Observation of Excited Charmed Baryon States Decaying to $\Lambda_c^+ \pi^+ \pi^-$

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Using data collected by the CLEO II detector, we have observed two states decaying to $\Lambda_c^+ \pi^+ \pi^-$. Relative to the Λ_c^+, their mass splittings are measured to be $+307.5 \pm 0.4 \pm 1.0$ and $+342.2 \pm 0.2 \pm$

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0.5 MeV/c^2, respectively; this represents the first measurement of the less massive state. These two states are consistent with being orbitally excited, isospin zero Λ_c^+ states.

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Soon after the discovery of charm, several models predicted a rich charmed baryon spectroscopy [1–5]. As expected in heavy quark effective theory (HQET) [6], the mass splittings observed in charmed systems, compared with those observed in strange baryons and mesons, were qualitatively consistent with the expected m_Q^{-1} (with m_Q designating the mass of the heavy quark) dependence of the color-magnetic dipole moment of quarks. This m_Q^{-1} dependence of the mass splittings is, in fact, one of the starting points of HQET. In HQET, the main features of hadron spectroscopy may be understood in terms of light quarks moving in the heavy quark's confinement potential, perturbed by various short-range interactions, as anticipated from one-gluon exchange.

In this Letter, we report the observation of two excited charmed baryons, which we will refer to as the $\Lambda_c^{*+}(2625)$ and the $\Lambda_c^{*+}(2593)$. The former of these has previously been reported by both the ARGUS [7] and E687 [8] collaborations; a preliminary version of the analysis contained herein, which reported evidence for the lower state, has been previously presented [9]. Evidence that these two excited charmed baryons correspond to the lowest lying spatial excitations of the Λ_c^+ baryon is also given.

The CLEO II detector is discussed in detail elsewhere [10]. This analysis involves mainly the central tracking system, consisting of two precision vertex chambers and a cylindrical wire drift chamber, all inside a 1.5 T axial magnetic field. Outside the drift chamber is a time-of-flight system, which is used, in conjunction with specific ionization measurements in the drift chamber, for particle identification. The data set used for this analysis corresponds to an integrated luminosity of approximately 3 fb^{-1} of e^+e^- collisions, taken at center of mass energies between 10.52 and 10.58 GeV.

We obtain a Λ_c^+ sample using six decay modes, $pK^-\pi^+$, $p\overline{K}^0$, $\Lambda\pi^+$, $\Lambda\pi^+\pi^0$, $\Lambda\pi^+\pi^-\pi^+$, and $\Sigma^+\pi^+\pi^-$ (charge conjugate modes are implicit). For the $pK^-\pi^+$ and $p\overline{K}^0$ modes we use a combination of the measurements of specific ionization in the drift chamber and time-of-flight information to identify the p and K^- candidates. The $\overline{K}^0$ mesons were identified through their decay $\overline{K}^0 \to K_S^0$, $K_S^0 \to \pi^+\pi^-$, and the Λ candidates by their decay $\Lambda \to p\pi^-$. In both cases a secondary vertex is reconstructed from a pair of oppositely charged tracks intersecting at a point well separated from the primary vertex. The pair is identified as a K_S^0 (Λ) candidate if the invariant mass of the $\pi^+\pi^-$ ($p\pi^-$) pair is consistent with the K_S^0 (Λ) mass, and if the momentum vector of the candidate K_S^0 (Λ) points back to the primary event vertex. Σ^+ candidates were found by forming $p\pi^0$ combinations which are consistent with coming from the decay of a Σ^+ with a decay point displaced from the primary vertex [11]. Our sample of π^0 candidates is defined by photon pairs having a measured invariant mass within $\pm 2.5\sigma$ of the known π^0 mass ($\sigma_{m_{\pi^0}} \sim 5$ MeV/c^2); any cluster in the calorimeter with greater than 50 MeV of deposited energy and not matched to the position of charged tracks extrapolated outward from the central tracking chamber is considered a photon candidate.

