Observation of Two Excited Charmed Baryons Decaying into $\Lambda_c^+\pi^\pm$


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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/c\(^2\) and a width of 17.9 \( \pm \) 3.3 \( \pm \) 4.0 MeV/c\(^2\), 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/c\(^2\) and a width of 13.0 \( \pm \) 3.0 \( \pm \) 4.0 MeV/c\(^2\). We interpret these data as evidence of the \( \Sigma_c^{++} \) and \( \Sigma_c^0 \), the spin 2\(^+\) excitations of the \( \Sigma_c \) baryons. [S0031-9007(97)02630-6]

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In the standard quark model, singly-charmed baryons consist of a heavy charmed quark and two light (\( u, d, \) or \( s \)) quarks. In the absence of orbital angular momentum, each three quark combination can exist in three different spin configurations. The lowest lying configuration has \( J^P = \frac{1}{2}^+ \) and the two light quark spins antiparallel, the next lowest mass configuration has \( J^P = \frac{3}{2}^+ \) and the two light quark spins parallel, and the highest mass configuration has \( J^P = \frac{5}{2}^+ \) and all three quark spins parallel. When the light quarks are \( u \) and/or \( d \) quarks, states with these three different spin configurations are referred to as \( \Lambda_c, \Sigma_c, \) and \( \Sigma_c \) baryons, respectively. When one of the light quarks is an \( s \) quark, the analogous states are referred to as \( \Xi_c, \Xi_c^0 \), and \( \Xi_c \) baryons. Recently, we reported [1,2] the observation of two narrow states decaying into \( \Xi_c \pi \), which we identified as the \( \Xi_c^0 \) and \( \Xi_c^+ \) baryons. Until now, however, evidence for \( \Sigma_c^* \) baryons has been restricted to a cluster of 6 \( \Lambda_c^+ \pi^+ \) events [3] with an estimated mass difference \( \Delta M = M(\Sigma_c^*) - M(\Lambda_c^+) \) of 245 \( \pm \) 5 \( \pm \) 5 MeV/c\(^2\). 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. Although the spin-parities of these states are not measured, our interpretation of the data is that the states we have found are the \( \Sigma_c^{++} \) and \( \Sigma_c^0 \) 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 Y(4S) resonance and in the continuum at energies just above and below the Y(4S). We detected charged tracks with a cylindrical drift chamber system inside a solenoidal magnetic field. Photons were detected using an electromagnetic calorimeter consisting of 7800 cesium iodide crystals.

We reconstructed \( \Lambda_c^+ \) 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 cuts have been optimized for high efficiency and low background. Briefly, particle identification of \( p, K^- \), and \( \pi \) candidates was performed using specific ionization measurements in the drift chamber, and when present, time-of-flight measurements. Hyperons were found by requiring their reconstructed decay points to be separated from the main event vertex. To obtain the \( \Lambda_c^+ \) yields, we fitted the invariant mass distributions for each \( \Lambda_c^+ \) 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 \( \Lambda_c^+ \) in each decay mode are taken as \( \Lambda_c^+ \) candidates; the signal yields and backgrounds within this mass window are given in Table I for each \( \Lambda_c^+ \) mode.

The \( \Lambda_c^+ \) candidates were then combined with each remaining charged track in the event and the mass difference \( M(\Lambda_c^+ \pi^+) - M(\Lambda_c^+) \) was calculated. To reduce the combinatorial background, we require \( x_p > 0.5 \), where \( x_p = p/p_{\max}, \quad p_{\max} = \sqrt{E_{\text{beam}}^2 - M^2} \), and \( p \) and \( M \) are the reconstructed momentum and mass of the \( \Lambda_c^+ \pi^+ \) combination. To demonstrate the high statistics and good signal to background ratios of the initial \( \Lambda_c^+ \) samples, for Table I we made a cut on the analogously defined quantity \( x_p(\Lambda_c^+) \), of \( x_p(\Lambda_c^+) > 0.45 \); this corresponds approximately to \( x_p > 0.5 \) for \( \Lambda_c^+ \pi \) combinations. 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 \( \theta_{\text{dec}} \) to be the angle between the \( \pi \) 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 \( \cos(\theta_{\text{dec}}) > -0.4 \).

