P. Alexander,[1] R. Baker,[1] C. Bebek,[1] B. E. Berger,[1] K. Berkelman,[1] V. Boisvert,[1] D. G. Cassel,[1] D. S. Crowcroft,[1] M. Dickson,[1] S. von Dombrowski,[1] P. S. Drell,[1] K. M. Ecklund,[1] R. Ehrlich,[1] A. D. Foland,[1] P. Gaidarev,[1] L. Gibbons,[1] B. Gittelman,[1] S. W. Gray,[1] D. L. Hartill,[1] B. K. Heltsley,[1] P. I. Hopman,[1] D. L. Kreinick,[1] T. Lee,[1] Y. Liu,[1] T. O. Meyer,[1] N. B. Mistry,[1] C. R. Ng,[1] E. Nordberg,[1] M. Ogg,[1,*] J. R. Patterson,[1] D. Peterson,[1] D. Riley,[1] J. G. Thayer,[1] P. G. Thies,[1] B. Valant-Spaight,[1] A. Warburton,[1] C. Ward,[1] M. Athanas,[2] P. Avery,[2] C. D. Jones,[2] M. Lohner,[2] C. Prescott,[2] A. I. Rubiera,[2] J. Yelton,[2] J. Zheng,[2] G. Brandenburg,[3] R. A. Briere,[3] A. Ershov,[3] Y. S. Gao,[3] D. Y.-J. Kim,[3] R. Wilson,[3] T. E. Browder,[4] Y. Li,[4] J. L. Rodriguez,[4] H. Yamamoto,[4] T. Bergfeld,[5] B. I. Eisenstein,[5] J. Ernst,[5] G. E. Gladding,[5] G. D. Gollin,[5] R. M. Hans,[5] E. Johnson,[5] I. Karliner,[5] M. A. Marsh,[5] M. Palmer,[5] C. Plager,[5] C. Sedlack,[5] M. Selen,[5] J. J. Thaler,[5] J. Williams,[5] K. W. Edwards,[6] R. Janicek,[7] P. M. Patel,[7] A. J. Sadoff,[8] R. Ammar,[9] P. Baringer,[9] A. Bean,[9] D. Besson,[9] D. Coppage,[9] R. Davis,[9] S. Kotov,[9] I. Kravchenko,[9] N. Kwak,[9] X. Zhao,[9] L. Zhou,[9] S. Anderson,[10] V. V. Frolov,[10] Y. Kubota,[10] S. J. Lee,[10] R. Mahapatra,[10] J. J. O'Neill,[10] R. Poling,[10] T. Riehle,[10] A. Smith,[10] M. S. Alam,[11] S. B. Athar,[11] A. H. Mahmood,[11] S. Timm,[11] F. Wappler,[11] A. Anastassov,[12] J. E. Duboscq,[12] K. K. Gan,[12] C. Gwon,[12] T. Hart,[12] K. Honscheid,[12] H. Kagan,[12] R. Kass,[12] J. Lorenc,[12] H. Schwarthoff,[12] E. von Toerne,[12] M. M. Zoeller,[12] S. J. Richichi,[13] H. Severini,[13] P. Skubic,[13] A. Undrus,[13] M. Bishai,[14] S. Chen,[14] J. Fast,[14] J. W. Hinson,[14] J. Lee,[14] N. Menon,[14] D. H. Miller,[14] E. I. Shibata,[14] I. P. J. Shipsey,[14] S. Glenn,[15] Y. Kwon,[15,†] A.L. Lyon,[15] E. H. Thorndike,[15] C. P. Jessop,[16] K. Lingel,[16] H. Marsiske,[16] M. L. Perl,[16] V. Savinov,[16] D. Ugolini,[16] X. Zhou,[16] T. E. Coan,[17] V. Fadeyev,[17] I. Korolkov,[17] Y. Maravin,[17] I. Narsky,[17] R. Stroynowski,[17] J. Ye,[17] T. Wlodek,[17] M. Artuso,[18] R. Ayad,[18] E. Dambasuren,[18] S. Kopp,[18] G. Majumder,[18] G. C. Moneti,[18] R. Mountain,[18] S. Schuh,[18] T. Skwarnicki,[18] S. Stone,[18] A. Titov,[18] G. Viehhauser,[18] J.C. Wang,[18] S. E. Csorna,[19] K. W. McLean,[19] S. Marka,[19] Z. Xu,[19] R. Godang,[20] K. Kinoshita,[20,‡] I. C. Lai,[20] P. Pomianowski,[20] S. Schrenk,[20] G. Bonvicini,[21] D. Cinabro,[21] R. Greene,[21] L. P. Perera,[21] G. J. Zhou,[21] S. Chan,[22] G. Eigen,[22] E. Lipeles,[22] M. Schmidtler,[22] A. Shapiro,[22] W. M. Sun,[22] J. Urheim,[22] A. J. Weinstein,[22] F. Würthwein,[22] D. E. Jaffe,[23] G. Masek,[23] H. P. Paar,[23] E. M. Potter,[23] S. Prell,[23] V. Sharma,[23] D. M. Asner,[24] A. Eppich,[24] J. Gronberg,[24] T. S. Hill,[24] D. J. Lange,[24] R. J. Morrison,[24] H. N. Nelson,[24] T. K. Nelson,[24] J. D. Richman,[24] D. Roberts,[24] B. H. Behrens,[25] W. T. Ford,[25] A. Gritsan,[25] H. Krieg,[25] J. Roy,[25] and J. G. Smith[25]

