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E687

Study of Higher Mass Charm Baryons Decaying to Λ_c^+

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The E687 Collaboration

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We report on the study of charm baryons decaying to Λ_c^+: $\Lambda_c^{*+}(2625) \to \Lambda_c^+\pi^+\pi^-$, $\Lambda_c^{*+}(2593) \to \Lambda_c^+\pi^+\pi^-$, $\Sigma_c^0 \to \Lambda_c^+\pi^-$ and $\Sigma_c^{++} \to \Lambda_c^+\pi^+$. We present a confirmation of the state $\Lambda_c^{*+}(2593)$ and determine its mass difference to be $M(\Lambda_c^{*+}(2593)) - M(\Lambda_c^+) = 309.2 \pm 0.7 \pm 0.3 MeV/c^2$. We determine the lower limit on the resonant branching ratio to be BR($\Lambda_c^{*+}(2593) \to \Sigma_c\pi^\pm / \Lambda_c^{*+}(2593) \to \Lambda_c^+\pi^+\pi^-$) > 0.51 (90% c.l.). We also measure the mass differences $M(\Sigma_c^0) - M(\Lambda_c^+) = 166.6 \pm 0.5 \pm 0.6 MeV/c^2$ and $M(\Sigma_c^{++}) - M(\Lambda_c^+) = 167.6 \pm 0.6 \pm 0.6 MeV/c^2$. Finally, we measure the relative photoproduction cross sections for Λ_c^{*+} and Σ_c with respect to the (inclusive) photoproduction cross section for Λ_c^+.

In this paper we report on the study of charm baryons which strongly decay to the lowest mass charm baryon Λ_c^+, namely $\Lambda_c^{*+}(2625) \rightarrow \Lambda_c^+\pi^+\pi^-$, $\Lambda_c^{*+}(2593) \rightarrow \Lambda_c^+\pi^+\pi^-$, $\Sigma_c^0 \rightarrow \Lambda_c^+\pi^-$ and $\Sigma_c^{++} \rightarrow \Lambda_c^+\pi^+$ (throughout this paper charge conjugate states are implicitly assumed). Several experiments have observed the isospin triplet states Σ_c^0, Σ_c^+, Σ_c^{++} which decay strongly to $\Lambda_c^+\pi$. Here we concentrate only on the two decays $\Sigma_c^0 \rightarrow \Lambda_c^+\pi^-$ and $\Sigma_c^{++} \rightarrow \Lambda_c^+\pi^+$, since our reconstruction efficiency for π^0 is considerably lower than for $\pi^\pm$. Few experiments have observed the Λ_c^{*+} excited states. ARGUS[1], CLEO[2] and E687[3] have reported the existence of one such state, the $\Lambda_c^{*+}(2625)$, with a mass difference $M(\Lambda_c^{*+}(2625)) - M(\Lambda_c^+) \simeq 341 MeV/c^2$, reconstructed through its decay to $\Lambda_c^+\pi^-\pi^+$. ARGUS reports a significant resonant component for the decay, $\Gamma(\Lambda_c^{*+}(2625) \rightarrow \Sigma_c\pi^\pm)/\Gamma(\Lambda_c^{*+}(2625) \rightarrow \Lambda_c^+\pi^+\pi^-) = 0.46 \pm 0.14$, yet both CLEO and E687 did not see any resonant decay: E687[3] estimated the total resonant fraction to be $BR(\Lambda_c^{*+}(2625) \rightarrow \Sigma_c\pi^\pm / \Lambda_c^{*+}(2625) \rightarrow \Lambda_c^+\pi^+\pi^-) < 0.36$ (90% c.l.) and CLEO[4] measured the two separate upper limits $BR(\Lambda_c^{*+}(2625) \rightarrow \Sigma_c^0\pi^+ / \Lambda_c^{*+}(2625) \rightarrow \Lambda_c^+\pi^+\pi^-) < 0.07$ and $BR(\Lambda_c^{*+}(2625) \rightarrow \Sigma_c^{++}\pi^- / \Lambda_c^{*+}(2625) \rightarrow \Lambda_c^+\pi^+\pi^-) < 0.08$ (90% c.l.). CLEO[4] has also reported evidence for a lower mass Λ_c^{*+} excited state, which we shall refer to as $\Lambda_c^{*+}(2593)$, at a mass difference $M(\Lambda_c^{*+}(2593)) - M(\Lambda_c^+) = 307.5 \pm 0.4 \pm 1.0 MeV/c^2$. The $\Lambda_c^{*+}(2593)$ was reconstructed from the final state $\Lambda_c^+\pi^-\pi^+$, and the resonant decay $\Lambda_c^{*+}(2593) \rightarrow \Sigma_c\pi^\pm$, $\Sigma_c \rightarrow \Lambda_c^+\pi^\mp$ (where the Σ_c can either be a Σ_c^0 or a Σ_c^{++}) was reported to be dominant. In our earlier Λ_c^{*+} paper, where we reconstrcted Λ_c^+ only in the decay mode $\Lambda_c^+ \rightarrow pK^-\pi^+$, we could neither confirm nor rule out the existence of such a state. In this paper we make use of more Λ_c^+ decay modes and tighter analysis conditions, and we are able to present evidence for a Λ_c^{*+} signal at approximately the same mass difference as the observed CLEO $\Lambda_c^{*+}(2593)$ state.

