Observation of a Narrow State Decaying into $\Xi_c^+ \pi^-$

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Using data recorded by the CLEO-II detector at Cornell Electron Storage Ring (CESR), we report the first observation of a narrow state decaying into $\Xi_c^+ \pi^-$. The state has mass difference $M(\Xi_c^+ \pi^-) - M(\Xi_c^+)$ of $178.2 \pm 0.5 \pm 1.0$ MeV/c^2, and a width of <5.5 MeV/c^2 (90% confidence

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level limit). The most likely explanation of this new state is that it is the Ξ_c^{*0}, the $J^P = \frac{3}{2}^+$ spin excitation of the Ξ_c^0 charmed baryon.

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Earlier CLEO and other experimental groups [1–6] have reported the observation of a ground state isodoublet, the Ξ_c^+ and Ξ_c^0 charmed baryons ($J^P = \frac{1}{2}^+$) . In these states the two lighter quarks are antisymmetric under interchange of flavor (i.e., in a spin-0 configuration). The next highest states are expected to be the $J^P = \frac{1}{2}^+$ Ξ_c' and the $J^P = \frac{3}{2}^+$ Ξ_c^* states, in which the lighter quarks are symmetric under the exchange of flavor and thus in a spin-1 configuration. According to theoretical predictions [7–13] the masses of the Ξ_c' states are expected to be below threshold for the decay to $\Xi_c\pi$, in which case they will decay electromagnetically; there has been one preliminary result indicating a possible signal in $\Xi_c'^+ \to \Xi_c^+\gamma$ with a mass difference of around 95 MeV/c^2 [14]. On the other hand, the Ξ_c^* states are expected to be heavy enough to decay by emission of a $\pi^\pm$. In this Letter, we present evidence of the existence of a particle decaying into $\Xi_c^+\pi^-$. In view of the theoretical models for the mass spectrum, we identify this state as the Ξ_c^{*0}.

The data presented here were taken by the CLEO II detector operating at the Cornell Electron Storage Ring (CESR). The sample used in this analysis corresponds to an integrated luminosity of 3.7 fb^{-1} from data taken on the $\Upsilon(4S)$ resonance and in the continuum at energies just above and below the $\Upsilon(4S)$.

We report the observation of a new particle decaying into $\Xi_c^+\pi^-$, where the Ξ_c^+ charmed baryon has been observed decaying into either $\Xi^-\pi^+\pi^+$ ($\Xi^- \to \Lambda\pi^-, \Lambda \to p\pi^-$), $\Xi^0\pi^+\pi^0$ ($\Xi^0 \to \Lambda\pi^0, \Lambda \to p\pi^-$), or Σ^+K^{*0} ($\Sigma^+ \to p\pi^0, K^{*0} \to K^-\pi^+$). Charge conjugate modes are implicit throughout. These decay modes of the Ξ_c^+ were chosen because they have the most significant signals. We have presented measurements [15,16] of the relative branching fraction of the Ξ_c^+ decaying into these channels. The analysis presented here is similar to that of Ref. [16], but optimized for greater detection efficiency, and includes an augmented data set.

The CLEO II detector is described elsewhere [17]; here we will briefly describe the parts of the detector most relevent to this analysis. The CLEO II detector is designed to detect both charged and neutral particles with excellent resolution and efficiency. The detector consists of a charged particle tracking system surrounded by a scintillation counter time-of-flight system and an electromagnetic shower detector consisting of 7800 thallium-doped cesium iodide crystals. These detectors are installed within a 1.5 T superconducting solenoidal magnet. The tracking chambers measure the particle trajectories in three dimensions; however, the cuts used to define displaced vertices use only the projection of the trajectory onto the plane perpendicular to the beam direction, as it is in these dimensions that the position information is most accurate. Particle identification is achieved by a combination of time-of-flight measurements and of energy-loss measurements in the drift chamber. In this analysis tracks are assigned a particular hypothesis if they have measurements loosely consistent with that particle; the efficiency of this requirement is around 99% per charged track. For the mode Σ^+K^{*0} a more restrictive cut is made to identify the K^- [16].