[1]Cornell University, Ithaca, New York 14853
[2]University of Florida, Gainesville, Florida 32611
[3]Harvard University, Cambridge, Massachusetts 02138
[4]University of Hawaii at Manoa, Honolulu, Hawaii 96822

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[*]Permanent address: University of Texas, Austin TX 78712.

[†]Permanent address: Yonsei University, Seoul 120-749, Korea.

[‡]Permanent address: University of Cincinnati, Cincinnati OH 45221

[5]University of Illinois, Urbana-Champaign, Illinois 61801
[6]Carleton University, Ottawa, Ontario, Canada K1S 5B6
and the Institute of Particle Physics, Canada
[7]McGill University, Montréal, Québec, Canada H3A 2T8
and the Institute of Particle Physics, Canada
[8]Ithaca College, Ithaca, New York 14850
[9]University of Kansas, Lawrence, Kansas 66045
[10]University of Minnesota, Minneapolis, Minnesota 55455
[11]State University of New York at Albany, Albany, New York 12222
[12]Ohio State University, Columbus, Ohio 43210
[13]University of Oklahoma, Norman, Oklahoma 73019
[14]Purdue University, West Lafayette, Indiana 47907
[15]University of Rochester, Rochester, New York 14627
[16]Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309
[17]Southern Methodist University, Dallas, Texas 75275
[18]Syracuse University, Syracuse, New York 13244
[19]Vanderbilt University, Nashville, Tennessee 37235
[20]Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
[21]Wayne State University, Detroit, Michigan 48202
[22]California Institute of Technology, Pasadena, California 91125
[23]University of California, San Diego, La Jolla, California 92093
[24]University of California, Santa Barbara, California 93106
[25]University of Colorado, Boulder, Colorado 80309-0390

In recent years there has been great progress in charmed baryon spectroscopy. Three experiments [1] have now seen a doublet of particles decaying into $\Lambda_c^+\pi^+\pi^-$, and the consensus is that these states are the lowest lying orbitally excited states of the Λ_c^+. The quark model picture of these excited Λ_c^+ baryons is that they consist of a light diquark which has one unit of orbital angular momentum with respect to the heavy (charmed) quark, leading to a $J^P = \frac{1}{2}^-, \frac{3}{2}^-$ doublet. They are now commonly referred to as the Λ_{c1}^+ particles [2], where the numerical subscript refers to the total angular momentum of the light degrees of freedom. Clearly similar orbital excitations must exist in the Ξ_c^+ sector. Using data from the CLEO II detector, we present the first evidence of two new states, one decaying into $\Xi_c^+\pi^+\pi^-$ via an intermediate Ξ_c^{*0}, and the other decaying into $\Xi_c^0\pi^+\pi^-$ via an intermediate Ξ_c^{*+}. We identify these states as the $J^P = \frac{3}{2}^-$ Ξ_{c1} isospin doublet. Such states correspond to csq quark combinations where q is a u or d quark, the q and s spins are antiparallel, and the qs diquark has orbital angular momentum $L = 1$ with respect to the charmed quark. Preliminary versions of this analysis were presented elsewhere [3,4]. The analysis presented here includes mass dependent fitting of the particle trajectories taking into account energy loss throughout the detector, improved secondary and tertiary vertex detection, and an increased number of Ξ_c decay modes used for Ξ_c^* reconstruction.

