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Observation of Two Narrow States Decaying Into $\Xi_c^+\gamma$ and $\Xi_c^0\gamma$

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Abstract

We report the first observation of two narrow charmed strange baryons decaying to $\Xi_c^+\gamma$ and $\Xi_c^0\gamma$, respectively, using data from the CLEO II detector at CESR. We interpret the observed signals as the $\Xi_c^{+\prime}(c\{su\})$ and $\Xi_c^{0\prime}(c\{sd\})$, the symmetric partners of the well-established antisymmetric $\Xi_c^+(c[su])$ and $\Xi_c^0(c[sd])$. The mass differences $M(\Xi_c^{+\prime}) - M(\Xi_c^+)$ and $M(\Xi_c^{0\prime}) - M(\Xi_c^0)$ are measured to be $107.8 \pm 1.7 \pm 2.5$ and $107.0 \pm 1.4 \pm 2.5$ MeV$/c^2$, respectively.

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CLEO [1,2] and other experimental groups [3–6] have previously reported the observation of the $J^P = (\frac{1}{2})^+$ ground states Ξ_c^0 ($c[sd]$) and Ξ_c^+ ($c[su]$) baryons, where [su] and [sd] denote the antisymmetric nature of their wave functions with respect to interchange of the light quarks. The partners of the above charmed strange baryons are the $\Xi_c^{0\prime}$ ($c\{sd\}$) and $\Xi_c^{+\prime}$ ($c\{su\}$), where $\{sd\}$ and $\{su\}$ specify that the wave functions are symmetric with respect to interchange of the light quarks. In this report we present the first observation of the $\Xi_c^{\prime}$ states [7]. The $J^P = \frac{3}{2}^+$ spin-excited states Ξ_c^{*0} and Ξ_c^{*+}, recently observed by CLEO [8,9], have spin-1 light diquarks like the $\Xi_c^{\prime}$, in contrast to spin-0 light diquarks in the Ξ_c states. The mass splitting $M(\Xi_c^{\prime}) - M(\Xi_c)$ [10–17] is expected to be in the range of $100 - 114$ MeV/c^2. With such a mass difference, the transition $\Xi_c^{\prime} \to \Xi_c\pi$ is kinematically forbidden, allowing only the decay $\Xi_c^{\prime} \to \Xi_c\gamma$. The above theoretical models also predict the mass difference $M(\Xi_c^*) - M(\Xi_c^{\prime})$ to be about 60-70 MeV/c^2.

The data used in this analysis was collected with the CLEO II detector [18] operating at CESR, and corresponds to an integrated luminosity of 4.96 fb^{-1} from the $\Upsilon(4S)$ resonance and continuum region at energies just below it. The charmed strange baryon Ξ_c^0 was reconstructed in the decay modes $\Xi^-\pi^+, \Xi^-\pi^+\pi^0, \Xi^0\pi^+\pi^-$ and Ω^-K^+, and Ξ_c^+ in the decay modes $\Xi^-\pi^+\pi^+$ and $\Xi^0\pi^+\pi^0$ [8,9,19]. In all cases, the signal area above the combinatorial background is found by fitting to the sum of one or more Gaussian functions with widths fixed at Monte Carlo predicted values, and a low-order Chebychev polynomial. Where particle identification is used, a joint probability for the pion, kaon, or proton hypothesis is defined using measurements of specific ionization (dE/dx) in the wire drift chambers and time-of-flight in the scintillation counters. A charged track is defined to be consistent with a particular mass hypothesis if the corresponding probability is greater than 0.1%.

Charmed baryons can be produced from either secondary decays of B mesons or directly from e^+e^- annihilations to $c\bar{c}$ jets. We define x_p and $x_p^{\prime}$ as the scaled momentum of the Ξ_c and $\Xi_c^{\prime}$, respectively. Here $x_p = p/p_{\max}$; p is the momentum of the charmed baryon, $p_{\max} = \sqrt{E_b^2 - M^2}$, E_b is the beam energy and M is the mass of the charmed baryon being considered. Charmed baryons produced from B decays are kinematically limited to $x_p < 0.4$, while $(60 - 70)$% of those produced from the continuum have $x_p > 0.4$. To reduce random combinatorial background, we apply a mode-dependent cut of $x_p > 0.5 - 0.6$, thus excluding charm baryons produced in B decays.

