Observation of New States Decaying into $\Lambda^+_c \pi^- \pi^+$

(CLEO Collaboration)

1Syracuse University, Syracuse, New York 13244
2University of Texas, Austin, Texas 78712
3University of Texas-Pan American, Edinburg, Texas 78539
4Vanderbilt University, Nashville, Tennessee 37235
5Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
6Wayne State University, Detroit, Michigan 48202
7California Institute of Technology, Pasadena, California 91125
8University of California, San Diego, La Jolla, California 92093
9University of California, Santa Barbara, California 93106
10Carnegie Mellon University, Pittsburgh, Pennsylvania 15213
11University of Colorado, Boulder, Colorado 80309-0390
12Cornell University, Ithaca, New York 14853
13University of Florida, Gainesville, Florida 32611
14Harvard University, Cambridge, Massachusetts 02138
15University of Illinois, Urbana-Champaign, Illinois 61801
16Carleton University, Ottawa, Ontario, Canada K1S 5B6
17McGill University, Montréal, Québec, Canada H3A 2T8
18Ithaca College, Ithaca, New York 14850
19University of Kansas, Lawrence, Kansas 66045
20University of Minnesota, Minneapolis, Minnesota 55455
21State University of New York at Albany, Albany, New York 12222
22Ohio State University, Columbus, Ohio 43210
23University of Oklahoma, Norman, Oklahoma 73019
24Purdue University, West Lafayette, Indiana 47907
25University of Rochester, Rochester, New York 14627
26Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309
27Southern Methodist University, Dallas, Texas 75275
Studies in the past decade have revealed a rich spectroscopy of charmed baryon states. Baryons consisting of a charmed quark and two light (up or down) quarks are denoted the $\Lambda_c$ and $\Sigma_c$ baryons, depending on the symmetry properties of the wave function. All three of the ground state $J^P = \frac{1}{2}^+$ $\Lambda_c$ and all three of the ground state $J^P = \frac{3}{2}^+$ $\Sigma_c$ particles have been identified. Knowledge of orbitally excited states in the sequence is presently limited to the observation of two states decaying into $\Lambda_c^+ \pi^+ \pi^-$ [1]. These have been identified as the $J^P = \frac{1}{2}^-, \frac{3}{2}^+$ $\Lambda_c^*$, particles, where the numerical subscript denotes one unit of light quark angular momentum. There must be many more excited states still to be found. Here we detail the results of a search for such states that decay into a $\Lambda_c^*$ baryon with the emission of two oppositely charged pions.

The data presented here were taken using the CLEO II and CLEO II.V detector configurations operating at the Cornell Electron Storage Ring (CESR). The sample used in this analysis corresponds to an integrated luminosity of 13.7 fb$^{-1}$ from data taken on the $Y(4S)$ resonance and in the continuum at energies just below the $Y(4S)$. Of this data, 4.7 fb$^{-1}$ was taken with the CLEO II detector [2], in which we detected charged tracks using a cylindrical drift chamber system inside a solenoidal magnet and photons using an electromagnetic calorimeter consisting of 7800 CsI crystals. The remainder of the data was taken with the CLEO II.V configuration [3], which has upgraded charged particle measurement capabilities, but the same CsI array, to observe photons.

In order to obtain large statistics we reconstructed the $\Lambda_c^+$ baryons using 15 different decay modes. (The decay modes are: $pK^+\pi^+$, $pK^+\pi^0$, $pK^{-}\pi^+$, $pK_0^0\pi^0$, $pK_0^0\pi^+$, $\Xi^-K^+\pi^+$, $\Xi^0K^+\pi^0$, $\Sigma^0\pi^+$, $\Sigma^+\pi^+$, $\Sigma^+\pi^+$, $\Lambda\pi^+$, $\Lambda\pi^+\pi^0$, $\Lambda\pi^+\pi^-$, and $\Lambda\bar{K}^0K^+$. Charge conjugate modes are implicit throughout.) Measurements of the branching fractions into these modes have previously been presented by CLEO collaboration [4], and the general procedures for finding those decay modes can be found in these references. For this search and data set, the exact analysis used has 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 available, time-of-flight measurements. Hyperons were found by detecting their decay points separated from the main event vertex.

We reduce the combinatorial background, which is highest for charmed baryon candidates with low momentum, by applying a cut on the scaled momentum $x_p = p/p_{\text{max}}$. Here $p$ is the momentum of the charmed baryon candidate, $p_{\text{max}} = \sqrt{E_{\text{bm}}^2 - M^2}$, $E_{\text{bm}}$ is the beam energy, and $M$ is the invariant mass of the candidate. Note that charmed baryons produced from decays of $B$ mesons are kinematically limited to $x_p < 0.4$. Requiring $x_p > 0.5$, we fit the invariant mass distributions for these modes to a sum of a Gaussian signal and a low-order polynomial background. Combinations within 1.6$\sigma$ of the mass of the $\Lambda_c^+$ in each decay mode are taken as $\Lambda_c^*$ candidates, where the resolution, $\sigma$, of each decay mode is taken from a GEANT-based [5] Monte Carlo simulation for the two detector configurations separately. In this $x_p$ region, we find a total yield of $\Lambda_c^*$ signal combinations of $\approx 58,000$, and a signal-to-background ratio $\approx 5:6$. This is the same sample of $\Lambda_c^*$ baryons that has been used in our discovery of the $\Sigma_c^{*+}$ [6]. This $x_p$ restriction was released before continuing with the analysis as we prefer to apply such a criterion only on the parent $\Lambda_c^+ \pi^+ \pi^-$ combinations.