The data presented here were taken by the CLEO II detector [5] operating at the Cornell Electron Storage Ring. The sample used in this analysis corresponds to an integrated luminosity of 4.8 fb^{-1} from data taken on the $\Upsilon(4S)$ resonance and in the continuum at energies just above and below the $\Upsilon(4S)$. 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 K's, π's and protons[1]. The analysis chain for reconstructing these particles follows closely that presented in our previous publications [6].

We fitted the invariant mass distributions for each decay mode to a sum of a Gaussian signal function and a second order polynomial background. The yields from all the decay modes are summarized in Table 1. We note that this is the first observation of the decay modes $\Xi_c^+ \to \Lambda\overline{K}^0\pi^+$ and $\Xi_c^0 \to \Lambda K^-\pi^+$. 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 measured mode-by-mode by a Monte Carlo simulation program. To illustrate the good statistics and signal to noise ratio of the Ξ_c signals, we have placed a cut $x_p > 0.5$, where $x_p = p/p_{max}$, p is the momentum of the charmed baryon, $p_{max} = \sqrt{E_{beam}^2 - M^2}$, and M is the calculated Ξ_c mass, and present the results for the various decay modes in Table 1. In the final analysis we prefer to apply an x_p cut only on the $\Xi_c\pi^-\pi^+$ combinations.

The Ξ_c candidates defined above were then combined with each remaining charged track in the event and the mass differences $\Delta M = M(\Xi_c^+\pi^-) - M(\Xi_c^+)$ and $M(\Xi_c^0\pi^+) - M(\Xi_c^0)$ were calculated. We consider those combinations within 5 MeV of the previously measured Ξ_c^* peaks found in these plots [6] as Ξ_c^* candidates.

We then combine these Ξ_c^* candidates with one more correctly charged track in the event

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[1] Charge conjugate states are implied throughout.

TABLE I. Measured yield for each sub-mode

Ξ_c Decay Mode	Ξ_c Yield ($x_p > 0.5$)
$\Xi^-\pi^+\pi^+$	369 ± 24
$\Xi^0\pi^+\pi^0$	231 ± 30
$\Lambda\overline{K^0}\pi^+$	61 ± 13
$\Xi^-\pi^+\pi^0$	130 ± 19
ΩK^+	37 ± 7
$\Xi^-\pi^+$	230 ± 18
$\Xi^0\pi^+\pi^-$	103 ± 22
$\Lambda K^-\pi^+$	86 ± 14
$\Lambda\overline{K^0}$	33 ± 10

and plot $M(\Xi_c\pi^-\pi^+) - M(\Xi_c)$ for both the Ξ_c^+ (Figure 1a) and the Ξ_c^0 (Figure 1b), with a requirement of $x_p > 0.6$ on the final combination. We prefer to present the data as a dipion mass difference rather than $M(\Xi_c^*\pi) - M(\Xi_c^*)$ because the latter measurement is complicated by the intrinsic width of the Ξ_c^*, which is not well known. In both figures there is a peak at around 348 MeV. We fit these two peaks to sums of Gaussians of fixed width ($\sigma = 1.8$ MeV, found from simulated events), and a polynomial background function. For the charged case, we find a signal of 19.7 ± 4.5 events at a ΔM of 348.6 ± 0.6 MeV. For the neutral case, we find an excess of 9.5 ± 3.2 events at ΔM of 347.2 ± 0.7 MeV. Both peaks are satisfactorily fit using this fitting function, however, to investigate the natural widths of these orbitally excited states, we have also fit to a Breit-Wigner function convoluted with a Gaussian resolution function. This gives limits to the natural widths of the states of $\Gamma < 3.5$ MeV and $\Gamma < 6.5$ MeV respectively, each at the 90% confidence level. We estimate the systematic uncertainty on the measured mass differences to be 1 MeV and 2 MeV respectively. This estimate takes into account the spread of results obtained using different fitting functions as well as uncertainties in the momentum measurements. The systematic uncertainty in the neutral case is large as this measurement is particularly sensitive to the choice of fitting function.