Candidates for Λ decays are reconstructed from $p\pi^-$ combinations, intersecting at a point greater than 2 mm from the primary event vertex. The candidates are required to have a measured invariant mass within 5.0 MeV/c^2 ($\approx 3\sigma$) of the known Λ mass.

The Ξ^- candidates are formed by combining each Λ candidate with each remaining negatively charged track. A vertex is formed from the intersection of the Λ track and the negatively charged track. The momentum components of the charged track are recalculated at the candidate Ξ^- vertex. We require that the measured flight path of the reconstructed Ξ^- be greater than 2 mm, the reconstructed Ξ^- be consistent with coming from the main event vertex, and the measured distance between the event vertex and the Ξ^- decay point be less than the distance between the event vertex and the Λ vertex. Combinations with a measured invariant mass within 5 MeV/c^2 ($\approx 3\sigma$) of the known Ξ^- mass are kinematically fit to this mass and used to reconstruct Ξ_c^+ candidates.

Candidates for Ξ^0 baryons are formed by combining each Λ candidate with each π^0 candidate. These π^0 candidates are formed from a pair of photons detected in the CsI calorimeter. As a first approximation they are assumed to come from the event vertex and only a loose cut is applied on the $\gamma\gamma$ invariant mass. The Λ candidates used for Ξ^0 reconstruction are required to have a measured flight path of greater than 1.5 cm and to not point back to the event vertex. The Ξ^0 is assumed to be created at the event vertex, and to have a momentum equal to the sum of the momenta of the Λ and π^0 candidates. The decay point of the Ξ^0 is taken to be the point of intersection between the Ξ^0 candidate and the Λ candidate. This decay point is required to be at least 3 mm from the event vertex. The 4 momentum of the π^0 candidate was recalculated using the Ξ^0 decay point as the point of origin of the photons, and its mass is required to be consistent ($<3.5\sigma$) with the known π^0 mass. The $\Lambda\pi^0$ invariant mass is then recalculated using this improved estimate of the π^0 momentum, and those combinations within 8 MeV/c^2 ($\approx 3\sigma$) of the known

Ξ^0 mass are kinematically fit to this mass and used to reconstruct Ξ_c^+'s.

Σ^+ candidates are found by forming $p\pi^0$ combinations which are consistent from coming from the decay of a Σ^+ with a decay point at least 0.6 mm from the primary vertex [18].

In order to select Ξ_c^+ candidates, each Ξ^- is combined with each remaining $\pi^+\pi^+$ pair in the event and each Ξ^0 is combined with each remaining $\pi^+\pi^0$ pair, where these π^0 candidates are required to have $p > 300$ MeV/c to reduce the background to the signal. The Σ^+ candidates are combined with $K^-\pi^+$ combinations and the reconstructed $K^-\pi^+$ invariant mass is required to be within 50 MeV/c^2 of the K^{*0} mass. To illustrate the good signal to noise ratio of the Ξ_c^+ signal, we add a mode-dependent cut on x_p, where $x_p = p/p_{\max}$; p is the momentum of the charmed baryon,

$$p_{\max} = \sqrt{E_{\text{beam}}^2 - M^2}\,,$$

and E_{beam} is the beam energy. This reduces the combinatorial background, which is worst for Ξ_c^+ candidates with low momentum. The invariant mass spectrum of $\Xi^-\pi^+\pi^+$ combinations with $x_p > 0.4$ is shown in Fig. 1(a); Fig. 1(b) shows the spectrum of $\Xi^0\pi^+\pi^0$ combinations with $x_p > 0.6$, and Fig. 1(c) shows the spectrum of Σ^+K^{*0} combinations with $x_p > 0.5$. In the fits, which are overlayed on these figures, the signals are parametrized by Gaussians with fixed widths ($\sigma = 7$ MeV/c^2, $\sigma = 15$ MeV/c^2, and $\sigma = 9$ MeV/c^2, respectively); they show yields of 160 ± 18, 76 ± 12, and 59 ± 12 events. These widths were determined using a GEANT based Monte Carlo simulation of the detector. The background functions used were polynomials, and in Fig. 1(c) there is an added background due to the reflection of misidentified $\Lambda_c^+ \to \Sigma^+\pi^+\pi^-$ events. Combinations within 2.5σ of the mass of the Ξ_c^+ in each decay mode are taken as Ξ_c^+ candidates. The x_p cut used in Fig. 1 was released before continuing with the analysis as we prefer to apply x_p cuts only on the $\Xi_c^+\pi^-$ combination.