The newly discovered Λ_c^{*+} states have been interpreted[5] as a fine structure doublet in which the light diquark ud carries a unit of orbital angular momentum $L = 1$ with respect to the heavy c quark. Combining this orbital angular momentum with the spin $S = \frac{1}{2}$ of the baryon, the two states have been assumed to have total angular momentum and parity J^P as follows: $\Lambda_c^{*+}(2593) = \frac{1}{2}^-$ and $\Lambda_c^{*+}(2625) = \frac{3}{2}^-$, with the isospin for both being $I = 0$. The Λ_c^{*+} can not decay to Λ_c^+ via single pion emission because of isospin conservation but requires two pions in the final state. Angular momentum and parity conservation allow the state $\Lambda_c^{*+}(\frac{1}{2}^-)$ to decay to the intermediate resonant state $\Sigma_c(\frac{1}{2}^+)$ via an S-wave, but the state $\Lambda_c^{*+}(\frac{3}{2}^-)$ would have to decay to $\Sigma_c(\frac{1}{2}^+)$ via a D-wave. Therefore the resonant decay $\Lambda_c^{*+}(2625) \rightarrow \Sigma_c\pi^\pm$ $(\Sigma_c \rightarrow \Lambda_c^+\pi)$ should be strongly suppressed, while the decay $\Lambda_c^{*+}(2593) \rightarrow \Sigma_c\pi^{\pm}$ ($\Sigma_c \rightarrow \Lambda_c^+\pi$) should not. Thus the analysis of the resonant components of the decays of the Λ_c^{*+} is important in establishing the true nature of the states.

The analysis presented in this paper is based on the data collected at Fermilab during the 1990-91 fixed target run by high energy photoproduction experiment E687. Photons of average tagged energy E_γ = 220 GeV impacted on a 4 cm long Beryllium target and produced charm hadrons. The charm decay products were detected by a multi-purpose spectrometer which is described in detail elsewhere[6]. This analysis makes use of the information from the charge tracking system and the Čerenkov counters for particle identification. The charged tracking system is composed of a high resolution silicon microvertex detector, 5 stations of multi-wire proportional chambers and two analyzing magnets with opposite polarities. We first reconstruct Λ_c^+ via their decays to $pK^-\pi^+$, $p\overline{K^0}$, $p\overline{K^0}\pi^+\pi^-$, $\Lambda^0\pi^+$and $\Lambda^0\pi^+\pi^-\pi^+$ and then we combine the Λ_c^+ with one or two additional pions to search for higher mass charm states (Λ_c^{*+}, Σ_c).

The Λ_c^+ candidates are reconstructed through a *candidate driven* vertex algorithm[6]. The neutral daughters of the Λ_c^+ decay ($\overline{K^0}$ and Λ^0) are identified via their decays $K_s^0 \rightarrow \pi^+\pi^-$ and $\Lambda^0 \rightarrow p\pi^-$. In both cases two oppositely charged tracks (reconstructed by either the silicon vertex detector and the PWC system or by the PWC system alone) are required to originate from a common vertex and the invariant mass of the pair is required to be contained within a certain range of the $\overline{K^0}$ or Λ^0 nominal masses. The charged Λ_c^+ decay daughters (p,$K^\pm$,$\pi^\pm$) are reconstructed as linked microstrip-PWC tracks which satisfy the identification by the Čerenkov system: the protons must be identified as proton definite or p/K ambiguous, the kaons must be kaon definite or p/K ambiguous and the pions must not be identified as definite electrons, kaons, protons or p/K ambiguous. For each decay mode, all the decay daughters have to extrapolate back to a single point (the secondary or decay vertex) with a confidence level greater than 1%. The primary vertex is constructed by intersecting the momentum vector of the reconstructed Λ_c^+ with the remaining microstrip tracks and by requiring the confidence level of the total object to be greater than 1%. The distance between the two vertices, L, is computed and divided by its error, σ_L to determine the significance of the detachment between production and decay vertices: L/σ_L. The Λ_c^+ must also satisfy some *isolation* criteria: tracks from the secondary vertex can not be compatible with coming from the primary vertex and other tracks in the event can not be compatible with coming from the secondary vertex. The full set of analysis cuts employed for each decay mode is described in Table I. In Figure 1 we show the cumulative Λ_c^+ sample reconstructed through the five decay modes mentioned above.

The invariant mass distribution is fit with a Gaussian function for the signal plus a second degree polynomial for the background, giving a yield of $Y(\Lambda_c^+) = 1564 \pm 101$ events.

For each decay mode, we select Λ_c^+ combinations which are contained within approximately $\pm 2\sigma$ of the nominal Λ_c^+ mass, and we compute the invariant mass of the Λ_c^+ with one or two (oppositely charged) tracks coming from the primary vertex. These additional tracks are linked microstrip-PWC tracks and the Čerenkov identification must be compatible with the pion hypothesis (same as above). In order to reduce systematic errors in the mass measurements, we measure the mass difference between the Λ_c^+ + pion(s) state and the original Λ_c^+ state.