In order to check that all the Ξ_{c1} decays proceed via an intermediate Ξ_c^*, we release the cuts on $M(\Xi_c\pi) - M(\Xi_c)$, select combinations within 5 MeV of our final signal peaks and plot $M(\Xi_c\pi) - M(\Xi_c)$. Both plots (Figures 2a and b) show signals which were fit to a Breit-Wigner convoluted with a Gaussian resolution function, plus a flat background. The masses and widths for the Ξ_c^* particles found in this way are consistent with our previously published results. It is clear that the data is consistent with all the Ξ_{c1} decays proceeding via an intermediate Ξ_c^*.

Although the statistics are very limited, they are sufficient to do a rough investigation of the momentum spectrum with which the new particles are produced. We add the two isospin states together as we would expect them to have very similar momentum distributions. We relax the x_p cut from 0.6 to 0.5, and fit the dipion mass difference plots (Figure 2) in bins of x_p. The fit uses a fixed width derived from the Monte-Carlo study, with the mass fixed at the value found for $x_p > 0.6$. The yields in each bin of x_p were corrected for the detector efficiency, and the resulting x_p distribution shown in Figure 5. The fit to this spectrum is of the functional form due to Peterson *et al.* [7]. The fitted parameter ϵ_r is measured to be

$\epsilon_r = 0.07^{+0.03}_{-0.02}$. This value is very similar to that found for the Λ_{c1}^+ spectrum [1], and harder than those found for charmed baryons with no orbital angular momentum.

There has been little theoretical work in recent years on the spectroscopy of orbitally excited Ξ_c states. However, the models [8] that do exist predict that the excitation energy of the first orbitally excited doublet should be similar to the analogous value in the Λ_c^+ case (308 and 342 MeV for the two states). Furthermore the decay patterns of the Ξ_{c1} states should be closely analogous to those of the Λ_{c1}^+. The preferred decay of the $J^P = \frac{3}{2}^-$ 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. Decays to Ξ_c' would have to proceed via a D-wave and would therefore be suppressed. In the case of the $J^P = \frac{1}{2}^-$ Ξ_{c1} the situation is reversed. It is natural therefore to expect a particle found by its decay to $\Xi_c^*\pi$ to have $J^P = \frac{3}{2}^-$. When the total spin and parity of the baryon is considered, decays directly to the ground state with one transition π, not allowed for the Λ_{c1}^+ because of isospin conservation, are allowed for the Ξ_{c1} via a D-wave. Taking into account the large phase space available, such decays might be expected to be large. However, in the Heavy Quark Effective Theory (HQET) [9], where the angular momentum and parity of the light diquark degrees of freedom must be considered separately from those of the heavy quark, such decays are forbidden. Thus in the HQET picture, we would expect that the dominant decay of a $J^P = \frac{3}{2}^-$ Ξ_{c1} would be to $\Xi_c^*\pi$, consistent with our observation.

Following our first analysis of the Ξ_{c1}^+, there have been two papers that include theoretical calculations of the expected Ξ_{c1} widths. Yan and Pirjol [10] calculate $2.37 - 15.00$ MeV, whereas Chiladze and Falk [11] calculate $5.4^{+3.8}_{-2.5}$ MeV. Both calculations use the experimentally measured width of the $\Lambda_{c1}(2593)$ as input. Our results favour a natural width for each of the Ξ_{c1} particles at the lower end of these predictions.