We require Λ_c^+ candidates to have an invariant mass within ± 20 MeV/c^2 of the known Λ_c^+ mass. For the purposes of background studies, we define two sideband samples for each mode, also ± 20 MeV/c^2 wide, and centered at ± 45 MeV/c^2 from the central Λ_c^+ mass value. Each Λ_c^+ candidate is then combined with all remaining pairs of oppositely charged particles, assumed to be pions, and the mass difference $M(\Lambda_c^+\pi^+\pi^-) - M(\Lambda_c^+)$ is then calculated. Loose particle identification requirements are imposed on the transition pions in order to suppress any possible backgrounds from $D^* \to D\gamma$ or $D^* \to D\pi^0$, which may produce a low-mass electron-positron pair in the case where a transition photon pair converts, or a transition π^0 undergoes a Dalitz decay. To improve signal to noise, the $\Lambda_c^+\pi^+\pi^-$ combinations must satisfy $x_p > 0.7$, where x_p is the ratio of the candidate momentum to the maximum kinematically allowed momentum for e^+e^- production of charmed particle pairs ($x_p = p/\sqrt{E_{\text{beam}}^2 - M_{\Lambda_c^{*+}}^2}$).

The mass difference spectrum for combinations satisfying the above cuts is shown by the data points in Fig. 1.

A large peak, visible at a mass difference of approximately 342 MeV/c^2, is due to the previously reported decay $\Lambda_c^{*+}(2625) \to \Lambda_c^+\pi^+\pi^-$. Also present is a smaller, but still significant, enhancement at a mass difference of $\approx$308 MeV/c^2. The sum of a polynomial background shape plus two signal functions is used to fit the mass difference distribution. Each signal is described as a spin-0 Breit-Wigner line shape, with a floating intrinsic width, convoluted with a Gaussian of fixed width to parametrize the detector resolution. The width of this Gaussian is taken from Monte Carlo studies. The fitted

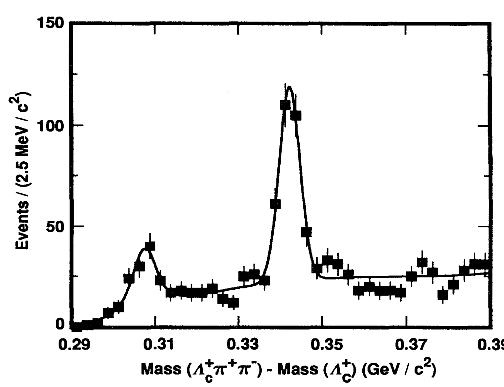

FIG. 1. Fit to mass difference: $M(\Lambda_c^+\pi^+\pi^-) - M(\Lambda_c^+)$.

signal sizes of the upper and lower peaks are 244.6 ± 19.0 and 112.5 ± 16.5 events, respectively. The results of the fits, giving the observed yield, extracted widths, and mass splittings relative to the Λ_c^+, are given in Table I. The systematic errors on the quoted widths are obtained by observing the variation in width when the event selection criteria are varied, or when the signal plus background parametrizations are varied. The systematic error on the mass difference reflects uncertainties in the overall momentum scale, signal parametrization, and energy loss correction in the detector at low momentum.

In order to verify that the signals are not an artifact of the selection criteria, two checks were performed, using combinations from the Λ_c^+ sidebands, as well as same-sign ($\Lambda_c^+\pi^\pm\pi^\pm$) combinations. Neither the mass difference plot for combinations from the Λ_c^+ mass sidebands nor the plot for same-sign combinations shows any departure from smooth behavior, and both are consistent in shape with our background parametrization.

