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

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Using 13.7 fb^{-1} of data recorded by the CLEO detector at the Cornell Electron Storage Ring, we investigate the spectrum of charmed baryons which decay into $\Lambda_c^+\pi^-\pi^+$ and are more massive than the $\Lambda_c^+(2625)$ baryon. We find evidence for two new states: one is broad and has an invariant mass roughly 480 MeV above that of the Λ_c^+ baryon; the other is narrow with an invariant mass of 596 $\pm$ 1 $\pm$ 2 MeV above the Λ_c^+ mass.

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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 Λ_c and Σ_c baryons, depending on the symmetry properties of the wave function. All three of the ground state $J^P = \frac{1}{2}^+ \Sigma_c$ 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 $J^P = \frac{1}{2}^-, \frac{3}{2}^- \Lambda_{c1}^+$ 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 Λ_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 $\Upsilon(4S)$ resonance and in the continuum at energies just below the $\Upsilon(4S)$. 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 Λ_c^+ baryons using 15 different decay modes. (The decay modes are: $pK^-\pi^+$, $pK\pi^+\pi^0$, $p\overline{K^0}$, $p\overline{K^0}\pi^0$, $p\overline{K^0}\pi^+\pi^-$, $\Xi^-K^+\pi^+$, Ξ^0K^+, $\Sigma^0\pi^+$, $\Sigma^+\pi^+\pi^-$, $\Sigma^+K^+K^-$, $\Sigma^+\pi^0$, $\Lambda\pi^+$, $\Lambda\pi^+\pi^0$, $\Lambda\pi^+\pi^-\pi^-$, and $\Lambda\overline{K^0}K^+$. 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 π 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 $x_p = p/p_{\max}$. Here p is the momentum of the charmed baryon candidate, $p_{\max} = \sqrt{E_{bm}^2 - M^2}$, E_{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 1.6σ of the mass of the Λ_c^+ in each decay mode are taken as Λ_c^+ candidates, where the resolution, σ, 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 Λ_c^+ signal combinations of ≈58 000, and a signal-to-background ratio ≈5:6. This is the same sample of Λ_c^+ baryons that has been used in our discovery of the Σ_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 Λ_c^+ candidates were then combined with two oppositely charged π candidates in the event. To obtain the best mass resolution, the trajectories of the π 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 Λ_{c1} resonances. Also shown in Fig. 1 are combinations formed using appropriately scaled sidebands of the Λ_c^+ signal. An attempt to fit the upper plot in Fig. 1 to only a second order polynomial shape yields an unacceptable χ^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 χ^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^{+57}_{-55}, $\Delta M_{\pi\pi} = 595.8 \pm 0.8$ 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 ≈2.0 and ≈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, Γ, of ≈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

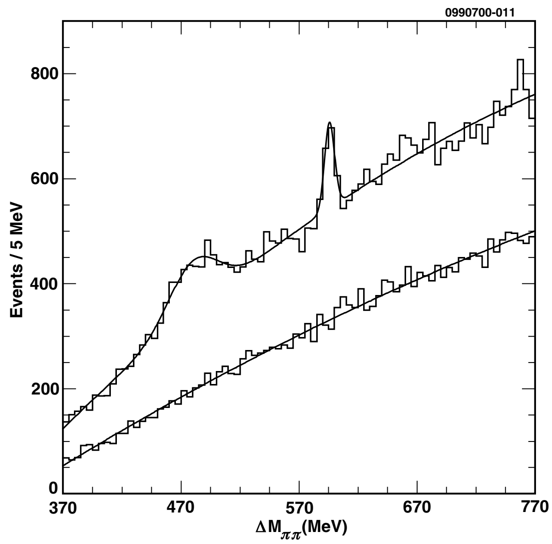

FIG. 1. The upper histogram shows $\Delta M_{\pi\pi} = M(\Lambda_c^+\pi^+\pi^-) - M(\Lambda_c^+)$ above the Λ_{c1} range; the fit is to a quadratic background shape plus two Gaussian signal functions. The lower histogram shows the same distribution for scaled Λ_c^+ sidebands, fit to a quadratic background shape.

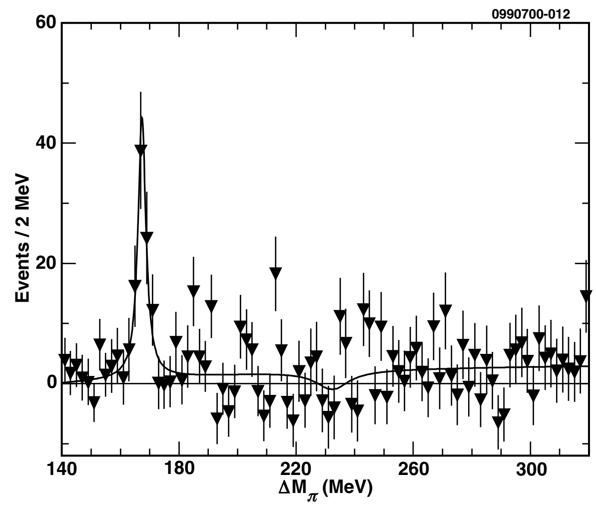

FIG. 2. $\Delta M_\pi = M(\Lambda_c^+\pi^\pm) - M(\Lambda_c^+)$ in the upper resonance region, after sideband subtraction.