In conclusion, we present evidence for the production of two new states. The first of these states decay into $\Xi_c^{*0}\pi^+$ with measured mass given by $M(\Xi_c^+\pi^-\pi^+) - M(\Xi_c^+) = 348.6 \pm 0.6 \pm 1.0$ MeV, and width, $\Gamma < 3.5$ MeV at the 90% confidence level. The second state decays into $\Xi_c^{*+}\pi^-$ with a mass given by $M(\Xi_c^0\pi^+\pi^-) - M(\Xi_c^0) = 347.2 \pm 0.7 \pm 2.0$ MeV, and width, $\Gamma < 6.5$ MeV at the 90% confidence level. Although we do not measure the spin or parity of these states, the observed decay modes, masses, and momentum distributions are all consistent with the new states being the $J^P = \frac{3}{2}^-$ Ξ_{c1}^+ and Ξ_{c1}^0 states, the charmed-strange analogues of the $\Lambda_{c1}^+(2625)$.

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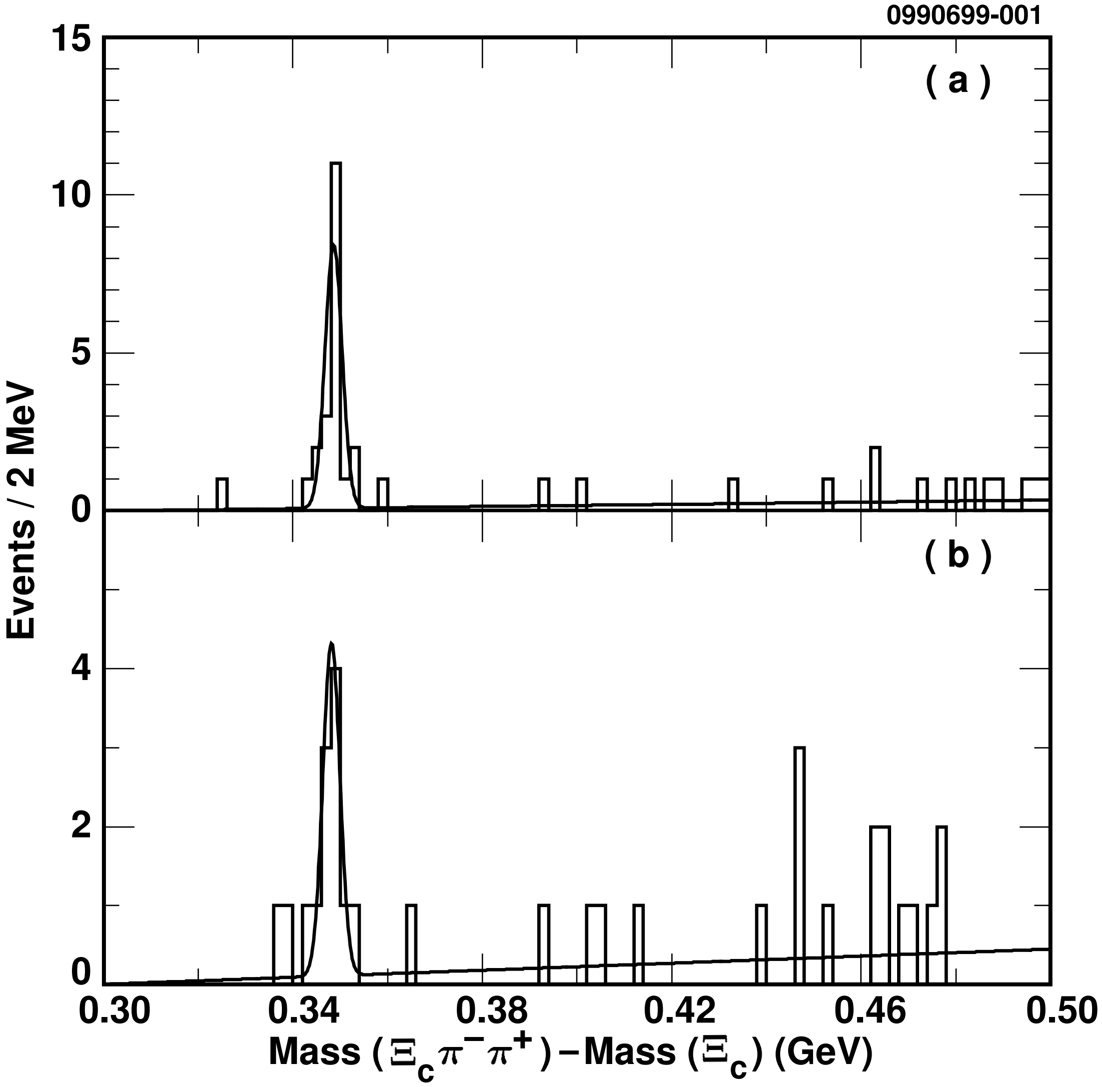