TABLE I. The number of \( \Lambda_c^+ \)'s found with \( x_p(\Lambda_c^+) > 0.45 \). Yields are integrated between \( \pm 1.6\sigma \) of the \( \Lambda_c^+ \) mass.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>( pK^-\pi^+ )</td>
<td>8364</td>
<td>16291</td>
</tr>
<tr>
<td>( pK^0 )</td>
<td>974</td>
<td>413</td>
</tr>
<tr>
<td>( \Lambda \pi )</td>
<td>1139</td>
<td>808</td>
</tr>
<tr>
<td>( \Lambda \pi^+\pi^0 )</td>
<td>917</td>
<td>969</td>
</tr>
<tr>
<td>( \Lambda \pi^+\pi^- )</td>
<td>771</td>
<td>773</td>
</tr>
<tr>
<td>( \Sigma^+\pi^0 )</td>
<td>704</td>
<td>880</td>
</tr>
<tr>
<td>( \Sigma^+\pi^- )</td>
<td>772</td>
<td>691</td>
</tr>
<tr>
<td>( \Sigma^0\pi^0 )</td>
<td>51</td>
<td>17</td>
</tr>
<tr>
<td>( \Xi^-\pi^0 )</td>
<td>225</td>
<td>55</td>
</tr>
<tr>
<td>( \Xi^-\pi^- )</td>
<td>128</td>
<td>49</td>
</tr>
<tr>
<td>( pK^-\pi^+ )</td>
<td>341</td>
<td>478</td>
</tr>
<tr>
<td>( pK^0\pi^0 )</td>
<td>228</td>
<td>199</td>
</tr>
<tr>
<td>( pK^0\pi^- )</td>
<td>266</td>
<td>220</td>
</tr>
</tbody>
</table>
which suppresses the large background from low momentum $\pi$ mesons. The mass difference spectra shown in Fig. 1 each show clear peaks near 167 MeV/$c^2$ due to $\Sigma_c$ decays, broad enhancements below 204 MeV/$c^2$ due to feed-down from $\Lambda_c^{++}(2630) \rightarrow \Lambda_c^+ \pi^+ \pi^-$ decays [9], and broad excesses near 233 MeV/$c^2$ which are our signals. We note that feed-down from $\Lambda_c^{++}(2590) \rightarrow \Lambda_c^+ \pi^+ \pi^-$ decays cannot enter the plot at mass differences above the $\Sigma_c$ peak. The overlaid histogram in each case shows the mass difference spectrum using normalized sidebands of the $\Lambda_c^+$; 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 Fig. 1 each have five components: (i) The fits to the normalized $\Lambda_c^+$ sidbands are used as representations of the contribution to $\Lambda_c^+ \pi$ candidates from fake $\Lambda_c^+$ candidates, (ii) second order polynomials, with shape derived from Monte Carlo simulation, are used with floating normalizations for the contributions of real $\Lambda_c^+$ baryons with random pions, (iii) Gaussians of floating mean and width were used for the $\Sigma_c$ contributions at $\Delta M = 167$ MeV/$c^2$, (iv) broader excesses in the region below 204 MeV/$c^2$ due to $\Lambda_c^{++}(2630)$ production are accounted for using the $\Lambda_c^+ \pi^+$ spectra from fully reconstructed $\Lambda_c^{++}(2630) \rightarrow \Lambda_c^+ \pi^+ \pi^-$ data events, with the normalization corrected for the relative efficiency of observing one versus two $\pi$ mesons obtained from Monte Carlo simulations, (v) signal functions of $P$-wave Breit-Wigners convoluted with a Gaussian resolution function of standard deviation 2.3 MeV/$c^2$. This resolution was determined using a Monte Carlo simulation based upon GEANT [10].

The fits yield significant signals in both $\Lambda_c^+ \pi^+$ and $\Lambda_c^+ \pi^-$ plots. 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/$c^2$, and a mass difference of $\Delta M = 234.5 \pm 1.1$ MeV/$c^2$. For the $\Lambda_c^+ \pi^-$ combinations, we obtain a signal area of $504^{+83}_{-93}$ events, a width of $\Gamma = 13.0^{+0.7}_{-0.6}$ MeV/$c^2$, and a mass difference of $\Delta M = 232.6 \pm 1.0$ MeV/$c^2$. 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 $\Lambda_c^{++}$ 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 $\pm 120$ events, and the systematic uncertainty on the width to be $\pm 4.0$ MeV/$c^2$. The masses of the signals are relatively stable for all fitting techniques used. In each case we estimate the systematic uncertainty to be $\pm 0.8$ MeV/$c^2$ due to a combination of fitting uncertainty ($0.7$ MeV/$c^2$) and uncertainty in the mass difference scale ($0.4$ MeV/$c^2$). This last uncertainty cancels in the measurement of the isospin mass splitting between the states, which we find to be $D(M(\Lambda_c^+ \pi^+) - M(\Lambda_c^+ \pi^-)) = 1.9 \pm 1.4 \pm 1.0$ MeV/$c^2$.

