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Observation of Two Excited Charmed Baryons Decaying into lambda(c)+ pi+-

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CLEO Collaboration

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Abstract

Using data recorded by the CLEO-II detector at CESR, we report evidence of a pair of excited charmed baryons, one decaying into $\Lambda_c^+\pi^+$ and the other into $\Lambda_c^+\pi^-$. The doubly charged state has a measured mass difference $M(\Lambda_c^+\pi^+) - M(\Lambda_c^+)$ of $234.5 \pm 1.1 \pm 0.8$ MeV and a width of $17.9^{+3.8}_{-3.2} \pm 4.0$ MeV, and the neutral state has a measured mass difference $M(\Lambda_c^+\pi^-) - M(\Lambda_c^+)$ of $232.6 \pm 1.0 \pm 0.8$ MeV and a width of $13.0^{+3.7}_{-3.0} \pm 4.0$ MeV. We identify these states as Σ_c^{*++} and Σ_c^{*0}, the spin $\frac{3}{2}^+$ excitations of the Σ_c baryons.

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Recently, we reported [1,2] the observation of two narrow states decaying into $\Xi_c \pi$, which we identified as the $J^P = \frac{3}{2}^+$ spin excitations of the charmed-strange Ξ_c^0 and Ξ_c^+ baryons. Until now, however, evidence for $J^P = \frac{3}{2}^+$ spin excitations of their non-strange analogues, the Σ_c^* baryons, has been restricted to a cluster of 6 $\Lambda_c^+ \pi^+$ events [3] with an estimated mass difference, $\Delta M \equiv M(\Sigma_c^*) - M(\Lambda_c^+)$ of $245 \pm 5 \pm 5$ MeV. Here we report evidence for two particles decaying into $\Lambda_c^+ \pi^+$ and $\Lambda_c^+ \pi^-$, respectively. The two states have similar cross sections, masses and widths. We identify these states as the Σ_c^{*++} and Σ_c^{*0} baryons [4].

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 reconstructed Λ_c^+ baryons using 13 different decay modes [6]. Measurements of the branching fractions into all these modes and the general procedures for finding them have previously been presented by the CLEO collaboration [7,8]. For this search and data set, the exact cuts have been optimized for high efficiency and low background. Briefly, particle identification of p, K^-, and π candidates was performed using specific ionization measurements in the drift chamber, and when present, time-of-flight measurements. Hyperons were found by detecting their decay points separated from the main event vertex. To obtain the Λ_c^+ yields, we fitted the invariant mass distributions for each Λ_c^+ mode to a sum of a Gaussian signal and a low-order polynomial background. Combinations within 1.6 standard deviations of the mass of the Λ_c^+ in each decay mode are taken as Λ_c^+ candidates; the signal yields and backgrounds within this mass window are given in Table I for each Λ_c^+ mode.

The Λ_c^+ candidates were then combined with each remaining charged track in the event and the mass difference $M(\Lambda_c^+ \pi^\pm) - M(\Lambda_c^+)$ was calculated. To reduce the combinatorial background, we require $x_p > 0.5$, where $x_p = p/p_{max}$, $p_{max} = \sqrt{E_{beam}^2 - M^2}$, and p and M are the reconstructed momentum and mass of the $\Sigma_c^* \to \Lambda_c^+ \pi^\pm$ candidate. To demonstrate the high statistics and good signal to background ratios of the initial Λ_c^+ samples, for Table I we made a cut on the analagously defined quantity $x_p(\Lambda_c^+)$, of $x_p(\Lambda_c^+) > 0.45$; this corresponds approximately to $x_p > 0.5$ for real Σ_c^* signal. We note that charmed baryons produced from decays of B mesons are kinematically limited to $x_p < 0.4$, so the x_p cut restricts our analysis to charmed baryons produced by e^+e^- annihilation into $c\bar{c}$ jets, which are known to have a hard momentum spectrum.

We define θ_{dec} to be the angle between the π momentum measured in the rest frame of the $\Lambda_c^+ \pi$, and the direction of the $\Lambda_c^+ \pi$ in the laboratory frame. The combinations are required to pass a cut of $cos(\theta_{dec}) > -0.4$, which suppresses the large background from low momentum π mesons. The mass difference spectra, shown in Figure 1, each show clear peaks near 167 MeV due to Σ_c decays, broad enhancements below 204 MeV due to feed-down from $\Lambda_c^{*+}(2630) \to \Lambda_c^+ \pi^+ \pi^-$ decays [9], and broad excesses near 233 MeV which are our signals. The overlaid histogram in each case shows the mass difference spectrum using normalized sidebands of the Λ_c^+; no enhancements are observed in these histograms, and good fits are obtained to them when fit with smooth second-order polynomials.