FIG. 1. (a)The mass difference $M(\Xi_c^+\pi^+\pi^-) - M(\Xi_c^+)$ for combinations that lie in the Ξ_c^{*0} band. and (b) the mass difference $M(\Xi_c^0\pi^+\pi^-) - M(\Xi_c^0)$ for combinations that lie in the Ξ_c^{*+} band. In both cases an $x_p > 0.6$ cut is applied.

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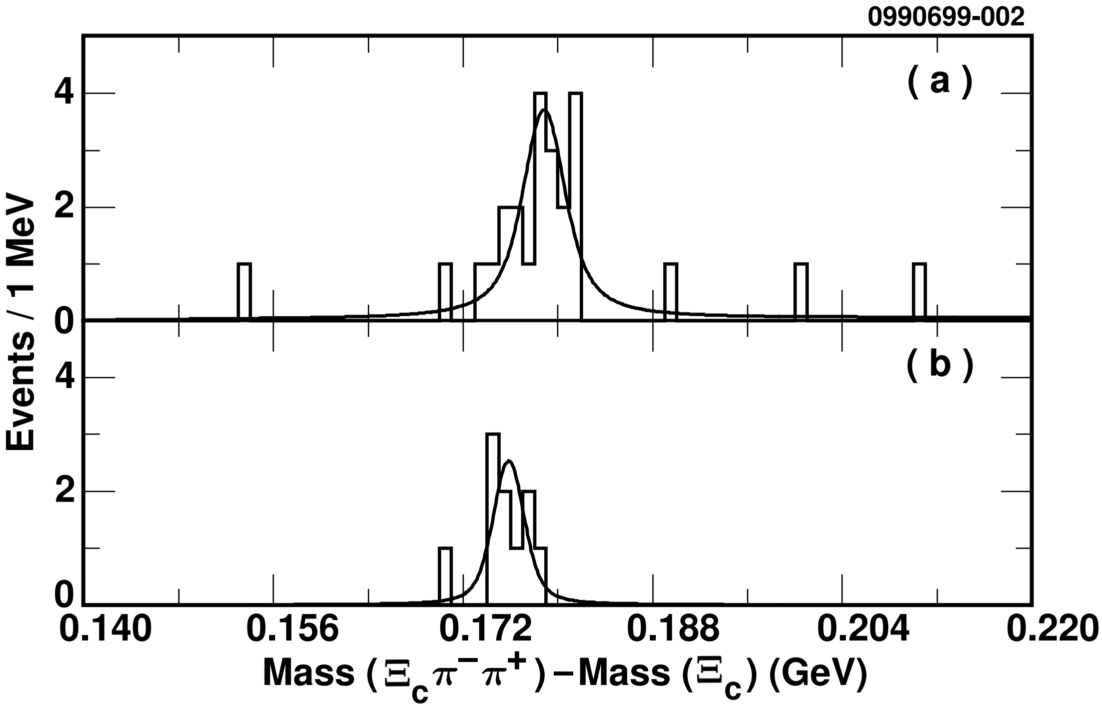

FIG. 2. After selecting combinations in the signals shown in Figure 1, we plot (a) $M(\Xi_c^+\pi^-) - M(\Xi_c^+)$ and (b) $M(\Xi_c^0\pi^+) - M(\Xi_c^0)$. Clear Ξ_c^* peaks are seen in both plots.

