# Evidence of new states decaying into Xi*(c)pi

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

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Using 13.7 $\mathrm{fb}^{-1}$ of data recorded by the CLEO detector at Cornell Electron Storage Ring, we report evidence of 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 $J^P = \frac{1}{2}^-$ $\Xi_{c1}$ particles, the charmed-strange analogs of the $\Lambda_{c1}^+(2593)$.

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The $\Xi_c$ 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 $\Xi_c^0$ and $\Xi_c^+$, have $J^P = \frac{1}{2}^+$ and no orbital angular momentum, and, like the $\Lambda_c^+$, have a wave function that is antisymmetric 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 $J^P = \frac{3}{2}^+$ $\Xi_c^*$ states, and one of these observations has since been confirmed [2]. In 1999, CLEO discovered [3] the $\Xi_c^\prime$ 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 $\Sigma_c$. 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 diquark 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 $\Xi_{c1}$ 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 $J^P = \frac{3}{2}^-$ $\Xi_{c1}$ 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 $\Xi_c^\prime\pi$. This is the expected decay mode of the $J^P = \frac{1}{2}^-$ $\Xi_{c1}$ states. That fact, in addition to our measured masses, leads 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 $\mathrm{fb}^{-1}$ from data taken on the $\Upsilon(4S)$ resonance and in the continuum at energies just below the $\Upsilon(4S)$. Of these data, 4.7 $\mathrm{fb}^{-1}$ 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 $\Xi_c^+$ and $\Xi_c^0$ particles, using their decays into $\Lambda$, $\Xi^-$, $\Omega^-$, and $\Xi^0$ hyperons as well as kaons, pions, and protons. (Charge conjugate states are implied throughout.) 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. $\Xi_c$ candidates were defined as those combinations within $2\sigma$ of the known mass of the $\Xi_c^+$ or $\Xi_c^0$, where $\sigma$ 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 $\Xi_c$ signals, and to reduce the combinatorial background, we placed a cut $x_p > 0.6$, where $x_p = p/p_{\max}$, and $p$ is the momentum of the charmed baryon, $p_{\max} = \sqrt{E_{\text{beam}}^2 - M^2}$, where $M$ is the reconstructed $\Xi_c$ 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 $\Xi_c^\prime\pi$ combinations.

The $\Xi_c$ 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

TABLE I. $\Xi_c^0$ and $\Xi_c^+$ decay mode yields, integrated over $\pm 2\sigma$ of the peak.

| Particle | Mode | $\Xi_c$ Yield, $x_p > 0.6$ | Background |
|---|---|---|---|
| $\Xi_c^0$ | $\Xi^-\pi^+$ | 440 | 112 |
| | $\Xi^-\pi^+\pi^-\pi^+$ | 106 | 133 |
| | $\Xi^-\pi^+\pi^0$ | 357 | 377 |
| | $\Omega^-K^+$ | 59 | 12 |
| | $\Xi^0\pi^+\pi^-$ | 196 | 202 |
| | $\Lambda K^-\pi^+$ | 179 | 238 |
| | $\Lambda K_s^0$ | 106 | 80 |
| Total | | 1443 | 1154 |
| $\Xi_c^+$ | $\Xi^0\pi^+$ | 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 |

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 $\theta$ 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 $\pi^0$ was rejected. Those combinations with calculated mass differences within 8 MeV ($\approx 2\sigma$) of the measured mass differences for the $\Xi_c'$ particles [3] were retained for further analysis. As the $\Xi_c'$ decays electromagnetically, its intrinsic width is negligible, and so the candidates were kinematically constrained to the $\Xi_c'$ masses using the measured mass differences.

We then combine these $\Xi_c'$ 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 Fig. 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 $\Xi_c$ daughters. In both 1(a) and 1(b) there is a peak at about 320 MeV, indicative of the decay of a $\Xi_{c1}^+$ [Fig. 1(a)] and a $\Xi_{c1}^0$ [Fig. 1(b)]. We fit each of the two peaks to a sum of a Gaussian signal function of floating width, and a first order 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 $5.6 \pm 1.7$ MeV. For the $\Xi_c^{+\prime}\pi^-$ case, we find an excess of $14.2^{+4.6}_{-3.9}$ events and a width of $3.9 \pm 1.5$ MeV. These values are larger than the resolution of these decays in the CLEO detector which is about 1.2 MeV in the CLEO II.V data and about 1.4 MeV in the CLEO II data. We have also fit each plot to the sum of a Breit-Wigner function convolved with a double Gaussian resolution function and a first order polynomial background function, using a maximum likelihood method and a bin width of 0.5 MeV. The widths of the resolution function were 0.84 and 3.87 MeV, the broader Gaussian had an area 31% of the narrower, and the central values of the two Gaussians were constrained to be equal. These values were obtained on a fit to Monte Carlo data, generated with the same proportions of CLEO II.V and CLEO II detector configurations as the real data. The resolution function parameters were fixed in the fit to the data in Fig. 1. 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 Fig. 1(a), 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 Fig. 1(b). These fits are superimposed on the data in Fig. 1. The results for $\Gamma$ are limited in their precision by the low statistics, but indicate that it is very likely that these states have an intrinsic 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 $\Xi_{c1}$ decays proceed via an intermediate $\Xi_c'$ 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 [Figs. 2(a) and 2(b)] is fit to the sum of a fixed width $\Xi_c'$ signal and a polynomial background function, and they show signals which are consistent in mass with our published results for the $\Xi_c'$ pair [3]. It is clear that