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/$c^2$. Two recent models have the benefit of having data for the $\Sigma_c^+$ and $\Omega_c$ masses available as constraints. Rosner [12] uses spin-flavor wave functions and predicts $\Delta M = 229$ MeV/$c^2$; Savage [13] uses chiral perturbation theory and predicts $\Delta M = 233$ MeV/$c^2$. The mass differences we measure are in very good agreement with these models. Interpreting our resonances as the $\Sigma_c^{++}$ and $\Sigma_c^+$, and combining our result with previous results [14] for the $\Sigma_c$ baryons, we find the mass splitting between the spin-state weighted mass of the $\Sigma_c^0$ system and the $\Lambda_c^+$ to be $[4M(\Sigma_c^0) + 2M(\Sigma_c^+)]/6 - (M(\Lambda_c^+)) = 211$ MeV/$c^2$. This value is similar to the analogous value for the non-charmed hyperons of about 206 MeV/$c^2$, and also the value of about 210 MeV/$c^2$ 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 $\Sigma_c^+$ has been estimated [12] from extrapolation of the $\Sigma_c^0$ hyperon width to be around.
20 MeV/$c^2$, with the possibility of QCD corrections lowering this number; this is also in good agreement with our measurements. Therefore, the most likely interpretation of these peaks is that they are the $\Sigma_c^{++}$ and $\Sigma_c^{*0}$ baryons [17].

In order to study the decay angle and momentum distribution of the $\Sigma_c^*$ candidates, we relax the decay angle cut and refit our signals in bins of $\cos(\theta_{\text{dec}})$ and $x_p$, fixing the mass and width of each of the particles to the values obtained above. We restrict the $\Delta M$ plots to $205 < \Delta M < 380$ MeV/$c^2$ so that there are no complications from $\Sigma_c$ production and $\Lambda_c^*$ 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 $\cos(\theta_{\text{dec}})$. Using the treatment of Falk and Peskin [18], this distribution can be fit to a form $\frac{dF}{d\cos\theta_{\text{dec}}} \propto \frac{1}{\pi} [1 + 3 \cos^2 \theta_{\text{dec}} - \frac{6}{5} w_1 \cos^2 \theta_{\text{dec}} - \frac{\pi}{5}]$, where $w_1$ is the fraction of the light diquark in a helicity $\pm 1$ configuration. We find $w_1 = 0.71 \pm 0.13$, where statistical errors dominate. This is consistent with a value of $w_1 = \frac{2}{3}$, which corresponds to a flat $\cos(\theta_{\text{dec}})$ distribution and unaligned $\Sigma_c^*$ production. This value of $w_1$ is very different from the value of $=0$ found by the DELPHI Collaboration in their preliminary analysis of $\Sigma_b^*$ production from $Z^0$ decays [15].

In order to study the fragmentation function we extend our study down to $x_p > 0.4$, determine the yields in bins of $x_p$, and correct the yields using efficiencies obtained from Monte Carlo simulations. Figure 3 shows the $dN/dx_p$ 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 $\Lambda_c^+, \Xi_c^+, \Xi_c^{*0}$, and $\Xi_c^{*+}$ baryons, but corresponds to a softer momentum spectrum than that of the charmed baryons with nonzero orbital angular momentum [9]. In order to calculate the percentage of $\Lambda_c^+$ baryons that are the decay products of these resonances, we need to extrapolate the yields of $\Lambda_c^+$ baryons and $\Lambda_c^{*+}\pi$ combinations down to $x_p = 0$. We calculate that $(12.8^{+1.5}_{-1.3} \pm 3.2)\%$ of $\Lambda_c^*$ baryons are produced from the sum of the two found resonances. 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 decaying into $\Lambda_c^+\pi^+$ and $\Lambda_c^{*+}\pi^-$. For the doubly charged state $M(\Lambda_c^+\pi^+) - M(\Lambda_c^{*+})$, is measured to be $234.5 \pm 1.1 \pm 0.8$ MeV/$c^2$ and $\Gamma = 17.9^{+3.8}_{-3.2} \pm 4.0$ MeV/$c^2$, and for the neutral state $M(\Lambda_c^+\pi^-) - M(\Lambda_c^{*+})$ is measured to be $232.6 \pm 1.0 \pm 0.8$ MeV/$c^2$ and $\Gamma = 13.0^{+3.0}_{-3.0} \pm 4.0$ MeV/$c^2$. The isospin mass of the two resonances, $M(\Lambda_c^+\pi^+) - M(\Lambda_c^{*+}\pi^-)$, is measured to be $1.9 \pm 1.4 \pm 1.0$ MeV/$c^2$. We interpret these resonances as the $\Sigma_c^{*++}$ and $\Sigma_c^{*0}$ baryons.

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[4] Our sensitivity to the decay $\Sigma_k^{+} \rightarrow \Lambda_{c}^{+}\pi^{0}$ is considerably less than that of $\Sigma_k^{+} \rightarrow \Lambda_{c}^{+}\pi^{\pm}$ due to larger backgrounds and lower reconstruction efficiency.
[6] Charge conjugate modes are implicit throughout.
[16] This material is covered in many introductory high energy physics textbooks; see, for example, D. H. Perkins, Introduction to High Energy Physics (Addison-Wesley, Menlo Park, California, 1987), 3rd ed., Table 5.4.