The $\Lambda_c^+$ candidates were then combined with two oppositely charged $\pi$ candidates in the event. To obtain the best mass resolution, the trajectories of the $\pi$ candidates were constrained to pass through the main event vertex. The large combinatoric backgrounds and the hardness of the momentum spectrum of the known excited charmed baryons led us to place a cut of $x_p > 0.7$ on the combination. Figure 1 shows the mass difference spectrum, $\Delta M_{\pi\pi} = M(\Lambda_c^+ \pi^+ \pi^-) - M(\Lambda_c^*)$, for the region above the well-known $\Lambda_c1$ resonances. Also shown in Fig. 1 are combinations formed using appropriately scaled side-bands of the $\Lambda_c^*$ signal. An attempt to fit the upper plot in Fig. 1 to only a second order polynomial shape yields an unacceptable $\chi^2$ of 184 for 77 degrees of freedom. However, if it is fit to the sum of a second order polynomial and two Gaussian signals, the resultant $\chi^2$ is 59 for 71 degrees of freedom. Of these two signals, the lower one has a yield of $997^{+141}_{-129}$, $\Delta M_{\pi\pi} = 480.1 \pm 2.4$ MeV, and a width of $\sigma = 20.9 \pm 2.6$ MeV. The upper signal has a yield of $350^{+35}_{-33}$, $\Delta M_{\pi\pi} = 595.8 \pm 0.8$ MeV and $\sigma = 4.2 \pm 0.7$ MeV. All of these uncertainties are statistical, coming from the fit. The mass resolutions in these regions are $\approx 2.0$ and $\approx 2.8$ MeV, respectively, based on our Monte Carlo simulation. The lower peak clearly has a width greater than the experimental resolution. If we fit it to a Breit-Wigner function, we obtain a width, $\Gamma$, of $\approx 50$ MeV, but it can equally well be fit to a sum of more than one wide peak. If we fit the upper peak to a Breit-Wigner convolved with a double
Gaussian detector resolution function, we obtain a width of 
\[ \Gamma = 4 \pm 2 \pm 2 \text{ MeV} \], where the uncertainties are sta-
tistical and systematic, respectively. The dominant system-
atic uncertainty comes from uncertainties in the detector 
resolution function. This experimental width is not sig-
nificantly different from zero; we place an upper limit of 
\[ \Gamma < 8 \text{ MeV} \] at 90% confidence level. We estimate the sys-
tematic uncertainty on the mass difference measurement of 
the upper state to be \pm 2 \text{ MeV}, due principally to uncer-
tainties in the momenta measurements and differences in 
the mass obtained using different fitting procedures.

To help identify these new states, we investigate 
whether the decays proceed via intermediate \( \Sigma_c \) and/or 
\( \Sigma_c^* \) baryons. There is very little isospin splitting in 
the masses of these intermediate states, and, by isospin 
conservation, we expect equally many decays to proceed 
via a doubly charged \( \Sigma_c^{(*)} \) as via a neutral one. To search 
for resonant substructure in the upper, narrower, state we 
use a signal mass band of 589 < \( \Delta M_{\pi\pi} \) < 603 MeV 
and sidebands of 527 < \( \Delta M_{\pi\pi} \) < 575 MeV and 
617 < \( \Delta M_{\pi\pi} \) < 665 MeV. This signal band has a signal 
yield of 314 ± 50. We then plot the single \( \pi \) mass differ-
ence, \( \Delta M_{\pi} = M(\Lambda_c^+ \pi^\pm) - M(\Lambda_c^+) \) for both transition 
piions in the signal region and subtract the sideband data, 
appropriately scaled. The resultant plot (Fig. 2) is fit to a 
sum of a polynomial background and two signal shapes 
for the \( \Sigma_c \) and \( \Sigma_c^* \) baryons, with these shapes obtained 
by fitting the inclusive \( \Delta M_{\pi} \) plot, i.e., without any cut 
on \( \Delta M_{\pi\pi} \). The signal yields obtained by the fit are 
96 ± 18 and −34 ± 28 events, respectively. This gives 
a fraction of this state proceeding via an intermediate \( \Sigma_c \) 
of (31 ± 6 ± 3)\%, and an upper limit on the fraction 
proceeding through \( \Sigma_c^* \) of 11\% at 90\% confidence level.

The dominant contribution to the systematic uncertainty in 
the \( \Sigma_c \) fraction is from our fitting procedures. We cannot 
perform the same analysis for the lower state because the 
low \( Q^2 \) of the decays makes kinematic reflections in the 
\( \Delta M_{\pi\pi} \) mass difference plots that the subtraction procedure 
cannot remove.