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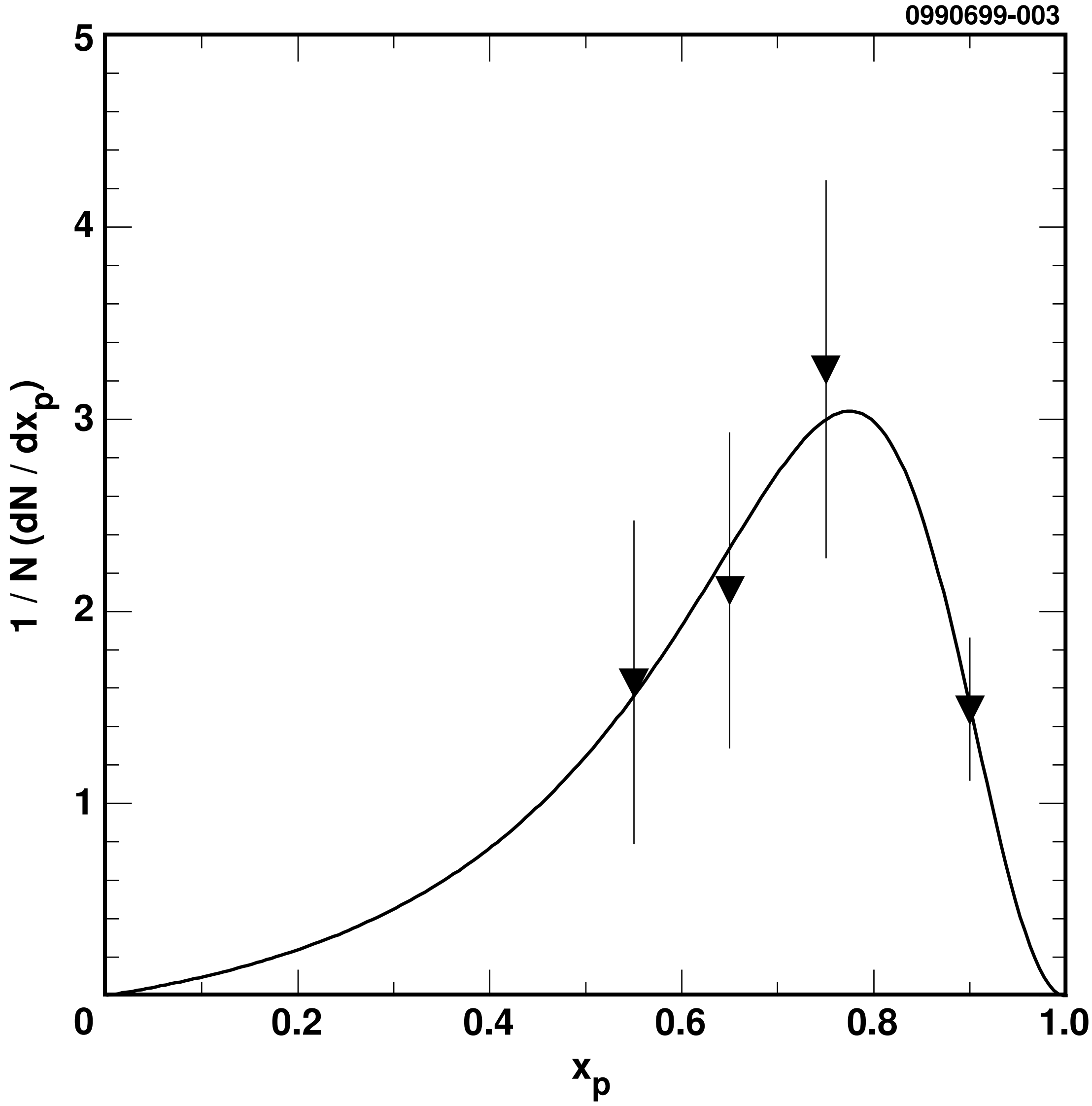

FIG. 3. Scaled momentum distribution of the new particles. The fit is of the form of the Peterson function.