If these states are isospin zero objects, then a strong decay into $\Lambda_c^+\pi$ is prohibited. An electromagnetic decay into $\Lambda_c^+\gamma$ is allowed, and may be competitive with dipion transitions if the intrinsic widths of the states are sufficiently narrow. If, on the other hand, these objects are excited Σ_c baryons, in which the *ud* diquark is in an isospin 1 state, then their dominant decay should be to $\Lambda_c^+\pi$. We have therefore also searched for these resonances in the final states $\Lambda_c^+\pi^0$ (neutral pions as defined previously) and $\Lambda_c^+\gamma$ (photons as defined previously, but with the added requirement that the measured energy exceed 200 MeV). Results of our searches in these modes are given in Table I; no signals are found and we therefore quote only upper limits. We determine $\mathcal{B}(\Lambda_c^{*+}(2593) \to \Lambda_c^+\pi^0)/\mathcal{B}(\Lambda_c^{*+}(2593) \to \Lambda_c^+\pi^+\pi^-) < 3.53$ and $\mathcal{B}(\Lambda_c^{*+}(2593) \to \Lambda_c^+\gamma)/\mathcal{B}(\Lambda_c^{*+}(2593) \to \Lambda_c^+\pi^+\pi^-) < 0.98$. The corresponding upper limits for the $\Lambda_c^{*+}(2625)$ are 0.91 and 0.52, respectively. For a charmed baryon just above $\Lambda_c^+\pi^+\pi^-$ threshold, the phase space for $\Lambda_c^+\pi$ decay is much more favorable than for $\Lambda_c^+\pi^+\pi^-$ decay. The combination of our nonobservation of Λ_c^{*+} in the $\Lambda_c^+\pi$ channel, coupled with observation in the $\Lambda_c^+\pi^+\pi^-$ channel, supports the interpretation of these states as Λ_c^{*+} baryons rather than Σ_c^{*+} baryons [13].

The presence of substructure in the $\Lambda_c^+\pi^+\pi^-$ final state ($\Sigma_c\pi$, e.g.) can also provide information on the identities of these states. Of interest is the fraction, f_{Σ_c}, of the $\Lambda_c^{*+}(2625) \to \Lambda_c^+\pi^+\pi^-$ decay rate which proceeds through an intermediate Σ_c. Previous analyses of this final state by the ARGUS [7] and E687 [8] collaborations determined f_{Σ_c} to be 0.46 ± 0.14 and <36%, respectively. Figure 2 shows the $\Lambda_c^+\pi^- - \Lambda_c^+$ mass difference plotted against the $\Lambda_c^+\pi^+ - \Lambda_c^+$ mass difference for our $\Lambda_c^+\pi^+\pi^-$ final sample. A cluster of events, corresponding to transitions of the $\Lambda_c^{*+}(2593)$ decaying to Λ_c^+ through an intermediate Σ_c, is prominent at each end of the diagonal band near the lower left corner of the plot. Such clustering is not evident for the band corresponding to the $\Lambda_c^{*+}(2625)$. To determine the fraction of times that the decay $\Lambda_c^{*+} \to \Lambda_c^+\pi^+\pi^-$ occurs through the intermediate state $\Lambda_c^{*+} \to \Sigma_c\pi$, we measure the Λ_c^{*+} yield as a function of $\Lambda_c^+\pi$ submass. By subtracting the Λ_c^{*+} yield when the $\Lambda_c^+\pi$ submass is in the Σ_c sidebands from the Λ_c^{*+} yield when the $\Lambda_c^+\pi$ mass is consistent with the Σ_c mass, we extract the values $f_{\Sigma_c^{++}}$ and $f_{\Sigma_c^0}$, corresponding to the $\Sigma_c^{++}\pi^-$ and $\Sigma_c^0\pi^+$ content, respectively, of the final state. Our measurements of these parameters are given in Table II [14].