We begin by reconstructing $\Lambda \to p\pi^-$, $\Xi^0 \to \Lambda\pi^0$, $\Xi^- \to \Lambda\pi^-$, and $\Omega^- \to \Lambda K^-$. We select hyperons by requiring the distance between the reconstructed secondary decay vertex and the beam interaction point as measured in the plane perpendicular to the beam line, to be at least 2 mm for Λ and Ξ^-, and 3 mm for Ξ^0, respectively. No such cut is applied for Ω^-.

Candidates for $\Lambda \to p\pi^-$ decays are reconstructed from pairs of oppositely charged tracks, assuming the higher momentum one to be a proton and requiring it to be consistent with the proton hypothesis. The invariant mass of the combination is calculated using a three-dimensional vertex-constrained fit at the point of intersection. All $p\pi^-$ combinations within 5 MeV/c^2 ($\approx$ 3 standard deviations (σ)) of the nominal mass are accepted as Λ candidates.

A Ξ^- candidate vertex is reconstructed by finding the intersection between a Λ candidate and π^- track, and requiring the Ξ^- direction to be consistent with coming from the event vertex. A fit to the resultant distribution of $\Lambda\pi^-$ invariant mass combinations yields a total of 11578 ± 125 reconstructed Ξ^- candidates. All such combinations within 5 MeV/c^2 ($\approx 3\sigma$) of the nominal mass are accepted as Ξ^- candidates.

For Ω^- reconstruction, we combine each Λ candidate with any negatively charged track that is consistent with the kaon hypothesis. The Ω^- vertex is found using a procedure very similar to that used for finding Ξ^-. A fit to the distribution of ΛK^- invariant mass combinations yields a signal of 373 ± 32 events, and combinations within 5 MeV/c^2 of the nominal mass are selected as Ω^- candidates.

The Ξ^0 candidates are reconstructed from Λ and π^0 pairs. Candidates for π^0 are formed from pairs of photons detected in the CsI calorimeter, with at least one photon coming from the barrel ($|\cos\theta| < 0.7$) rather than the endcap regions, where θ is the polar angle with respect to the e^+ direction. Only photons with energy greater than 50 MeV and distinctly separated from charged tracks are used. As a first approximation, the π^0 mass is calculated assuming the event vertex to be its point of origin. A Ξ^0 vertex is then found from the intersection of the Λ and π^0 directions. The mass and four-momentum of the π^0 is recalculated assuming the Ξ^0 vertex to be its origin. A new vertex is calculated using the new π^0 and Λ directions. A fit to the $\Lambda\pi^0$ mass distribution yields 7568 ± 227 signal events, and all $\Lambda\pi^0$ combinations within 8 MeV/c^2 of the nominal mass are defined as Ξ^0 candidates.

We first discuss the reconstruction of Ξ_c^+ candidates in the decay modes $\Xi^-\pi^+\pi^+$ and $\Xi^0\pi^+\pi^0$. As presented earlier, Ξ^- and Ξ^0 candidates are combined with charged or neutral pions which are consistent with originating from the event vertex. In the case of the first decay mode, only charged tracks with momentum greater than 100 MeV/c are used. For the second decay mode, which has more combinatorial background because of the π^0, both the charged and neutral pions are required to have momenta greater than 250 MeV/c. We form invariant mass distributions of $\Xi^-\pi^+\pi^+$ combinations with $x_p > 0.5$ and $\Xi^0\pi^+\pi^0$ combinations with $x_p > 0.6$. Fitting these distributions with Monte Carlo predicted widths of 8.5 and 15 MeV/c^2, respectively, we obtain yields of (155 ± 15) and (70 ± 14) signal events in these two decay modes or a combined yield of (225 ± 21). Combinations within 2σ of the fitted peak masses in each decay mode are then selected as Ξ_c^+ candidates. The invariant mass distribution for the summed combinations in both Ξ_c^+ decay modes is shown in Fig. 1(a).