The Ξ_c^+ candidates defined above were then combined with each remaining π^- track and the mass difference $M(\Xi_c^+\pi^-) - M(\Xi_c^+)$ is calculated. We then placed x_p cuts on the $\Xi_c^+\pi^-$ combinations, $x_p > 0.4$ for those involving the decay $\Xi^-\pi^+\pi^+$, $x_p > 0.6$ for those involving $\Xi^0\pi^+\pi^0$, and $x_p > 0.5$ for those involving Σ^+K^{*0}. Charmed baryons produced from decays of B mesons are kinematically limited to $x_p < 0.4$, so, as well as rejecting background, the x_p cut also rejects those candidates from B decays. This leaves only those produced by e^+e^- annihilation into $c\bar{c}$ jets, which are known to have a hard momentum spectrum. The mass difference plot, shown in Fig. 2, shows a clear peak at around 178 MeV/c^2. We fit this mass spectrum to the sum of a Chebyshev polynomial with threshold suppression, and a Breit-Wigner convoluted with a Gaussian resolution function

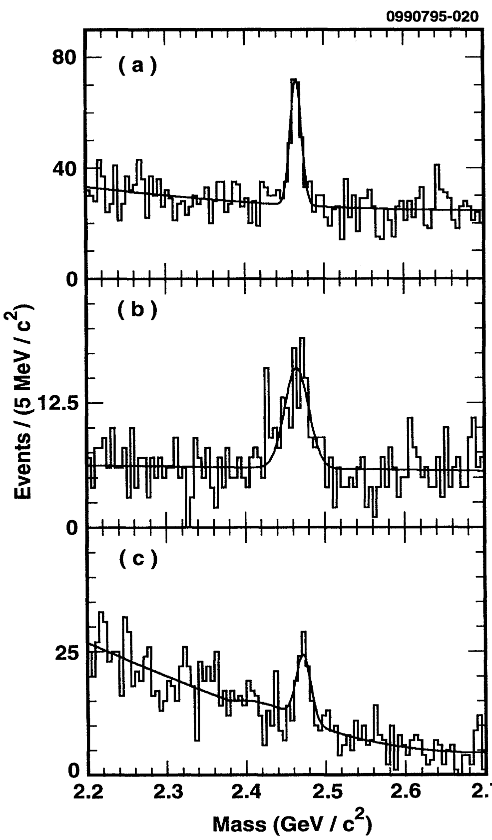

FIG. 1. Combinations of (a) $\Xi^-\pi^+\pi^+$ with $x_p > 0.4$, (b) $\Xi^0\pi^+\pi^0$ with $x_p > 0.6$, and (c) Σ^+K^{*0} with $x_p > 0.5$. All show clear Ξ_c^+ peaks. The fits are described in the text.

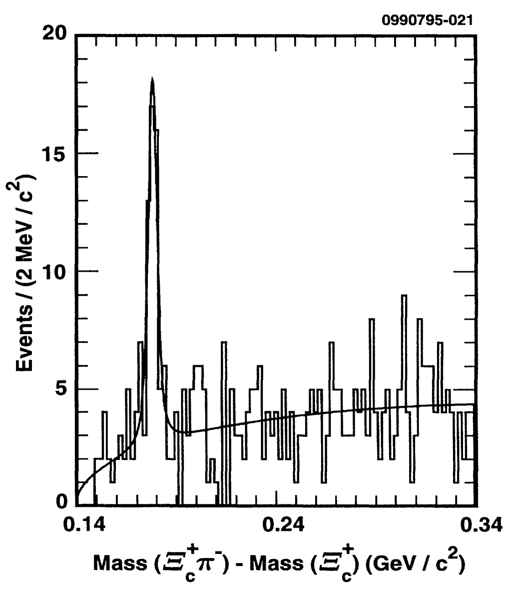

FIG. 2. The spectrum of the mass difference $M(\Xi_c^+\pi^-) - M(\Xi_c^+)$ for all three decay chains.