In Figure 2 we present the mass difference $M(\Lambda_c^+\pi^-\pi^+) - M(\Lambda_c^+)$: there is evidence for two peaks above the background. The histogram is fit with two Gaussian functions for the signals plus a second degree polynomial for the background. The fit yields $Y_1 = 13.9 \pm 4.5$ events for the lower mass peak, and $Y_2 = 38.8 \pm 8.0$ events for the upper mass peak. The fitted mass differences are $\Delta M_1 = 309.2 \pm 0.7 MeV/c^2$ and $\Delta M_2 = 341.4 \pm 0.4 MeV/c^2$, respectively. Since our value ΔM_1 agrees with the mass difference measured by CLEO[4] for the $\Lambda_c^{*+}(2593)$ state (see Table II), we confirm the existence of the $\Lambda_c^{*+}(2593)$. The width of the $\Lambda_c^{*+}(2593)$ peak is measured to be $\sigma_1 = 1.8 \pm 0.6 MeV/c^2$, which is consistent with our Monte Carlo simulation of a zero intrinsic width particle. We checked the stability of the $\Lambda_c^{*+}(2593)$ signal when different sets of analysis cuts were applied and found that both the $\Lambda_c^{*+}(2593)$ mass and the ratio of the two yields $Y(\Lambda_c^{*+}(2593))/Y(\Lambda_c^{*+}(2625))$ were consistent within the statistical errors to the quoted values for each cut tested.

We quote a conservative upper limit of $0.3 MeV/c^2$ as a systematic error in the $\Lambda_c^{*+}(2593)$ mass measurement. This uncertainty is derived from fluctuations in the fitted mass observed when different fitting techniques and analysis cuts are applied and when the $pK^-\pi^+$ mode alone is used to reconstuct Λ_c^+ candidates. Monte Carlo studies show that the shift between the generated and reconstructed mass difference $M(\Lambda_c^{*+}(2593)) - M(\Lambda_c^+)$ is negligible.

In our previous paper[3] we investigated the resonant decays $\Lambda_c^* \to \Sigma_c^0\pi^+$ ($\Sigma_c^0 \to \Lambda_c^+\pi^-$) and $\Lambda_c^* \to \Sigma_c^{++}\pi^-$ ($\Sigma_c^{++} \to \Lambda_c^+\pi^+$) for the $\Lambda_c^{*+}(2625)$ state. Since we did not find any evidence for an intermediate resonant state, we measured the upper limit BR($\Lambda_c^{*+}(2625) \to \Sigma_c\pi^\pm$/ $\Lambda_c^{*+}(2625) \to \Lambda_c^+\pi^+\pi^-$) < 0.36 at 90% confidence level. In this paper we perform the same study for the $\Lambda_c^{*+}(2593)$ state, using only our cleanest and most copious Λ_c^+ signal, that which is reconstructed via the $\Lambda_c^+ \to pK^-\pi^+$ decay mode (with the analysis cuts described in Table I). In Figure 3(a), 3(b) and 3(c) we plot the mass differences $M(\Lambda_c^+\pi^-\pi^+) - M(\Lambda_c^+)$, $M(\Lambda_c^+\pi^-) - M(\Lambda_c^+)$

and $M(\Lambda_c^+\pi^+) - M(\Lambda_c^+)$ (where in all cases $\Lambda_c^+ \to pK^-\pi^+$), showing evidence for the four states $\Lambda_c^{*+}(2593)$, $\Lambda_c^{*+}(2625)$, Σ_c^0 and Σ_c^{++}, respectively. The histograms are fit with Gaussian curves for signals plus a second degree polynomial for the background. The yields resulting from the fits are listed in Table III, together with the corresponding Monte Carlo reconstruction efficiency for each channel. In Figure 3(d) we plot again the mass differences $M(\Lambda_c^+\pi^-\pi^+) - M(\Lambda_c^+)$ with the additional requirement that one of the two submasses $\Lambda_c^+\pi^\pm$ is compatible with being either a Σ_c^0 or a Σ_c^{++} (within $\pm 4 MeV/c^2$ ($\sim 2\sigma$) of the values for the Σ_c^0 and Σ_c^{++} masses obtained from histograms 3(b) and 3(c)). The fitted yields for the Λ_c^{*+} states after the Σ_c requirement has been imposed are $Y(\Lambda_c^{*+}(2593)) = 10.4 \pm 3.4$ and $Y(\Lambda_c^{*+}(2625)) = 10.6 \pm 3.7$ events (which must be compared to the yields obtained without the Σ_c requirement: $Y(\Lambda_c^{*+}(2593)) = 10.2 \pm 3.7$ and $Y(\Lambda_c^{*+}(2625)) = 24.4 \pm 6.3$). If the same Σ_c cut is applied to *non-resonant* $\Lambda_c^{*+}(2593) \to \Lambda_c^+\pi^+\pi^-$ and $\Lambda_c^{*+}(2625) \to \Lambda_c^+\pi^+\pi^-$ Monte Carlo samples, it is found that 33.2% and 31.2% (respectively) of the original Λ_c^{*+} yield is retained. This shows that the $\Lambda_c^{*+}(2593)$ sample is consistent with being completely resonant, while the $\Lambda_c^{*+}(2625)$ sample (as expected from our previous analysis) is consistent with being completely non-resonant.