We reconstruct Ξ_c^0 in the four decay modes $\Xi^-\pi^+$, $\Xi^-\pi^+\pi^0$, Ω^-K^+, and $\Xi^0\pi^+\pi^-$. We start with the hyperon candidates, which are defined according to procedures discussed previously, and add charged tracks which are consistent with coming from the event vertex. For the decay mode $\Xi^-\pi^+\pi^0$, we assume the photons used for reconstructing $\pi^0 \to \gamma\gamma$ are coming from the event vertex. Only $\gamma\gamma$ combinations having invariant mass within 12.5 MeV/c^2 (2.5σ) of the nominal mass are used as π^0 candidates. In the case of Ω^-K^+, we use only primary charged tracks consistent with the kaon hypothesis. Only combinations with $x_p > 0.5$ are used in the case of the first three decay modes; for the last decay mode, since the combinatorial background is higher, a cut of $x_p > 0.6$ is used. Fitting the invariant mass distributions corresponding to the decay modes $\Xi^-\pi^+$, $\Xi^-\pi^+\pi^0$, Ω^-K^+, and $\Xi^0\pi^+\pi^-$ with Monte Carlo predicted widths of $8, 10, 7$ and 12 MeV/c^2, we obtain yields of (133 ± 41), (86 ± 13), (24 ± 5) and (46 ± 10) signal events, respectively. This gives a combined Ξ_c^0 yield of (289 ± 44) events. The sum of the four Ξ_c^0 invariant mass distributions is shown in Fig. 1 (b).

To search for $\Xi_c^{+\prime}$ and $\Xi_c^{0\prime}$, we start with the Ξ_c^+ and Ξ_c^0 candidates reconstructed according to the procedure described in the earlier sections. We then form $\Xi_c^+\gamma$ and $\Xi_c^0\gamma$ combinations using photons with energy greater than 100 MeV. Only showers detected in the barrel CsI crystal calorimeter ($|\cos\theta| < 0.7$), with clear isolation from nearby charged tracks and shower fragments are used as photon candidates. The lateral shower profile of the candidate is required to be consistent with that of a photon. A photon is also rejected if it is part of a good π^0 candidate, as defined in the section on Ξ_c^0 reconstruction. About $(30-50)\%$ of photons from Ξ_c' are lost due to this veto. Instead of plotting the $\Xi_c\gamma$ invariant mass combinations, we plot the mass difference $\Delta M = M(\Xi_c\gamma) - M(\Xi_c)$, which has better mass resolution as the errors from Ξ_c reconstruction are common to both terms and therefore cancel. In plotting the ΔM distributions, the x_p cut on Ξ_c reconstruction is removed and instead we place a cut on x_p', the x_p of the $\Xi_c\gamma$ combination. Final states including Ξ_0 have larger combinatorial backgrounds. We therefore require $x_p' > 0.6$ for these states and $x_p' > 0.5$ for all other final states.

Fitting the mass difference $\Delta M^+ = M(\Xi_c^+\gamma) - M(\Xi_c^+)$ distributions corresponding to the two Ξ_c^+ decay modes used in the analysis, we obtain (16.1 ± 5.1) and (7.5 ± 3.6) signal events, respectively. Similarly, fits to the mass difference $\Delta M^0 = M(\Xi_c^0\gamma) - M(\Xi_c^0)$ distributions corresponding to the four Ξ_c^0 decay modes separately yield signal areas of (7.0 ± 4.0), (11.6 ± 4.4), (3.8 ± 2.0), and (6.0 ± 3.3) events, respectively. It may be noted that there is at least one mode in each case with an enhancement of 3σ statistical significance and corroborating enhancements in the other decay modes in the mass difference region around 108 MeV/c^2. Fig. 2 (a) and (b) show the combined mass difference distributions for the $\Xi_c^+\gamma$ and $\Xi_c^0\gamma$ combinations, respectively, where the contributions from the different decay modes have been summed. The distributions are fitted with widths fixed at the Monte Carlo values of 5 MeV/c^2 in both cases. In Fig. 2 (a), the narrow resonance corresponds to a signal area of (25.5 ± 6.5) events at a mass difference $\Delta M^+ = (107.8\pm1.7)$ MeV/c^2 with a statistical significance of 3.9σ . Similarly, a fit to Fig. 2 (b) yields a signal area of (28.0 ± 7.1) events at a mass difference $\Delta M^0 = (107.0\pm1.4)$ MeV/c^2 with statistical significance of 3.9σ. We associate these resonances with the isospin doublet $\Xi_c^{+\prime}$ and $\Xi_c^{0\prime}$. To rule out the possibility that the signal is due to random background under the Ξ_c signal, we reconstruct $\Xi_c\gamma$ combinations using fake Ξ_c candidates from the side-band of the Ξ_c nominal mass region. The corresponding mass difference distributions (ΔM) show no evidence of peaking in the region of interest.

