Observation of an Excited State of the Λ_c^+ Baryon

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An observation of an excited Λ_c^{+*} baryon decaying to $\Lambda_c^+\pi^+\pi^-$, with $\Lambda_c^+ \to pK^-\pi^+$, is presented. We reconstruct 39.7±8.7 Λ_c^{+*} baryons with a mass of 340.4±0.6±0.3 MeV/c^2 above the Λ_c^+ mass. The upper limit on the resonant branching ratio is $B(\Lambda_c^{+*} \to \Sigma_c\pi^\pm)/B(\Lambda_c^{+*} \to \Lambda_c^+\pi^+\pi^-) < 36\%$ at the 90% confidence level.

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Charm spectroscopy has provided excellent tests of QCD quark models and lattice gauge calculations. The higher mass of the charm quark, relative to the strange quark, allows for more reliable results using QCD calculations. These tests have been limited mainly to $c\bar{c}$ meson spectroscopy. Data on charm baryon spectroscopy can be used to test further the agreement of various QCD mass predictions, in particular, relativistic effects associated with the light quarks in the charm baryon.

Table I shows predictions for the masses of the $J^P = \frac{1}{2}^-$ and $\frac{3}{2}^-$ excited states of the Λ_c^+ and Σ_c baryons in a relativistic quark model with chromodynamics by Capstick and Isgur [1]. The Λ_c^{+*} baryon is forbidden to decay to $\Lambda_c^+\pi^0$ since isospin is conserved in strong decays. If the Λ_c^{+*} has enough mass it can decay to $\Lambda_c^+\pi^+\pi^-$ (and $\Lambda_c^+\pi^0\pi^0$). Note that if the Σ_c^{+*} baryon has enough mass it can also decay to $\Lambda_c^+\pi^+\pi^-$ as well as $\Lambda_c^+\pi^0$.

Evidence for an excited charm baryon state was first presented by ARGUS [2]. They reported a state decaying to $\Lambda_c^+\pi^+\pi^-$ with a mass of 2626.6±0.5±1.5 MeV/c^2. They also report the branching fraction $B(\Lambda_c^{+*} \to \Sigma_c\pi^\pm)/B(\Lambda_c^{+*} \to \Lambda_c^+\pi^+\pi^-) = 0.46 \pm 0.14$. Although the observed signal could be due to either a Λ_c^* or a Σ_c^* baryon, it is almost certainly a Λ_c^* baryon, either the $\frac{1}{2}^-$ or/and the $\frac{3}{2}^-$ state, because these are the two lowest lying states (see Table I). These two states are predicted to have approximately the observed mass difference while the Σ_c^* states are predicted to have a much higher mass difference [1]. Furthermore, the Σ_c^* state should also be observable via its decay to $\Lambda_c^+\pi^0$. Although a search for a Σ_c^{+*} state decaying to $\Lambda_c^+\pi^0$ has not been reported, there is no evidence for the isospin related states decaying to $\Lambda_c^+\pi^\pm$ [3]. We shall refer to the state first observed by ARGUS as the Λ_c^* or the $\Lambda_c(2625)$. Preliminary results from both CLEO II [4] and E687 [5] confirm the existence of the $\Lambda_c(2625)$. CLEO II reports 174±21 events for $\Lambda_c^{+*} \to \Lambda_c^+\pi^+\pi^-$ with a mass difference of 342.1±0.4±0.5 MeV/c^2 and 57±15 events for $\Lambda_c^{+*} \to \Lambda_c^+\pi^0\pi^0$ with a mass difference of 340.7±0.9±1.4 MeV/c^2. CLEO II also reports that they see no evidence for the intermediate Σ_c^0 or Σ_c^{++} states in the decay $\Lambda_c^{+*} \to \Lambda_c^+\pi^+\pi^-$.

TABLE I. Mass predictions for the ground state and some excited states of the Λ_c^+ and Σ_c baryons taken from Ref. [1].

State	J^P	Mass (MeV/c^2)	ΔM^a (MeV/c^2)
Λ_c	$\frac{1}{2}^+$	2265	
Λ_c^*	$\frac{1}{2}^-$	2630	365
Λ_c^*	$\frac{3}{2}^-$	2640	375
Σ_c^*	$\frac{1}{2}^-$	2765	500
Σ_c^*	$\frac{3}{2}^-$	2770	505

^{a}Mass above the ground state of the Λ_c.