The fits shown for the signal spectra in Figure 1 each have five components: i) the

Mode	Signal	Background
$pK^-\pi^+$	8364	16291
$p\overline{K^0}$	974	413
$\Lambda\pi^+$	1139	808
$\Lambda\pi^+\pi^0$	917	969
$\Lambda\pi^+\pi^-\pi^+$	771	773
$\Sigma^0\pi^+$	704	880
$\Sigma^+\pi^+\pi^-$	772	691
$\Sigma^+K^+K^-$	61	17
$\Xi^-K^+\pi^+$	225	55
Ξ^0K^+	128	49
$pK^-\pi^+\pi^0$	341	478
$p\overline{K^0}\pi^0$	228	199
$p\overline{K^0}\pi^+\pi^-$	266	220

TABLE I. The number of Λ_c^+'s found with $x_p(\Lambda_c^+) > 0.45$

fits to the normalized sidebands are used as representations of the contribution to $\Lambda_c^+\pi$ candidates from fake Λ_c^+ candidates, ii) second order polynomials, with shape derived from Monte Carlo simulation, are used with floating normalizations for the contributions of real Λ_c^+ baryons with random pions, iii) Gaussians of floating mean and width were used for the Σ_c contributions at $\Delta(M) = 167$ MeV, iv) broader excesses in the region below 204 MeV due to $\Lambda_c^{*+}(2630)$ production are accounted for using the $\Lambda_c^+\pi^\pm$ spectra from fully reconstructed $\Lambda_c^{*+}(2630) \to \Lambda_c^+\pi^+\pi^-$ data events, with the normalization corrected for the relative efficiency of observing one versus two π mesons obtained from Monte-Carlo, v) we use Σ_c^* signal functions of P-wave Breit-Wigners convoluted with a Gaussian resolution function of standard deviation 2.3 MeV. This resolution was determined using a Monte Carlo simulation based upon GEANT [10].

The fits yield significant signals for both $\Sigma_c^* \to \Lambda_c^+\pi^+$ and $\Lambda_c^+\pi^-$. In the case of $\Lambda_c^+\pi^+$ we obtain a signal of 677^{+101}_{-93} events, a width of $\Gamma = 17.9^{+3.8}_{-3.2}$ MeV, and a mass difference of $\Delta M = 234.5 \pm 1.1$ MeV. For the the $\Lambda_c^+\pi^-$ combinations, we obtain a signal area of 504^{+93}_{-83} events, a width of $\Gamma = 13.0^{+3.7}_{-3.0}$ MeV, and a mass difference of $\Delta M = 232.6 \pm 1.0$ MeV. The quoted errors are all statistical.

The extracted parameters are sensitive to the fitting procedure used. We have tried many variations of the background functions, including allowing the first two components of each fit to be incorporated into second-order polynomials with floating shape and normalization. We have also tried varying the shape of the Λ_c^{*+} feed-down component, varying the normalization of this component by as much as 50%, and varying the mass difference range over which the fits are made. The systematic uncertainties in the measurements due to the fitting procedures are taken as the maximum range of parameters obtained using different reasonable fits of these types. This is the dominant systematic uncertainty for both the yields and widths; we note that these two parameters are highly correlated. For each charged state we estimate the systematic uncertainty on the yield to be ± 120 events, and the systematic uncertainty on the width to be ± 4.0 MeV. The masses of the signals are relatively stable for all fitting techniques used. In each case we estimate the systematic uncertainty to be ± 0.8 MeV due to a combination of fitting uncertainty (0.7 MeV) and uncertainty in the mass difference scale (0.4 MeV). This last uncertainty cancels in the measurement of the isospin mass splitting, which we find to be $M(\Sigma_c^{*++}) - M(\Sigma_c^{*0}) = 1.9 \pm 1.4 \pm 1.0$ MeV.

Since the discovery of charm, many models [11] have been used to predict the spectroscopy of charmed baryons. The range of the predicted mass difference, $\Delta M = M(\Sigma_c^*) - M(\Lambda_c^+)$ is around 200-300 MeV. Two recent models have the benefit of having data for the Ξ_c^* and Ω_c masses available as constraints. Rosner [12] uses spin-flavor wave-functions and predicts $\Delta M = 229$ MeV; Savage [13] uses chiral perturbation theory and predicts $\Delta M = 233$ MeV. The mass differences we measure are in very good agreement with these models. Combining our result with previous results [14] we find the mass splitting between the spin-state weighted mass of the $\Sigma_c^{(*)}$ system and the Λ_c^+ to be $(4M(\Sigma_c^*) + 2M(\Sigma_c))/6 - M(\Lambda_c^+) \approx 211$ MeV. This value is similar to the analogous value for the non-charmed hyperons of about 206 MeV, and also the value of about 210 MeV obtained using preliminary DELPHI results for the masses of the bottom baryons [15]. These three values are predicted to be the same in naive baryonic mass models [16]. We also note that the width of the Σ_c^* has been estimated [12] from extrapolation of the Σ^* hyperon width to be around 20 MeV, with the possibility of QCD corrections lowering this number; this is also in good agreement with our measurements. We therefore identify these peaks as the Σ_c^{*++} and Σ_c^{*0} baryons [17].