We also measured a lower limit for the resonant fraction of the $\Lambda_c^{*+}(2593) \to \Lambda_c^+\pi^+\pi^-$ decay. We looked at the $M(\Lambda_c^+\pi^-\pi^+) - M(\Lambda_c^+)$ mass difference when one of the two submasses $\Lambda_c^+\pi^\pm$ is contained within one of two (properly normalized) sidebands of the Σ_c^0, Σ_c^{++} masses and subtracted this contribution from the $\Lambda_c^{*+}(2593)$ yield obtained in Figure 3(d). At 90% confidence level, we found:

$$BR(\frac{\Lambda_c^{+*}(2593) \to \Sigma_c\pi^\pm}{\Lambda_c^{+*}(2593) \to \Lambda_c^+\pi^+\pi^-}) > 51\%$$

Our results for the resonant fraction of the $\Lambda_c^{*+}(2593) \to \Lambda_c^+\pi^+\pi^-$ and $\Lambda_c^{*+}(2625) \to \Lambda_c^+\pi^+\pi^-$ decays agree with the results found by CLEO[4] and support the interpretation of the $\Lambda_c^{*+}(2593)$ as the $J^P = \frac{1}{2}^-$ state and the $\Lambda_c^{*+}(2625)$ as the $J^P = \frac{3}{2}^-$ state of the orbitally excited Λ_c^{*+} doublet.

We use the charm baryon signals in Figures 3(a), 3(b) and 3(c) to measure the inclusive photoproduction cross sections of Λ_c^{*+} and Σ_c relative to the inclusive photoproduction cross section of Λ_c^+. For Σ_c we use the formula:

$$\frac{\sigma_{\Sigma_c}}{\sigma_{\Lambda_c}} = \frac{Y(\Sigma_c)}{\epsilon(\Sigma_c \to \Lambda_c\pi, \Lambda_c \to pK\pi) \cdot BR(\Sigma_c \to \Lambda_c\pi) \cdot BR(\Lambda_c \to pK\pi)} \times \frac{\epsilon(\Lambda_c \to pK\pi) \cdot BR(\Lambda_c \to pK\pi)}{Y(\Lambda_c)}$$

(ϵ denotes the Monte Carlo reconstruction efficiency and BR a Branching Ratio), where we assume $BR(\Sigma_c \to \Lambda_c\pi) = 1$.

In the case of $\Lambda_c^\star$ we use the formula:

$$\frac{\sigma_{\Lambda_c^\star}}{\sigma_{\Lambda_c}} = \frac{Y(\Lambda_c^\star)}{\epsilon(\Lambda_c^\star \to \Lambda_c\pi\pi, \Lambda_c \to pK\pi)\cdot BR(\Lambda_c^\star \to \Lambda_c\pi^+\pi^-)} \times \frac{\epsilon(\Lambda_c \to pK\pi)}{Y(\Lambda_c)}$$

but this time $BR(\Lambda_c^{+\star} \to \Lambda_c^+\pi^+\pi^-) \neq 1$ since the $\Lambda_c^{+\star}$ can also decay to $\Lambda_c^+\pi^0\pi^0$. We thus measure the combined quantity:

$$BR(\Lambda_c^{+\star} \to \Lambda_c^+\pi^+\pi^-) \times \frac{\sigma_{\Lambda_c^\star}}{\sigma_{\Lambda_c}} = \frac{Y(\Lambda_c^\star)}{\epsilon(\Lambda_c^\star \to \Lambda_c\pi\pi, \Lambda_c \to pK\pi)} \times \frac{\epsilon(\Lambda_c \to pK\pi)}{Y(\Lambda_c)}$$

The measured relative photoproduction cross sections are listed in Table III. We conservatively estimate that any systematics due to tracking is less than $\pm 4\%$ per track. We checked the stability of our results by using different analysis cuts and different fitting techniques and found that the fluctuations were consistent within statistical errors to the quoted values for each test. We also investigated a possible dependence of the measured values on the momentum of the reconstructed Λ_c^+. We divided the Λ_c^+ momentum spectrum into three different ranges (between 30 and 60 GeV/c, between 60 and 90 GeV/c, above 90 GeV/c); fitted each data histogram separately; computed the Monte Carlo reconstruction efficiency for each momentum range; and finally summed the three efficiency-corrected yields. The results obtained with this momentum dependent efficiency technique proved to be in agreement, within the statistical errors, with the ones obtained by use of global reconstruction efficiencies.

We can perform a rough estimate of the number of Λ_c^+ originating from higher mass charm baryons by summing the relative photoproduction cross sections for each of the $\Lambda_c^{\star +}$ and Σ_c states observed. For the Σ_c, we average the two results for Σ_c^0 and Σ_c^{++} and multiply by 3 to take into account the decay mode $\Sigma_c^+ \to \Lambda_c^+\pi^0$, which is not reconstructed in this analysis but nevertheless contributes to the total $\Lambda_c^+ \to pK^-\pi^+$ sample observed. For the $\Lambda_c^{\star +}$, we assume that the decay $\Lambda_c^{\star +}(2593) \to \Lambda_c^+\pi^+\pi^-$ is completely dominated by the resonant mode $\Lambda_c^{\star +}(2593) \to \Sigma_c\pi^\pm$ ($\Sigma_c \to \Lambda_c^+\pi^\mp$), so that these events are already included in the Σ_c^0, Σ_c^{++} photoproduction cross sections. On the other hand we assume the decay $\Lambda_c^{\star +}(2625) \to \Lambda_c^+\pi^+\pi^-$ to be completely non-resonant and also take BR($\Lambda_c^{\star +}(2625) \to \Lambda_c^+\pi^+\pi^-$) to be 2/3 (from isospin invariance). We obtain:

$$\frac{\sigma_{(}\Sigma_c, \Lambda_c^\star)}{\sigma_{\Lambda_c}} \simeq \frac{3}{2}\left(\frac{\sigma_{\Sigma_c^0}}{\sigma_{\Lambda_c}} + \frac{\sigma_{\Sigma_c^{++}}}{\sigma_{\Lambda_c}}\right) + \frac{3}{2}BR(\Lambda_c^\star(2625) \to \Lambda_c\pi^+\pi^-)\cdot\frac{\sigma_{\Lambda_c^\star(2625)}}{\sigma_{\Lambda_c}} = (32.2 \pm 5.1 \pm 1.7)\%.$$

Finally we measure the mass difference between each of the two Σ_c states and the Λ_c^+. For the measurement, we use the Σ_c signals reconstructed through the $\Lambda_c^+ \to pK^-\pi^+$ decay mode, but we subject the signals to tighter analysis cuts than those listed in Table I in order to improve the signal to noise: we require the confidence level of the Λ_c^+ decay vertex to be greater than 5% and at least one of the two heavy prongs of the decay (i.e. the proton or the kaon) to be positively identified by the Čerenkov counters. We also use Σ_c candidates reconstructed via the $\Lambda_c^+ \to p\overline{K^0}$ decay mode, where (with respect to the cuts used in Table I) we tighten the invariant mass cut around the nominal Λ_c^+ mass to be $\Delta M = \pm 20 MeV$ and we require the error on the primary and secondary vertex separation to be less than $\sigma_L < 1.5mm$. Figure 4(a) and 4(b) show the $M(\Lambda_c^+\pi^-) - M(\Lambda_c^+)$ and $M(\Lambda_c^+\pi^+) - M(\Lambda_c^+)$ mass differences for the combined $pK^-\pi^+ + p\overline{K^0}$ sample with the additional analysis cuts. Both histograms are fit with a Gaussian curve for the signal (with a fixed width of $\sigma = 2.2MeV$ determined from Monte Carlo simulation) plus a second degree polynomial for the background. The resulting mass differences are $M(\Sigma_c^0) - M(\Lambda_c^+) = 166.6 \pm 0.5 \pm 0.6 MeV/c^2$ and $M(\Sigma_c^{++}) - M(\Lambda_c^+) = 167.6 \pm 0.6 \pm 0.6 MeV/c^2$ where the second error is the systematic uncertainty. The systematic error is determined from non-statistical fluctuations of the measured values when the total Σ_c^0, Σ_c^{++} samples are split into four statistically separate subsamples: candidates originating from different Λ_c^+ decays ($pK^-\pi^+$ or $p\overline{K^0}$) and data taken by our experiment during two different run periods (1990 or 1991). The larger systematic error in the measurement of the Σ_c masses, as compared to the measurement of the $\Lambda_c^{*+}(2593)$ mass, reflects the higher level of background under the Σ_c^0, Σ_c^{++} signals.

In Table II we summarize our measurements for the $M(\Lambda_c^{*+}) - M(\Lambda_c^+)$ and $M(\Sigma_c) - M(\Lambda_c^+)$ mass differences and compare them to the values obtained by CLEO [4] [8] and to the current PDG world averages[9].

In conclusion, we present confirming evidence for the excited state $\Lambda_c^{*+}(2593)$ first observed by CLEO[4] and we measure its mass to be $M(\Lambda_c^{*+}(2593)) - M(\Lambda_c^+) = 309.2 \pm 0.7 \pm 0.3 MeV/c^2$ above the Λ_c^+ mass. We observe the resonant fraction of the decay $\Lambda_c^{*+}(2593) \to \Sigma_c\pi^\pm$ to be dominant and we estimate the lower limit BR($\Lambda_c^{*+}(2593) \to \Sigma_c\pi^\pm / \Lambda_c^{*+}(2593) \to \Lambda_c^+\pi^+\pi^-$) > 0.51 (90% c.l.). We further measure the mass differences between the Σ_c^0, Σ_c^{++} and the Λ_c^+ to be $M(\Sigma_c^0) - M(\Lambda_c^+) = 166.6 \pm 0.5 \pm 0.6 MeV/c^2$ and $M(\Sigma_c^{++}) - M(\Lambda_c^+) = 167.6 \pm 0.6 \pm 0.6 MeV/c^2$. We measure the photoproduction cross section for the $\Lambda_c^{*+}(2625)$, $\Lambda_c^{*+}(2593)$, Σ_c^0 and Σ_c^{++} relative to the inclusive photoproduction cross section for the Λ_c^+. Our data indicate that roughly a third of the photoproduced Λ_c^+ comes from the decay of higher mass charm baryon states.