This paper presents confirmation of a photoproduced $\Lambda_c(2625)$ decaying to $\Lambda_c^+\pi^+\pi^-$, where the Λ_c^+ is reconstructed via its decay to $pK^-\pi^+$. Throughout this paper, the charge conjugate state is implied when a decay mode of a specific charge is stated.

The data for this analysis were collected in 1990 and 1991 in the Fermilab wideband photoproduction experiment E687. About 5×10^8 triggers were recorded on tape during this period. The E687 detector is described in detail elsewhere [6].

A number of cuts were used to select $pK^-\pi^+$ combinations. Each of the decay secondaries must be reconstructed in both the microstrip and multiwire proportional chamber systems, and the two sets of track parameters must agree within measurement errors. Information from the Čerenkov counters is used to select protons, kaons, and pions.

The Λ_c^+ decays were reconstructed by a *candidate driven* method [6]. The three microstrip tracks of the $pK^-\pi^+$ combination forming the secondary vertex are required to extrapolate back to a single point with a confidence level greater than 1%. The candidate Λ_c^+ track must form a primary vertex with at least one other microstrip track with a confidence level greater than 1%. An important cut in isolating charm signals from noncharm background is the significance of detachment of the primary and secondary vertices. We use the variable ℓ/σ_ℓ, where ℓ is the signed three dimensional separation between the primary and secondary vertices, and σ_ℓ is the error on ℓ computed on an event by event basis taking into account the effects of multiple Coulomb scattering.

Figure 1(a) shows the $pK^-\pi^+$ invariant mass plot for $\ell/\sigma_\ell > 4$ and a momentum cut on the $pK^-\pi^+$ combination of $p_{\Lambda_c^+} > 50$ GeV/c. Monte Carlo studies show that $pK^-\pi^+$ combinations from Λ_c^+ baryons have a harder momentum spectrum than background $pK^-\pi^+$ combinations. The momentum cut keeps almost all the signal and improves the signal-to-noise so that a looser ℓ/σ_ℓ cut can be used.

In the $pK^-\pi^+\tilde{\pi}^+\tilde{\pi}^-$ combination, the two *primary* ($\tilde{\pi}^+\tilde{\pi}^-$) pions are required to be reconstructed in both the microstrip and the multiwire proportional chamber

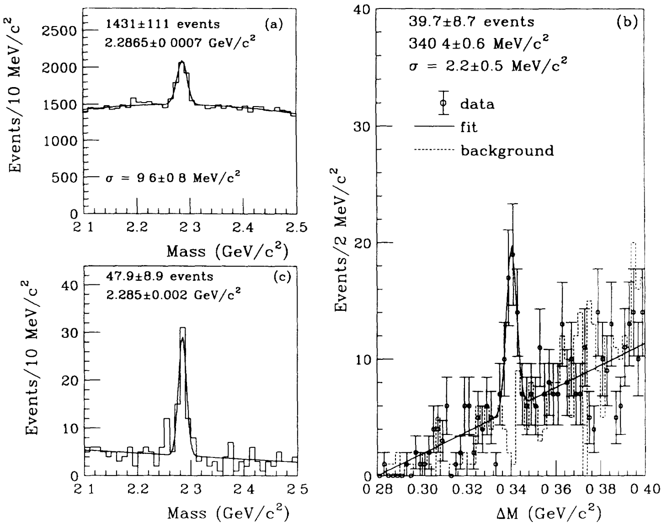

FIG. 1. (a) $pK^-\pi^+$ invariant mass plot for $\ell/\sigma_\ell > 4$ and $p_{\Lambda_c^+} > 50$ GeV/c; (b) using the data of (a), $\Delta M = M(pK^-\pi^+\tilde{\pi}^+\tilde{\pi}^-) - M(pK^-\pi^+)$ mass difference for $|M(pK^-\pi^+) - 2.285| < 19.2$ MeV/c^2 (circles) and for background (dashed histogram); (c) $pK^-\pi^+$ invariant mass plot as in (a) together with $|\Delta M - 0.3404| < 4.4$ MeV/c^2. The fits shown on the plots are to a Gaussian signal with a quadratic background (a) or a linear background function (b) and (c).