In order to study the decay angle and momentum distribution of the Σ_c^* candidates, we relax the decay angle cut and refit our signals in bins of $\cos(\theta_{dec})$ and x_p, fixing the mass and width of each of the particles to the values obtained above. We restrict the ΔM plots to $205 < \Delta M < 380$ MeV so that there are no complications from Σ_c production and Λ_c^* feed-down. We find no significant differences between the characteristics of the two isospin states, so we add the yields from the two in each bin to increase the precision of the measurements.

Figure 2 shows the data divided into five bins of $cos(\theta_{dec})$. Using the treatment of Falk and Peskin [18], this distribution can be fit to a form $\frac{1}{\Gamma}\frac{d\Gamma}{d\ cos\theta_{dec}} = \frac{1}{4}(1 + 3cos^2\theta_{dec} - \frac{9}{2}w_1(cos^2\theta_{dec} - \frac{1}{3}))$, where w_1 is the fraction of the light diquark in a helicity ± 1 configuration. We find $w_1 = 0.71 \pm 0.13$, where statistical errors dominate. This is consistent with a value of $w_1 = 2/3$, which corresponds to a flat $\cos(\theta_{dec})$ distribution and unaligned Σ_c^* production. This value of w_1 is very different from the value of ≈ 0 found by the DELPHI collaboration in their preliminary analysis of Σ_b^* production from Z^0 decays [15].

In order to study the fragmentation function we divide the data into bins of x_p, determine the yields in each bin and correct the yields using efficiencies obtained from Monte Carlo simulations. Figure 3 shows the $\frac{dN}{dx_p}$ distribution, and the overlaid fit using the Peterson [19] form of $dN/dx_p \propto x_p^{-1}(1 - 1/x_p - \epsilon/(1 - x_p))^{-2}$. The fit gives a value of $\epsilon = 0.30^{+0.10}_{-0.07}$. This is similar to the CLEO measurements [1,2,7,20] for Λ_c^+, Ξ_c^+, Ξ_c^{*0} and Ξ_c^{*+} baryons, but corresponds to a softer momentum spectrum than that of the charmed baryons with non-zero orbital angular momentum [9]. In order to calculate the percentage of Λ_c^+ baryons that are the decay products of Σ_c^* decays, we need to extrapolate the yields of Λ_c^+ and Σ_c^* baryons down to $x_p = 0$. We calculate that $(12.8^{+1.5}_{-1.3} \pm 3.2)\%$ of Λ_c^+ baryons are produced from the sum of Σ_c^{*++} and Σ_c^{*0} decays. The systematic error includes the uncertainties in fitting the signals and the uncertainty in the extrapolation down to $x_p = 0$.

In conclusion, we present evidence for two resonances which we identify as the Σ_c^{*++}

and Σ_c^{*0} baryons. For the doubly charged state, $M(\Sigma_c^{*++}) - M(\Lambda_c^+)$ is measured to be $234.5 \pm 1.1 \pm 0.8$ MeV and $\Gamma = 17.9^{+3.8}_{-3.2} \pm 4.0$ MeV, and for the neutral state $M(\Sigma_c^{*0}) - M(\Lambda_c^+)$ is measured to be $232.6 \pm 1.0 \pm 0.8$ MeV and $\Gamma = 13.0^{+3.7}_{-3.0} \pm 4.0$ MeV. The isospin mass splitting $M(\Sigma_c^{*++}) - M(\Sigma_c^{*0})$ is measured to be $1.9 \pm 1.4 \pm 1.0$ MeV.