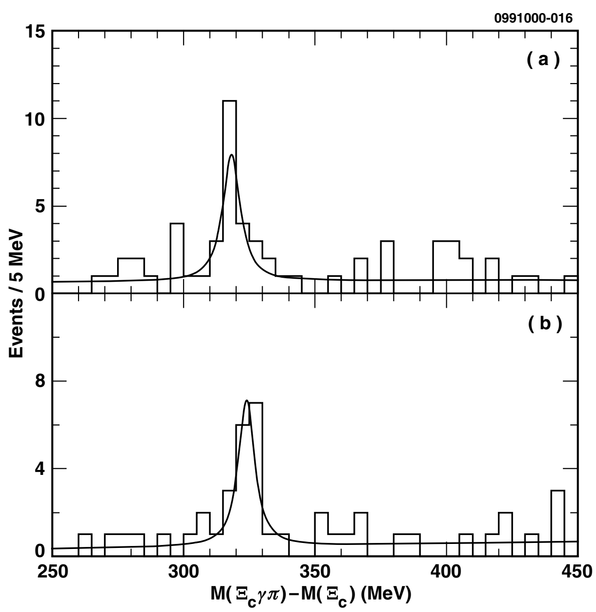


FIG. 1. Mass differences (a) $M(\Xi_c^0\gamma\pi^+) - M(\Xi_c^0)$ and (b) $M(\Xi_c^+\gamma\pi^-) - M(\Xi_c^+)$. Each plot shows a distinct peak. Note that the $\Xi_c'$ mass has been fixed in these plots, so that we could equivalently show $M(\Xi_c'\pi) - M(\Xi_c')$ as this would just be a translation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

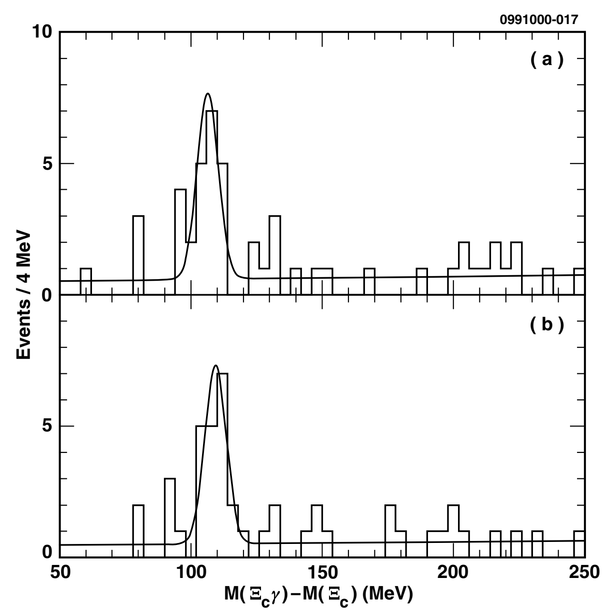


FIG. 2. Mass differences (a) $M(\Xi_c^0\gamma) - M(\Xi_c^0)$ and (b) $M(\Xi_c^+\gamma) - M(\Xi_c^+)$ for events in the $\Xi_{c1}$ mass windows ($\pm 8$ MeV of the found peaks). The fits are described in the text.

our data are consistent with all the $J^P = \frac{1}{2}^- \; \Xi_{c1}$ decays proceeding via an intermediate $\Xi_c'$.

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 $\Xi_c'$ 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 $\gamma$ transitions which have poorer resolution and lower signal-to-noise ratio than charged particle transitions.

The decay patterns of the $\Xi_{c1}$ states should be closely analogous to those of the $\Lambda_{c1}^+$. The preferred decay of the $J^P = \frac{1}{2}^- \; \Xi_{c1}$ 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 $\Xi_c^*$ would have to proceed via a $D$ wave. In heavy quark effective theory (HQET) [8], where the angular momentum and parity of the light diquark degrees of freedom must be considered separately from those of the heavy quark, decays of the $\Xi_{c1}$ directly to ground state $\Xi_c$ baryons are not allowed. Thus we identify our two peaks as the $J^P = \frac{1}{2}^- \; \Xi_{c1}^0$ and $\Xi_{c1}^+$. Combining our results found here with our previous results on the $J^P = \frac{3}{2}^- \; \Xi_{c1}$ states [4], and using world average values [9] for the isospin splitting of the ground state $\Xi_c$ baryons, we find the splitting between the $J^P = \frac{3}{2}^-$ and the $J^P = \frac{1}{2}^-$ 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 $\Lambda_c^+$ and charmed meson systems [9], 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 $\Xi_c$ have smaller isospin splittings than that of the ground states. The $J^P = \frac{1}{2} \; \Xi_{c1}$ 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 intrinsic width of a few MeV. It is not surprising, therefore, that the $J^P = \frac{1}{2}^- \; \Xi_{c1}$ 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 $J^P = \frac{1}{2}^- \; \Xi_{c1}^+$ and $\Xi_{c1}^0$ states, the charmed-strange analogs of the $\Lambda_{c1}^+(2593)$.

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