Also of interest is the fragmentation function of these states compared to that of the ground state $\Lambda_c^+(2285)$. The orbitally excited charmed mesons $D_1(2420)$ and $D_2(2460)$, as well as the orbitally excited D_{sJ} states, have measured fragmentation functions which are noticeably harder than either those of the ground state D and D_s pseudoscalar mesons or those of the corresponding vector states [15]. Figure 3 shows the efficiency corrected fragmentation functions for the Λ_c^{*+} sample. We have fit our data using the fragmentation function parametrization of Peterson *et al.* [16] in terms of one parameter ϵ_P; as the average scaled momentum $\langle x_p \rangle$ approaches 1, ϵ_P approaches zero. The values of Peterson ϵ_P we extract for the Λ_c^{*+} samples are given in Table II. For purposes of comparison, ϵ_P of the ground state Λ_c^+ is also included in the table. The Λ_c^{*+} baryons clearly display harder momentum spectra. The systematic errors given in our determination of ϵ_P are dominated by uncertainties in the absolute tracking efficiency of the soft transition pions.

TABLE I. Parameters of fit to Λ_c^{*+} signals. Also shown are results from the ARGUS and E687 experiments.

Decay	Events	$\Gamma_{\Lambda_c^{*+}}$ (MeV/c^2)	$M(\Lambda_c^{*+}) - M(\Lambda_c^+)$ (MeV/c^2)
$\Lambda_c^{*+}(2625) \to \Lambda_c^+\pi^+\pi^-$	244.6 ± 19.0	<1.9	342.2 ± 0.2 ± 0.5
$\Lambda_c^{*+}(2593) \to \Lambda_c^+\pi^+\pi^-$	112.5 ± 16.5	$3.9^{+1.4+2.0}_{-1.2-1.0}$	307.5 ± 0.4 ± 1.0
$\Lambda_c^{*+}(2625) \to \Lambda_c^+\pi^0$	62 ± 50		
$\Lambda_c^{*+}(2625) \to \Lambda_c^+\gamma$	−5 ± 24		
$\Lambda_c^{*+}(2593) \to \Lambda_c^+\pi^0$	−44 ± 47		
$\Lambda_c^{*+}(2593) \to \Lambda_c^+\gamma$	11 ± 26		
(Previous results)			
$\Lambda_c^{*+}(2625) \to \Lambda_c^+\pi^+\pi^-$ [7]	45.6 ± 10.1	<3.2	341.5 ± 0.6 ± 1.6 [12]
$\Lambda_c^{*+}(2625) \to \Lambda_c^+\pi^+\pi^-$ [8]	39.7 ± 8.7		340.4 ± 0.6 ± 0.3