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TABLE I. Analysis Cuts for Λ_c^+ decay modes

$pk\pi$	$p\overline{K^0}\pi\pi$	$\Lambda^0\pi\pi\pi$	$p\overline{K^0}$	$\Lambda^0\pi$
$L/\sigma_L > 4$	$L/\sigma_L > 4$	$L/\sigma_L > 4$	$L/\sigma_L > 2$	$L/\sigma_L > 5$
$cs > 1\%$	$cs > 1\%$	$cs > 1\%$	$cs > 1\%$	$cs > 1\%$
$cp > 1\%$	$cp > 1\%$	$cp > 1\%$	$cp > 1\%$	$cp > 1\%$
$iso1 < 90\%$	$iso1 < 90\%$	$iso1 < 90\%$	$rin < 250\mu m$	$rin < 250\mu m$
$iso2 < 0.5\%$	$iso2 < 0.5\%$	$iso2 < 0.5\%$	$rtr < 25\mu m$	$rtr < 25\mu m$
$q(\Lambda_c^+) > 30$	$q(\Lambda_c^+) > 30$	$q(\Lambda_c^+) > 30$	$q(p) > 20$	
$ct < 323\mu m$	$ct < 323\mu m$	$ct < 323\mu m$	$ct < 323\mu m$	$ct < 323\mu m$
$\Delta M < 20$	$\Delta M < 20$	$\Delta M < 20$	$\Delta M < 25$	$\Delta M < 20$

L/σ_L: significance of separation between primary and secondary vertices

cp, cs: confidence levels of primary and secondary vertex

$iso1$: confidence level of isolation of secondary vertex tracks from the primary vertex

$iso2$: confidence level of isolation of secondary vertex from other tracks in the event (not assigned to the primary vertex)

rin, rtr: in one-prong decays ($\Lambda_c^+ \to \Lambda^0\pi^+$ and $\Lambda_c^+ \to p\overline{K^0}$), impact parameters of charged prongs (p or π^+) to the primary vertex, in the decay plane or in the transverse direction

$q(\Lambda_c^+)$: total momentum of the Λ_c^+ candidate, $q(p)$: momentum of the proton (GeV/c)

ct: proper time of the Λ_c^+ candidate (required to be less than $\sim$5 times the nominal Λ_c^+ lifetime)

ΔM: invariant mass cut around the nominal Λ_c^+ mass (MeV/c^2)

TABLE II. Comparison of Mass Difference Measurements (MeV/c^2)

	E687	CLEO	PDG
M($\Lambda_c^{*+}(2625)$)-M(Λ_c^+)	$340.4 \pm 0.6 \pm 0.3$[3]	$342.2 \pm 0.2 \pm 0.5$[4]	
M($\Lambda_c^{*+}(2593)$)-M(Λ_c^+)	$309.2 \pm 0.7 \pm 0.3$	$307.5 \pm 0.4 \pm 1.0$[4]	
M(Σ_c^{++})-M(Λ_c^+)	$167.6 \pm 0.6 \pm 0.6$	$168.2 \pm 0.3 \pm 0.2$[8]	168.04 ± 0.27[9]
M(Σ_c^0)-M(Λ_c^+)	$166.6 \pm 0.5 \pm 0.6$	$167.1 \pm 0.3 \pm 0.2$[8]	167.3 ± 0.4[9]

TABLE III. Relative Photoproduction Cross Sections

	Yield	Efficiency (%)	$\sigma_{\Sigma_c}/\sigma_{\Lambda_c}$ or $BR \cdot \sigma_{\Lambda_c^*}/\sigma_{\Lambda_c}$ (%)
Λ_c^+	994.2 ± 77.4	1.98 ± 0.04	
Σ_c^0	43.2 ± 10.9	1.11 ± 0.03	$7.77 \pm 2.07 \pm 0.31$
Σ_c^{++}	39.0 ± 10.7	1.16 ± 0.03	$6.70 \pm 1.92 \pm 0.27$
$\Lambda_c^{*+}(2593)$	10.2 ± 3.7	0.61 ± 0.02	$3.34 \pm 1.23 \pm 0.27$
$\Lambda_c^{*+}(2625)$	24.4 ± 6.3	0.69 ± 0.03	$7.01 \pm 1.93 \pm 0.56$

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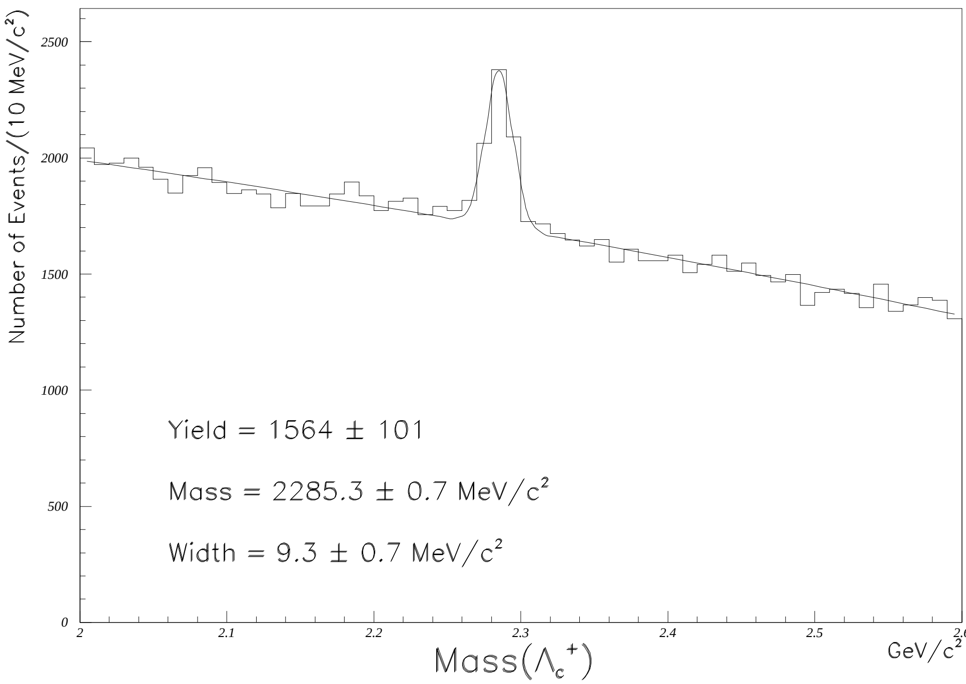
FIGURES