In order to probe the systematic stability of the measured mass differences, we studied the effect of different background shapes, alternate selection criteria, and the calibration of the calorimeter absolute energy scale. The major contributor to systematic shifts was found to be the removal of the π^0 veto. This has the effect of increasing the efficiency by 30% and 60% for $\Xi_c^{+\prime}$ and $\Xi_c^{0\prime}$, respectively, but also doubling the background, dominantly from $\Xi_c^* \to \Xi_c\pi^0$ in which one of the photons from π^0 decay is ignored in the reconstruction. Based on all these studies we assign a systematic error to the mass differences of ±2.5 MeV/c^2.

To measure the x_p' spectrum for Ξ_c' production, we assume that at the level of statistics available in our data, the fragmentation functions for $\Xi_c^{+\prime}$ and $\Xi_c^{0\prime}$ are the same, so that we can combine the data for the two resonances together. The yield is then obtained as a function of x_p' for all the decay modes of both the resonances from $0.5 < x_p' < 1.0$ and corrected for x_p'-dependent reconstruction efficiencies. The normalized distribution is shown in Fig. 3. A fit to the Peterson fragmentation function [20] yields the fragmentation parameter $\epsilon_q =$

$0.20^{+0.23}_{-0.09} \pm 0.07$, which is similar to the previously published result of $\epsilon_q = 0.23^{+0.06}_{-0.05} \pm 0.03$ for Ξ_c^+ production [19].

We measure that $(37 \pm 11 \pm 7)\%$ of all Ξ_c^+ produced from the continuum are from $\Xi_c^{+\prime}$ decays, while $(35 \pm 9 \pm 7)\%$ of all Ξ_c^0 are from $\Xi_c^{0\prime}$ decays. The comparable fraction of Ξ_c^+s from Ξ_c^{*0} decays is $(27 \pm 6 \pm 6)\%$ [8]. The fraction of Ξ_c from Ξ_c' is predicted by Adamov and Goldstein [21] to be 1.7 times that from Ξ_c^*.

In conclusion, we have observed two narrow resonances decaying to $\Xi_c^+\gamma$ and $\Xi_c^0\gamma$. The mass differences $M(\Xi_c^+\gamma) - M(\Xi_c^+)$ and $M(\Xi_c^0\gamma) - M(\Xi_c^0)$ are measured to be $(107.8 \pm 1.7 \pm 2.5)$ and $(107.0 \pm 1.4 \pm 2.5)$ MeV$/c^2$, respectively; the second error in each case is systematic. This is in good agreement with theoretical expectations for these mass differences, assuming the resonances to be $\Xi_c^{+\prime}$ and $\Xi_c^{0\prime}$, respectively. This is also in good agreement with the models which predict the mass difference $M(\Xi_c^*) - M(\Xi_c')$ to be about 60-70 MeV$/c^2$. Since the $J^P = (\frac{3}{2})^+$ charmed strange baryons Ξ_c^{*+} and Ξ_c^{*0} have already been observed, the most likely interpretation of the observed resonances would be as the $J^P = (\frac{1}{2})^+$ charmed strange baryons $\Xi_c^{+\prime}$ and $\Xi_c^{0\prime}$, respectively.