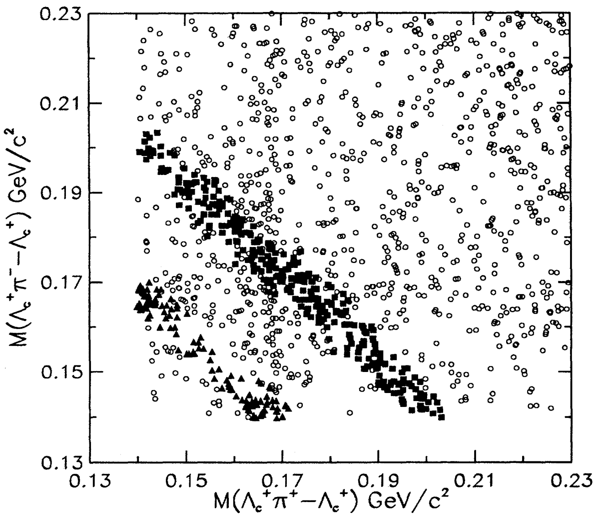

FIG. 2. Scatter plot of the mass difference $M(\Lambda_c^+\pi^-) - M(\Lambda_c^+)$ vs the mass difference $M(\Lambda_c^+\pi^+) - M(\Lambda_c^+)$, for events with $M(\Lambda_c^+\pi^+\pi^-) < 2650$ MeV/c^2. Visible in the figure are (1) the vertical band at $\Lambda_c^+\pi^+$ mass difference of 168 MeV/c^2, corresponding to $\Sigma_c^{++} \to \Lambda_c^+\pi^+$; (2) the horizontal band at $\Lambda_c^+\pi^-$ mass difference of 168 MeV/c^2, corresponding to $\Sigma_c^0 \to \Lambda_c^+\pi^-$; (3) the diagonal band extending from (0.14,0.20) to (0.20,0.14), corresponding to combinations taken from the $\Lambda_c^{*+}(2625)$ signal region in Fig. 1 (squares); and (4) the diagonal band extending from (0.14,0.168) to (0.168,0.14), corresponding to combinations taken from the $\Lambda_c^{*+}(2593)$ signal region in Fig. 1 (triangles), within which there are two lobes at the kinematic limits: (a) the enhancement in the Σ_c^{++} band, just above the threshold for $\Lambda_c^+\pi^-$, and (b) the enhancement in the Σ_c^0 band, just above the threshold for $\Lambda_c^+\pi^+$.

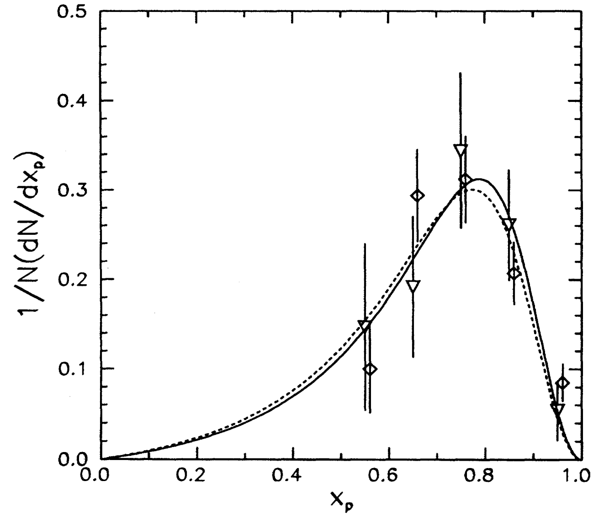

FIG. 3. Normalized dN/dx_p spectra of the Λ_c^{*+} samples. Shown are the data for the $\Lambda_c^{*+}(2625)$ (diamonds) and the $\Lambda_c^{*+}(2593)$ (inverted triangles), with fits to the Peterson function overlaid as the dashed and solid curves, respectively.

From the efficiency corrected cross section, $\sigma(e^+e^- \to \Lambda_c^{*+}X)\,\mathcal{B}(\Lambda_c^{*+} \to \Lambda_c^+\pi^+\pi^-)$, we can determine the fraction of Λ_c^+ baryons observed in CLEO which are actually produced as Λ_c^{*+} daughters through $\Lambda_c^{*+} \to \Lambda_c^+\pi^+\pi^-$ (using the Peterson function to extrapolate to zero momentum) [17]. We determine these fractions to be $1.44 \pm 0.24 \pm 0.30\%$ and $3.51 \pm 0.34 \pm 0.28\%$, for the $\Lambda_c^{*+}(2593)$ and $\Lambda_c^{*+}(2625)$, respectively, as shown in Table II. This is comparable to the fraction of $L = 0$ charmed mesons which are determined to be decay products of orbitally excited $D_1(2420)$ or $D_2^*(2460)$ mesons [15]. The systematic error in this fraction is dominated by uncertainties in our track reconstruction efficiency.