($\sigma = 1.6$ MeV/c^2, calculated by the detector simulation program). The fit yields a signal area of 54.6 ± 12.1 combinations, a mean mass difference of 178.2 ± 0.5 MeV/c^2 and an intrinsic width, $\Gamma = 2.6^{+1.7}_{-1.4}$ MeV/c^2, where the errors shown are statistical errors only. Considering systematic errors due to the fitting procedures and to energy-loss corrections for charged tracks, we find a mass difference for this new state of $178.2 \pm 0.5 \pm 1.0$ MeV/c^2. The measurement of the width is consistent with zero, so we present a 90% confidence level upper limit of $\Gamma < 5.5$ MeV/c^2.

Figures 3(a), 3(b), and 3(c), respectively, show the same mass difference as presented in Fig. 2, but separated into combinations involving the three Ξ_c^+ decay chains separately. In the fits overlayed on these histograms, the mass and width of the signal were constrained to the values found by the fit to Fig. 2. The number of events in the peaks is found to be 31.8 ± 6.6 events for Fig. 3(a), 10.5 ± 4.6 events for Fig. 3(b), and 10.9 ± 4.3 for Fig. 3(c).

We identify this new state as the Ξ_c^{*0}. In order to study the fragmentation function we study only those events in which $\Xi_c^+ \to \Xi^- \pi^- \pi^+$, as this mode has a good signal as low as $x_p = 0.4$. We divide the data shown in Fig. 3(a) into bins of x_p from 0.4 to 1.0, determine the Ξ_c^{*0} yield in each bin, and correct the yields using efficiencies obtained from Monte Carlo calculations. Figure 4 shows $\frac{1}{N}\frac{dN}{dx}$, for data points from $x_p = 0.4$ to $x_p = 1.0$. The overlayed fit, which uses the parametrization of Peterson *et al.* [19], $dN/dx_p \propto x_p^{-1}[1 - 1/x_p - \epsilon/(1 - x_p)]^{-2}$, gives a value of $\epsilon = 0.22^{+0.15}_{-0.08}$. This is similar to that obtained for Ξ_c^+ baryons [20], but larger than that of the $L = 1$ charmed baryons [21]. Using all three decay chains, and extrapolating the efficiency-corrected Ξ_c^+ and Ξ_c^{*0} baryons yields down to $x_p = 0$, we calculate that $(27 \pm 6 \pm 6)\%$ of the Ξ_c^+'s come from Ξ_c^{*0} decays, where the uncertainties are statistical and systematic, respectively. The dominating systematic uncertainty is due to the extrapolation of the fragmentation functions. We further calculate that the product of the cross-section times branching fraction for $\Xi_c^{*0} \to \Xi_c^+ \pi^- \to (\Xi^- \pi^+ \pi^+)\pi^-$ with $x_p > 0.4$ is $0.17 \pm 0.04 \pm 0.03$ pb, where we incorporate the results of Ref. 15.