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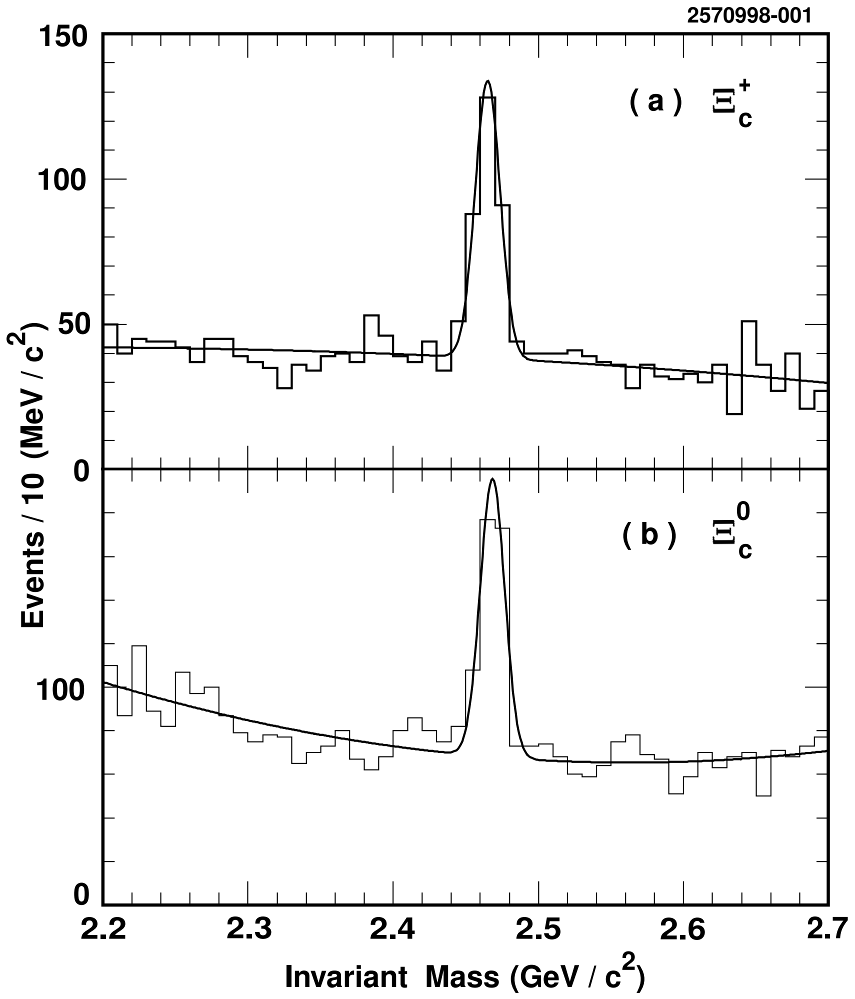

FIG. 1. (a) Summed invariant mass distributions for $\Xi^-\pi^+\pi^+$ and $\Xi^0\pi^+\pi^0$ combinations with $x_p > 0.5$ and 0.6, respectively, and (b) for $\Xi^-\pi^+$, $\Xi^-\pi^+\pi^0$, $\Omega^- K^+$, and $\Xi^0\pi^+\pi^-$ combinations with $x_p >$0.5, 0.5, 0.5 and 0.6, respectively.