In the strange baryon sector, the two lowest lying spatial excitations have total spin 1/2 and 3/2 [the $\Lambda(1405)$ and the $\Lambda(1520)$, respectively]. These belong to a multiplet with the (ud) diquark in a state of $S = 0, L = 0$, orbiting the strange quark with relative orbital angular momentum $L = 1$. This orbital angular momentum (which corresponds to the total angular momentum of the light degrees of freedom) combines with the spin of the heavier strange quark to produce two states, one having total spin 1/2 and the other having total spin 3/2. It has been predicted [1–5] that there should be two analogous Λ_c^{*+} states in the charm sector. These orbitally excited Λ_c^{*+} baryons would have preferred decays to $\Sigma_c\pi$ and $\Sigma_c^*\pi$, respectively, much as the orbitally excited strange baryons decay dominantly to $\Sigma\pi$ rather than to $\Lambda\pi^+\pi^-$. In this model, the $\Lambda_c^{*+}(2593)$ corresponds to the lower mass $\Lambda(1405)$, whereas the $\Lambda_c^{*+}(2625)$ corresponds to the higher mass $\Lambda(1520)$ state. Although both Λ_c^{*+} states can decay to $\Sigma_c\pi$, only the lower state has an allowed S-wave decay to $\Sigma_c\pi$; conservation of angular momentum and parity conservation requires that the decay $\Lambda_c^{*+}(2625) \to E_c\pi$ must be D wave. For the higher mass state, since the Σ_c^{*+} pole mass is kinematically inaccessible [19], the S-wave decay $\Sigma_c^*\pi$ is allowed only through the low-mass tail of the Σ_c^* [13]. Therefore one expects the $\Lambda_c^{*+}(2625)$ to have a smaller width than the $\Lambda_c^{*+}(2593)$, in agreement with our

TABLE II. $\Lambda_c^{*+}e^+e^-$ production and decay results from this analysis and ARGUS [7].

Signal	ϵ_P	$f_{\Sigma_c^{++}}$	$f_{\Sigma_c^0}$ (%)	$\frac{\sigma(\Lambda_c^{*+}\to\Lambda_c^+\pi^+\pi^-)}{\sigma(\Lambda_c^+)}$ (%)
$\Lambda_c^+(2285)$ [18]	0.27 ± 0.05			
$\Lambda_c^{*+}(2593)$	$0.057 \pm 0.023 \pm 0.016$	$0.36 \pm 0.09 \pm 0.09$	$0.42 \pm 0.09 \pm 0.09$	$1.44 \pm 0.24 \pm 0.30$
$\Lambda_c^{*+}(2625)$	$0.065 \pm 0.016 \pm 0.013$	<0.08 (90% C.L.)	<0.07 (90% C.L.)	$3.51 \pm 0.34 \pm 0.28$
$\Lambda_c^{*+}(2625)$ [7]	0.044 ± 0.018	$f_{\Sigma_c^{++}} + f_{\Sigma_c^0} = 0.46 \pm 0.14$		$4.1 \pm 1.0 \pm 0.8$

measurements. The absence of any evident $\Sigma_c \pi$ structure in the $\Lambda_c^{*+}(2625)$ band in Fig. 2 is also consistent with this interpretation of the data.

It is interesting to note the splitting between the two states $\Lambda_c^{*+}(2625)$ and $\Lambda_c^{*+}(2593)$, which we measure to be $34.7 \pm 0.5 \pm 1.2$ MeV/c^2. It is considerably less than the mass splitting between the $\Lambda(1520)$-$\Lambda(1405)$, as expected both from HQET and from potential models. As anticipated in the HQET picture, it is essentially identical to the splittings observed in the mesonic sector; by comparison, $M[D_2^*(2460)^0] - M[D_1(2420)^0]$ is determined to be 35 ± 6 MeV/c^2 [15].

In conclusion, we have observed two peaks in the $M(\Lambda_c^+ \pi^+ \pi^-) - M(\Lambda_c^+)$ mass difference plot, one of which represents the first observation of a new state. The most likely explanation of these peaks is the decay of two orbitally excited Λ_c^+ baryons, one decaying dominantly through an intermediate $\Sigma_c \pi$. The mass differences, $M(\Lambda_c^{*+}) - M(\Lambda_c^+)$, of these states are measured to be $307.5 \pm 0.4 \pm 1.0$ and $342.2 \pm 0.2 \pm 0.5$ MeV/c^2, respectively.

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