We also display the data by first making a requirement 
of 163 < \( \Delta M_{\pi\pi} \) < 171 MeV and then plotting the dipion 
mass difference \( \Delta M_{\pi\pi} \) [see Fig. 3(a)]. This requirement 
includes most of the decays that proceed via a \( \Sigma_c \), but ex-
cludes the majority that decay nonresonantly to \( \Lambda_c^+ \pi^+ \pi^- \).

Figure 3(a) is fit to a sum of the two signal peaks, using 
fixed signal shapes and masses that were found from 
Fig. 1, and a polynomial background shape. The yields 

![FIG. 1. The upper histogram shows \( \Delta M_{\pi\pi} = M(\Lambda_c^+ \pi^\pm \pi^-) - M(\Lambda_c^+) \) above the \( \Lambda_c^1 \) range; the fit is 
to a quadratic background shape plus two Gaussian signal 
functions. The lower histogram shows the same distribution for 
sidebands of \( \Delta M_{\pi\pi} \).](image1)

![FIG. 2. \( \Delta M_{\pi} = M(\Lambda_c^+ \pi^\pm \pi^-) - M(\Lambda_c^+) \) in the upper resonance region, after sideband subtraction.](image2)

![FIG. 3. \( \Delta M_{\pi\pi} = M(\Lambda_c^+ \pi^\pm \pi^-) - M(\Lambda_c^+) \) with cuts as follows: (a) \( \Delta M_{\pi} = M(\Lambda_c^+ \pi) - M(\Lambda_c^+) \) is consistent with that 
expected for a \( \Sigma_c \), and (b) \( \Delta M_{\pi} = M(\Lambda_c^+ \pi) - M(\Lambda_c^+) \) is consistent 
with that expected for a \( \Sigma_c^* \). In both cases, the lower 
histogram is that obtained using scaled \( \Lambda_c \) sidebands.](image3)
for the two signals are 262 ± 45 and 105 ± 16, respectively. This second yield agrees well with the expectation from Fig. 2, and confirms that a large fraction of the upper peak decays via \( \Sigma_c \pi \). The yield of the lower peak also indicates that it also resonates through \( \Sigma_c \). We can also make a similar plot, using a cut on the single pion mass difference consistent with being due to a \( \Sigma_c^* \), namely, 223 < \( \Delta M_\pi \) < 243 MeV. This is more problematical, because this mass window will include much of the phase-space available for nonresonant decays, and will also not include the entire broad \( \Sigma_c^* \) region. The dipion mass difference plot [Fig. 3(b)] shows very little evidence of the upper peak, confirming the conclusion obtained from Fig. 2. It does show considerable excess (331 ± 47) events in the region of the lower peak, but it is difficult to calculate how much of this is really due to \( \Sigma_c^* \). We display Fig. 3 starting from \( \Delta M_\pi = 420 \) MeV to avoid irrelevant enhancements due to \( \Sigma_c \) production that appears below this threshold.

In summary, we find the lower peak to decay resonantly via \( \Sigma_c \) and probably also via \( \Sigma_c^* \); we cannot rule out a contribution from nonresonant \( \Lambda_c^+ \pi^+ \pi^- \). The upper peak is comparatively narrow, and appears to decay via \( \Sigma_c \pi \) and to nonresonant \( \Lambda_c^+ \pi^+ \pi^- \) but not via \( \Sigma_c^* \). The decays of \( \pi \) and \( \Sigma_c \) to nonresonant \( \Lambda_c^+ \pi^+ \pi^- \) contributions from nonresonant \( \Lambda_c^+ \pi^+ \pi^- \), but not via \( \Sigma_c^* \). Most models of charmed baryon spectroscopy start from the assumption that the baryon consists of a heavy charm quark and a light diquark which is itself in a well-defined spin and parity state, \( J^{P}_{\text{light}} \). The decays obey quantum mechanical decay rules for conservation of both \( \Sigma_c \) and \( \Sigma_c^* \). We display Fig. 3 starting from \( \Delta M_\pi = 420 \) MeV to avoid irrelevant enhancements due to \( \Sigma_c \) production that appears below this threshold.

In conclusion, we report the observation of structure in the \( M(\Lambda_c^+ \pi^+ \pi^-) - M(\Lambda_c^+) \) mass difference plot, which we believe corresponds to the discovery of new excited charmed baryons. One enhancement, at \( \Delta M_\pi = 480 \) MeV, is very wide (\( \Gamma = 50 \) MeV) and it appears to resonate through \( \Sigma_c \) and probably also \( \Sigma_c^* \). The other, with a mass of 596 ± 1 ± 2 MeV above the \( \Lambda_c^+ \), is much narrower (\( \Gamma < 8 \) MeV at 90% confidence level), and appears to decay both via \( \Sigma_c \pi \) and nonresonantly to \( \Lambda_c^+ \pi^+ \pi^- \), but not via \( \Sigma_c^* \). We have no measurements of the spin and parity of these new states, but we make educated guesses as to their identities.

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*Permanent address: Massachusetts Institute of Technology, Cambridge, Massachusetts 02139.