Our identification of the new state as the $J^P = \frac{3}{2}^+$ state relies upon theoretical models. Taking the mass difference above and adding the Ξ_c^+ mass of 2465.1 ± 1.6 MeV/c^2 [22], we obtain a Ξ_c^{*0} mass of 2643.3 ± 2.2 MeV/c^2. The model predictions for this state are in the range 2620 to 2690 MeV/c^2 [7–13]. Our measurement is not consistent with the expectations for the $\Xi_c'^0$ state by the same authors, nor is it similar to the preliminary measurement of the $\Xi_c'^+$ state reported by WA-89 [14]. Orbital ($L = 1$) excitations of Ξ_c states would be expected to occur at higher mass differences, as they do

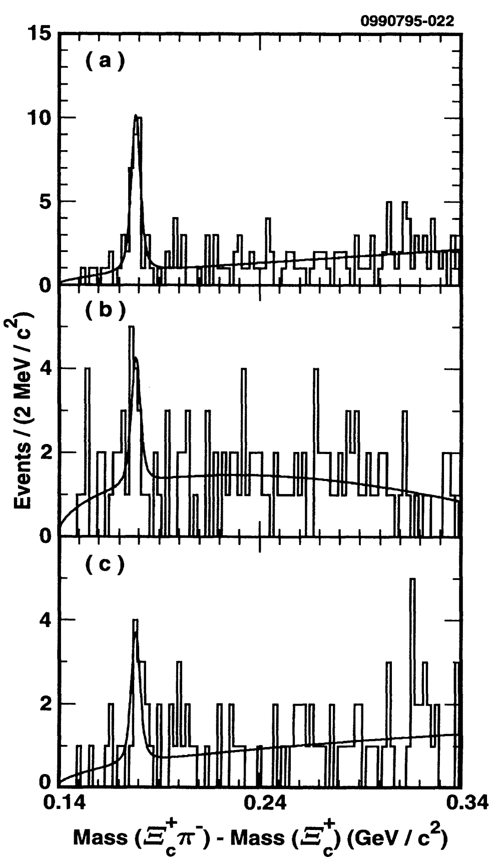

FIG. 3. The spectrum of the mass difference $M(\Xi_c^+ \pi^-) - M(\Xi_c^+)$ for (a) only $\Xi_c^+ \to \Xi^- \pi^+ \pi^+$, (b) only $\Xi^0 \pi^+ \pi^0$, and (c) only $\Xi_c^+ \to \Sigma^+ K^{*0}$. The fits are described in the text.

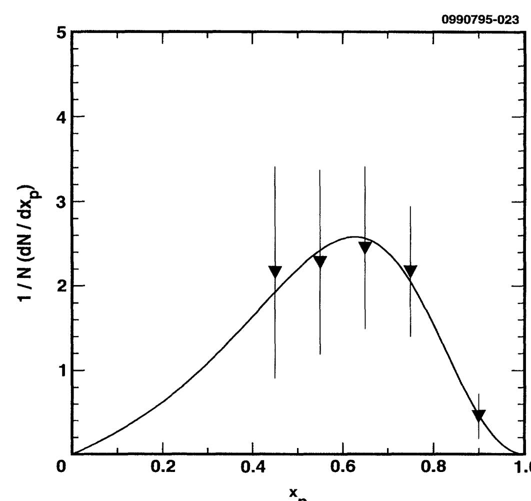

FIG. 4. The spectrum of scaled momentum, x_p, for the observed Ξ_c^{*0} candidates. The fit is of the form of the Peterson function.

in the Λ_c^+ system [21]. The expected width of a $J = \frac{3}{2}^+$ state can be calculated by analogy with the noncharmed Ξ^{*0}. We expect $\Gamma(\Xi_c^{*0})/\Gamma(\Xi^{*0})$ to be $0.75p_1^3/p_2^3$ where p_1 and p_2 are the decay momenta for the two processes, and where 0.75 is the appropriate ratio of the overlap of the spin wave functions [12]. Using our measured value of the mass difference, this calculation leads to an expected width of the Ξ_c^{*0} of ≈ 2.5 MeV$/c^2$, consistent with our observation of a narrow state.

In conclusion, we have observed a narrow ($\Gamma < 5.5$ MeV$/c^2$) peak which we believe corresponds to the decay $\Xi_c^{*0} \rightarrow \Xi_c^+ \pi^-$. The mass difference $M(\Xi_c^{*0}) - M(\Xi_c^+)$ is measured to be $178.2 \pm 0.5 \pm 1.0$ MeV$/c^2$.

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