Gaussian detector resolution function, we obtain a width of $\Gamma = 4 \pm 2 \pm 2$ MeV, where the uncertainties are statistical and systematic, respectively. The dominant systematic uncertainty comes from uncertainties in the detector resolution function. This experimental width is not significantly different from zero; we place an upper limit of $\Gamma < 8$ MeV at 90% confidence level. We estimate the systematic uncertainty on the mass difference measurement of the upper state to be ± 2 MeV, due principally to uncertainties 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 Σ_c and/or Σ_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 π mass difference, $\Delta M_\pi = M(\Lambda_c^+\pi^\pm) - M(\Lambda_c^+)$ for both transition pions 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 Σ_c and Σ_c^* baryons, with these shapes obtained by fitting the inclusive ΔM_π 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 Σ_c of $(31 \pm 6 \pm 3)\%$, and an upper limit on the fraction proceeding through Σ_c^* of 11% at 90% confidence level. The dominant contribution to the systematic uncertainty in the Σ_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 ΔM_π mass difference plots that the subtraction procedure cannot remove.

We also display the data by first making a requirement of $163 < \Delta M_\pi < 171$ 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 Σ_c, but excludes 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

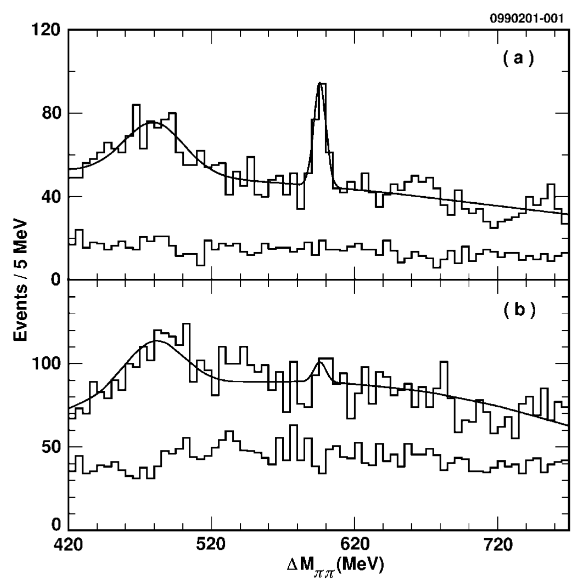

FIG. 3. $\Delta M_{\pi\pi} = M(\Lambda_c^+\pi^+\pi^-) - M(\Lambda_c^+)$ with cuts as follows: (a) $\Delta M_\pi = M(\Lambda_c^+\pi) - M(\Lambda_c^+)$ is consistent with that expected for a Σ_c, and (b) $\Delta M_\pi = M(\Lambda_c^+\pi) - M(\Lambda_c^+)$ is consistent with that expected for a Σ_c^*. In both cases, the lower histogram is that obtained using scaled Λ_c sidebands.

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 Σ_c. We can also make a similar plot, using a cut on the single pion mass difference consistent with being due to a Σ_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 Σ_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 Σ_c^*. We display Fig. 3 starting from $\Delta M_\pi = 420$ MeV to avoid irrelevant enhancements due to Σ_c production that appears below this threshold.

In summary, we find the lower peak to decay resonantly via Σ_c and probably also via Σ_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 $\Sigma_c^* \pi$.

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_{light}. The decays obey quantum mechanical decay rules for conservation of both J^P and J^P_{light} separately. The lowest lying orbital excitations in the Σ_c baryons should, like those of the Λ_c baryons, have the unit of orbital angular momentum between the diquark and the charm quark; this will give five isotriplets. At higher masses, there should be five Λ_c^+ particles and two isotriplets of Σ_c particles with $L = 1$ between the two light quarks. Here we will refer to this second generation of orbital excitations as Λ_c' and Σ_c' states. Many of the Σ_c, Σ_c', and Λ_c' particles with $L = 1$ will decay rapidly and have large intrinsic widths. Only one undiscovered state in the sequence has no allowed two-body decays to a lower mass charmed baryon, and that is the $\Lambda_{c0}^{+\prime}$, which has $J^P = \frac{1}{2}^-$ and $J^P_{\text{light}} = 0^-$. This is therefore a candidate for the upper peak that we have found. Conservation of J^P_{light}, as required by heavy quark effective theory, would not allow this particle to decay via $\Sigma_c \pi$. However, there is another state (the $\Lambda_{c1}^{+\prime}$) with same overall quantum numbers, but this time with $J^P_{\text{light}} = 1^-$, which is expected to be at a similar mass. As the two states have the same quantum numbers, they might mix, and, as the latter state can decay via an S wave to $\Sigma_c \pi$, this could explain the fraction of decays of our peak resonating in that manner. Identification of the lower, wider, state is also open to interpretation. One possibility is that it consists of a pair of Σ_{c1}^+ particles, with overall $J^P = \frac{1}{2}^-$ and $J^P = \frac{3}{2}^-$. These particles might be expected to be split in mass by about 30 MeV, and should have preferred decay modes of $\Sigma_c \pi$ and $\Sigma_c^*(\pi)$, respectively. Their widths have been predicted to be about 100 MeV [7]. We stress that there may be many other interpretations of our data, including the decay of radial excitations of charmed baryons.

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 $\Delta M_{\pi\pi} \approx 480$ MeV, is very wide ($\Gamma \approx 50$ MeV) and it appears to resonate through Σ_c and probably also Σ_c^*. The other, with a mass of $596 \pm 1 \pm 2$ MeV above the Λ_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 Σ_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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