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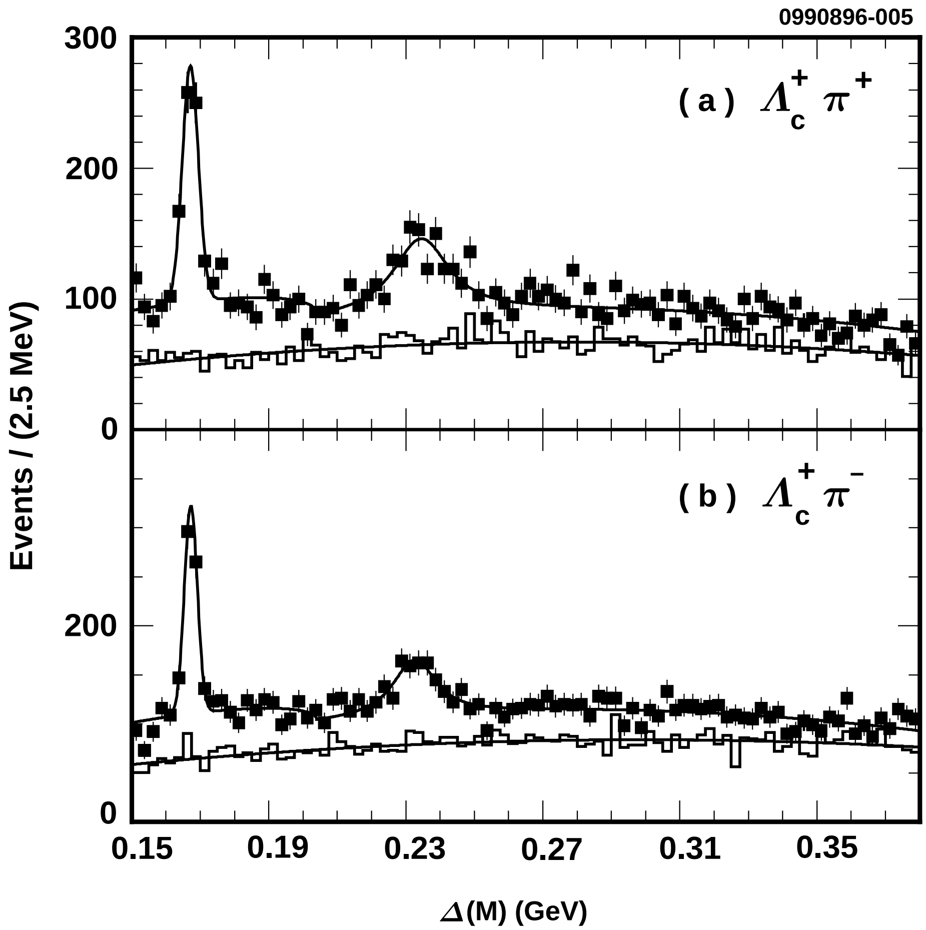

FIG. 1. Mass difference spectra for (a) $\Lambda_c^+\pi^+$ candidates, and (b) $\Lambda_c^+\pi^-$ candidates. The histogram shows the spectra for normalized sidebands of the Λ_c^+. The fits are described in the text.

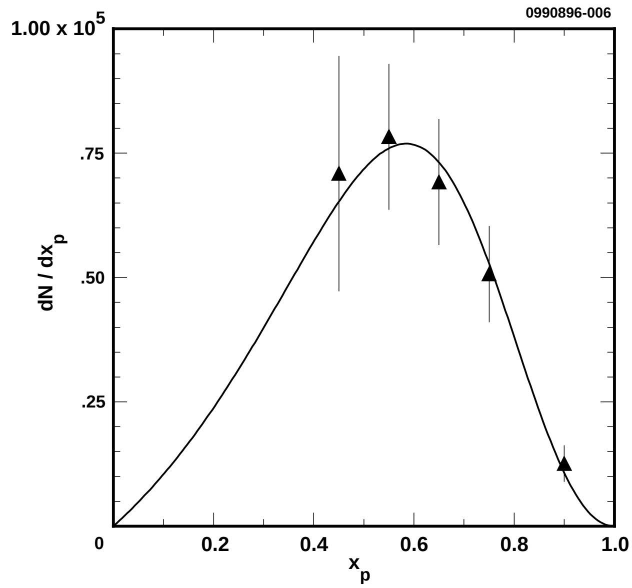

FIG. 2. The efficiency corrected spectrum of scaled momentum, x_p, for the observed Σ_c^* candidates. The fit is to the Peterson function.

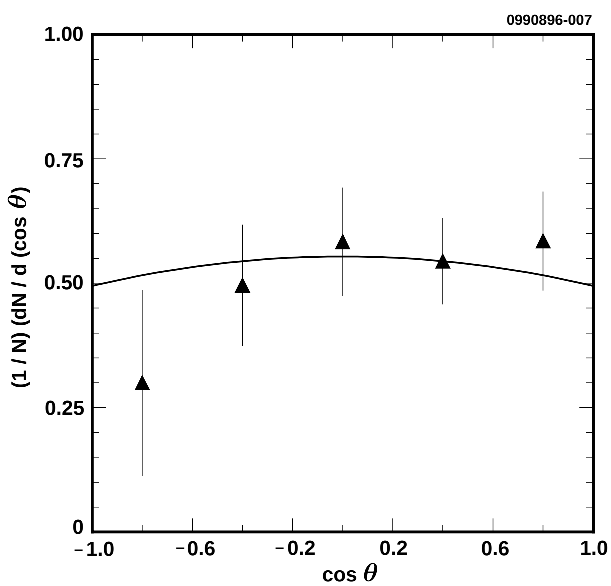

FIG. 3. The decay angle Θ_{dec} distribution for the observed Σ_c^* candidates.