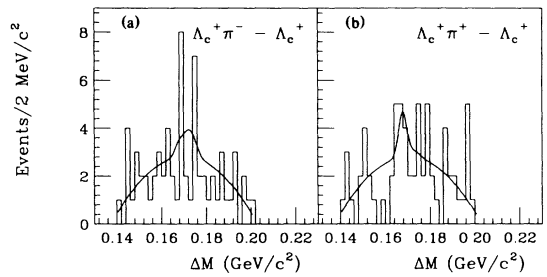

FIG. 2. (a) $(pK^-\pi^+\tilde{\pi}^-) - M(pK^-\pi^+)$ mass difference and (b) $(pK^-\pi^+\tilde{\pi}^+) - M(pK^-\pi^+)$ mass difference, where the $pK^-\pi^+$ invariant mass must be within $\pm 2\sigma$ of the Λ_c^+ mass and the $M(pK^-\pi^+\tilde{\pi}^+\tilde{\pi}^-) - M(pK^-\pi^+)$ mass difference must be within $\pm 2\sigma$ of 340.4 MeV/c^2. The fits shown are described in the text.

systems. In addition the microstrip tracks have to be part of the already reconstructed primary vertex. To reduce systematics we look at the mass difference between the $pK^-\pi^+\tilde{\pi}^+\tilde{\pi}^-$ combination and the $pK^-\pi^+$ combination: $\Delta M = M(pK^-\pi^+\tilde{\pi}^+\tilde{\pi}^-) - M(pK^-\pi^+)$. Note that for each event, all $\tilde{\pi}^+\tilde{\pi}^-$ combinations are used with each $pK^-\pi^+$ combination.

Figure 1(b) shows the mass difference with a $\pm 2\sigma$ (± 19.2 MeV/c^2) cut on the $pK^-\pi^+$ mass around 2.285 GeV/c^2. The mass difference distribution for background is shown by the dashed histogram. The background is from two sources: random $pK^-\pi^+$ combinations and real Λ_c^+ baryons with random $\tilde{\pi}^+\tilde{\pi}^-$ combinations. The random $pK^-\pi^+$ combination background is given by the (properly normalized) Λ_c^+ sidebands. A measure of the second background source is given by the $pK^-\pi^+\tilde{\pi}^+\tilde{\pi}^+$ and $pK^-\pi^+\tilde{\pi}^-\tilde{\pi}^-$ combinations where (random) $pK^-\pi^+$ sideband contributions have been subtracted. A maximum likelihood fit, using a Gaussian signal and linear background, to the mass difference distribution yields 39.7±8.7 events in the peak with a mass difference of 340.4±0.6±0.3 MeV/c^2. The first error is the statistical error and the second is the systematic uncertainty. The major contribution to the systematic uncertainty comes from fluctuations in the fitted mass difference for different data samples collected with various cuts, and for different fit functions and fit methods. Monte Carlo studies show that the shift in the mass difference due to acceptance is negligible (0.06 MeV/c^2), and our (high statistics) data on the $M(D^0\pi^+) - M(D^0)$ mass difference agree with the world average value [7] to within 0.01 MeV/c^2.

The width of the peak is found to be 2.2±0.5 MeV/c^2 which is consistent with the value of 2.87±0.04 MeV/c^2 due to resolution alone, as determined in a Monte Carlo study.

Figure 1(c) shows the $pK^-\pi^+$ invariant mass when a cut is made in the ΔM mass difference of $\pm 2\sigma$ about 340.4 MeV/c^2. A fit to a Gaussian and linear background yields 47.9±8.9 events. This gives further evidence that the peak in the mass difference is really associated with a Λ_c^+.