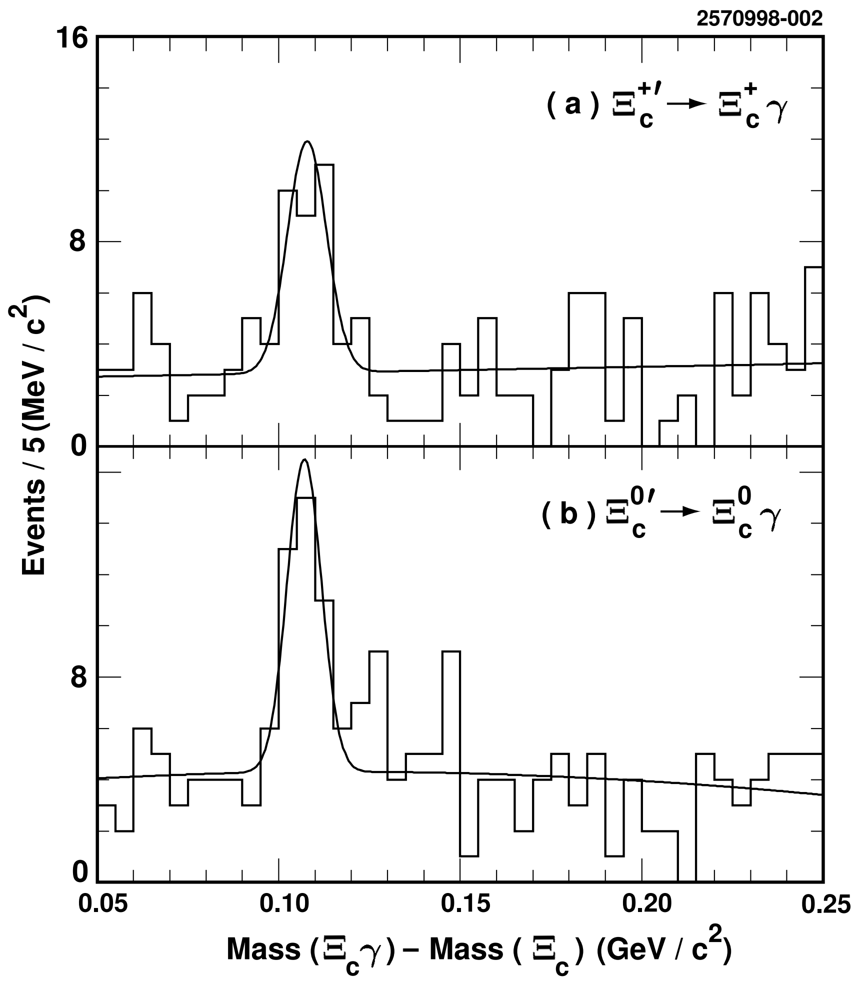

FIG. 2. Invariant mass difference $\Delta M(\Xi_c\gamma - \Xi_c)$ distributions for $\Xi_c^+\gamma$ and $\Xi_c^0\gamma$, where contributions from the different Ξ_c decay modes have been summed in each case.

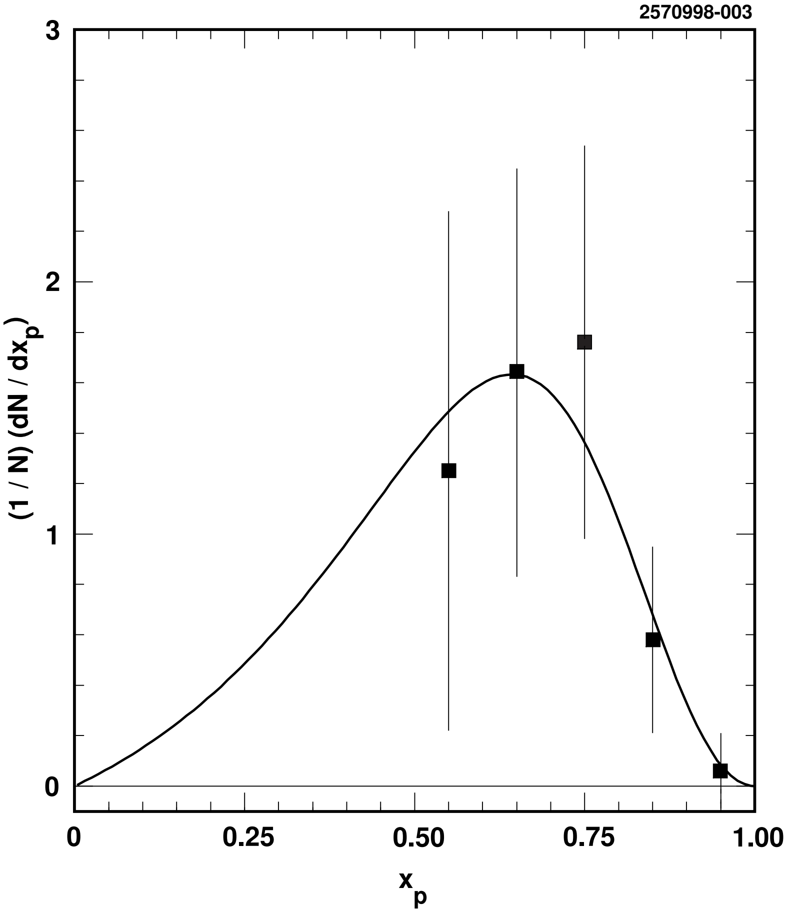

FIG. 3. Fragmentation function for Ξ_c' (weighted average of $\Xi_c^{+\prime}$ and $\Xi_c^{0\prime}$ momentum distributions).