FIG. 1. Λ_c^+ candidates reconstructed through their decays into $pK^-\pi^+$, $p\overline{K^0}$, $p\overline{K^0}\pi^+\pi^-$, $\Lambda^0\pi^+$ and $\Lambda^0\pi^+\pi^-\pi^+$ with the analysis conditions described in Table I.

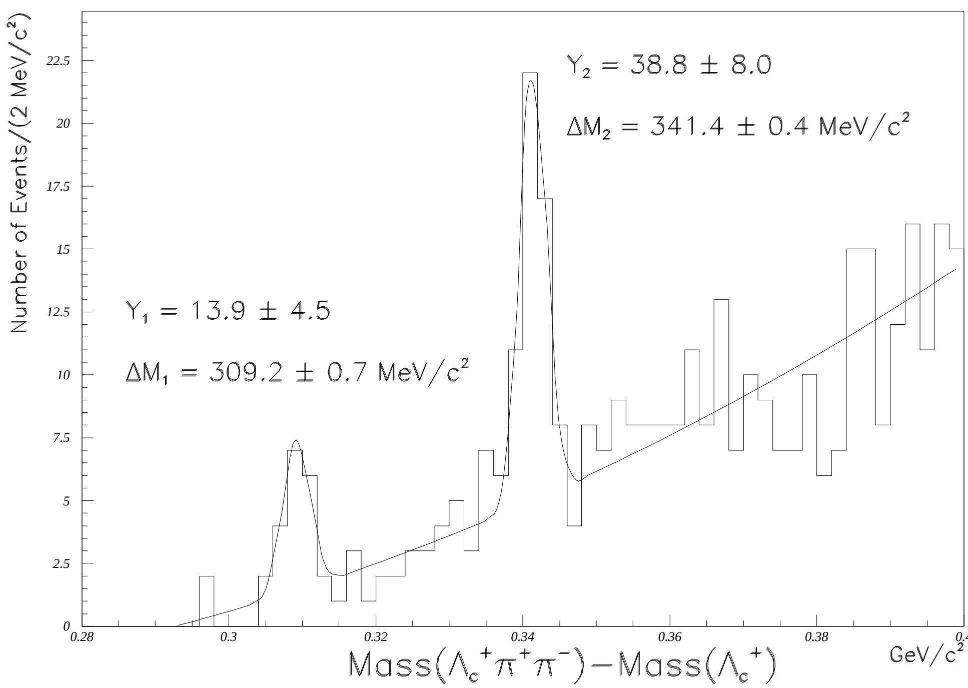
FIG. 2. $M(\Lambda_c^+\pi^-\pi^+) - M(\Lambda_c^+)$ mass difference distribution obtained with the total Λ_c^+ sample of Figure 1, showing evidence for both the $\Lambda_c^{*+}(2593)$ and $\Lambda_c^{*+}(2625)$ states.

FIG. 3. (a),(b),(c): mass differences obtained by combining $\Lambda_c^+ \rightarrow pK^-\pi^+$ candidates with one or two additional pions (the analysis cuts for $pK^-\pi^+$ are those listed in Table I). (d): same mass difference as in Figure 3(a), but with the additional Σ_c cut as described in the text.

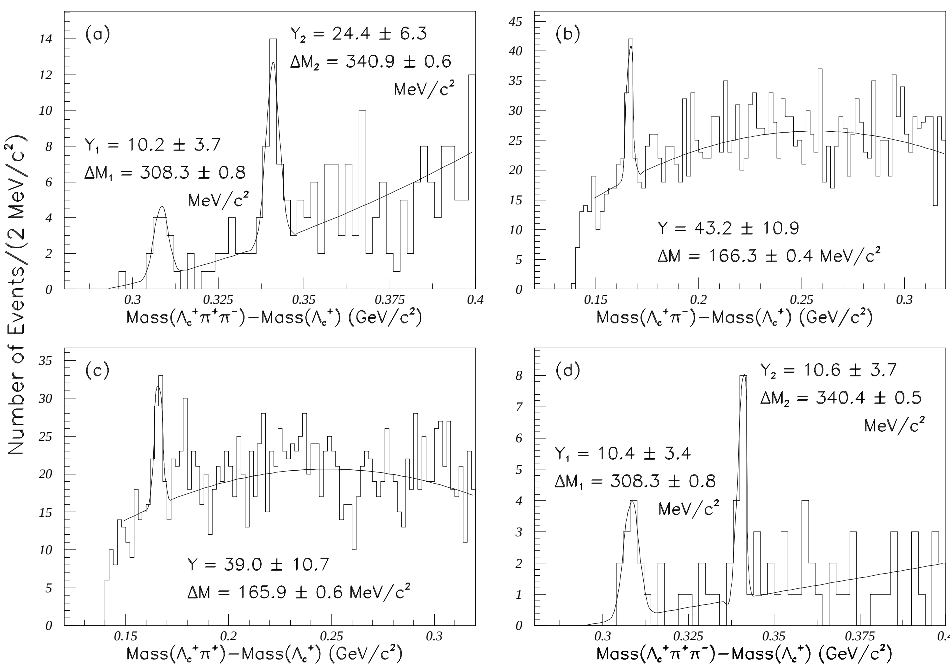
FIG. 4. Σ_c^0 and Σ_c^{++} signals obtained by use of $\Lambda_c^+ \rightarrow pK^-\pi^+$ and $\Lambda_c^+ \rightarrow p\overline{K^0}$ candidates with analysis cuts tighter than those contained in Table I (as described in the text).