The resonant decays $\Lambda_c^* \to \Sigma_c^0\pi^+$ and $\Lambda_c^* \to \Sigma_c^{++}\pi^-$ were investigated by plotting the $M(\Lambda_c^+\pi^+) - M(\Lambda_c^+)$ and $M(\Lambda_c^+\pi^-) - M(\Lambda_c^+)$ mass differences for a $\pm 2\sigma$ cut on the $pK^-\pi^+$ mass around 2.285 MeV/c^2 and a $\pm 2\sigma$ cut on the $\Delta M = M(pK^-\pi^+\tilde{\pi}^+\tilde{\pi}^-) - M(pK^-\pi^+)$ mass difference around 340.4 MeV/c^2. These mass difference plots are shown in Fig. 2. In these plots, a fit function consisting of a quadratic background function plus two Gaussians was used. Because of the limited range of mass combinations constrained by the two mass cuts used, an actual $\Lambda_c^* \to \Sigma_c^{++}\pi^-$ event will also produce an entry in the $M(\Lambda_c^+\pi^-) - M(\Lambda_c^+)$ mass difference plot leading to a "false" peak at a mass of $340.4 - [M(\Sigma_c^{++}) - M(\Lambda_c^+)]$ MeV/c^2. Similarly a Σ_c^0 signal will give rise to a "false" peak in the $M(\Lambda_c^+\pi^+) - M(\Lambda_c^+)$ mass difference plot. For the fit, the widths of the real Σ_c in the mass difference plot were fixed at 1.77 MeV/c^2 and the widths of the false peaks were fixed at 2.84 MeV/c^2. These widths were obtained in a Monte Carlo study. The Σ_c peak mass difference values were also fixed in the fit to 167.8 MeV/c^2 and the false peak fixed to 172.6 MeV/c^2. Equal masses for the Σ_c^{++} and the Σ_c^0 have been assumed and an average of the world average values for these masses [7] and recent values obtained by CLEO II [8] were used. The background function used was obtained from a Monte Carlo study of nonresonant decays of the Λ_c^*.

The fit of the two histograms shown in Fig. 2 was done in a combined maximum likelihood fit, so only three fit parameters were used in the fit of the two histograms: the number of Σ_c^{++}, the number of Σ_c^0, and the number of background events. The fit gave 4.1 ± 3.2 Σ_c^{++} and 1.0 ± 2.9 Σ_c^0 events. A study of the Λ_c^* sidebands shows no evidence for (background) Σ_c^{++} or Σ_c^0 in our sample. Other fitting methods and fit functions gave fit values within one (statistical) sigma of these values. In particular a fit was tried where the number of Σ_c^{++} and the number of Σ_c^0 were constrained to be the same; this might be expected from isospin conservation if one ignores any small differences in mass between the Σ_c^{++} and the Σ_c^0. Because of the limited statistics and the fact that the resonant decay is consistent with zero, we prefer to quote an upper limit for the resonant decay. The actual limit was determined by studying the limits obtained using various cuts and fit methods and is corrected by 4.6% for the fact that only a $\pm2\sigma$ region about the Λ_c^* mass was used in the analysis. The final 90% confidence level upper limit for the resonant decay is

$$\frac{B(\Lambda_c^* \to \Sigma_c^{++}\pi^-) + B(\Lambda_c^* \to \Sigma_c^0\pi^+)}{B(\Lambda_c^* \to \Lambda_c^+\pi^+\pi^-)} < 36\%.$$

Theory predicts two Λ_c^* states ($1/2^-$ and $3/2^-$) split by spin-orbit interactions. While nonrelativistic models predict relatively large spin-orbit splittings [9], relativistic models predict much smaller spin-orbit splittings [1]. We do not see any significant evidence of another peak in the mass difference distribution up to 450 MeV/c^2, whereas we might have expected to see both the $1/2^-$ and the $3/2^-$ states in this mass difference range. Three possible explanations are the following: the $1/2^-$ and $3/2^-$ splitting is too small to be resolved; the production of the two states is very different in our experiment; or the two states have very different branching ratios to $\Lambda_c^+\pi^+\pi^-$ (e.g., if one of the states has a low enough mass to be below the $\Lambda_c^+\pi^+\pi^-$ threshold).

It should be noted that there is some preliminary evidence from CLEO for a state decaying to $\Lambda_c^+\pi^+\pi^-$ with a mass difference of 308 MeV/c^2 [3]. However, the existence of this other state needs to be confirmed. Because of our limited statistics, the unknown relative production of the 340 MeV/c^2 and the 308 MeV/c^2 Λ_c^* states, and the unknown branching ratios, we can neither confirm nor rule out the existence of this additional Λ_c^* state.

In conclusion, we confirm the existence of an excited charm baryon state at a mass of $340.4\pm0.6\pm0.3$ MeV/c^2 above the Λ_c^+ mass. The upper limit on the resonant branching ratio to $\Sigma_c^{++}\pi^- + \Sigma_c^0\pi^+$ relative to $\Lambda_c^+\pi^+\pi^-$ is 36% at the 90% confidence level.

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