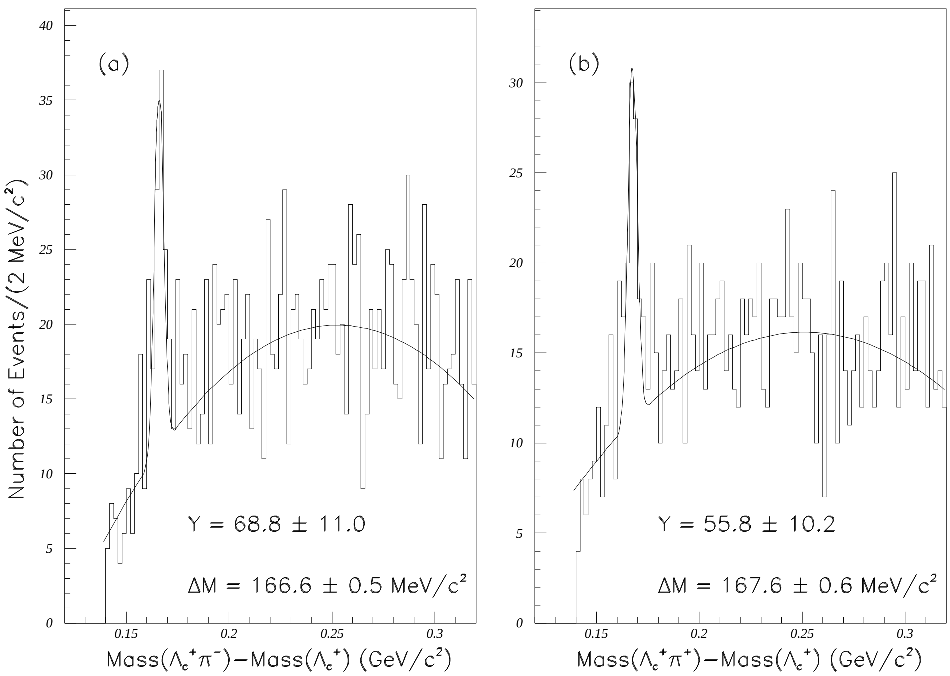


Number of Events/(10 MeV/c²)
2500
2000
1500
1000
500
0
Yield = 1564 ± 101
Mass = 2285.3 ± 0.7 MeV/c²
Width = 9.3 ± 0.7 MeV/c²
2
2.1
2.2
2.3
2.4
2.5
2.6
GeV/c²
Mass(Λc+)



Number of Events/(2 MeV/c^2)
Y_2 = 38.8 ± 8.0
ΔM_2 = 341.4 ± 0.4 MeV/c^2
Y_1 = 13.9 ± 4.5
ΔM_1 = 309.2 ± 0.7 MeV/c^2
Mass($\Lambda_c^+\pi^+\pi^-$)−Mass(Λ_c^+)
GeV/c^2


Number of Events/(2 MeV/c²)
(a)
Y₁ = 10.2 ± 3.7
ΔM₁ = 308.3 ± 0.8
MeV/c²
Y₂ = 24.4 ± 6.3
ΔM₂ = 340.9 ± 0.6
MeV/c²
Mass(Λc⁺π⁺π⁻)−Mass(Λc⁺) (GeV/c²)
(b)
Y = 43.2 ± 10.9
ΔM = 166.3 ± 0.4 MeV/c²
Mass(Λc⁺π⁻)−Mass(Λc⁺) (GeV/c²)
(c)
Y = 39.0 ± 10.7
ΔM = 165.9 ± 0.6 MeV/c²
Mass(Λc⁺π⁺)−Mass(Λc⁺) (GeV/c²)
(d)
Y₁ = 10.4 ± 3.4
ΔM₁ = 308.3 ± 0.8
MeV/c²
Y₂ = 10.6 ± 3.7
ΔM₂ = 340.4 ± 0.5
MeV/c²
Mass(Λc⁺π⁺π⁻)−Mass(Λc⁺) (GeV/c²)


Number of Events/(2 MeV/c²)
(a)
Y = 68.8 ± 11.0
ΔM = 166.6 ± 0.5 MeV/c²
Mass(Λc⁺π⁻)−Mass(Λc⁺) (GeV/c²)
(b)
Y = 55.8 ± 10.2
ΔM = 167.6 ± 0.6 MeV/c²
Mass(Λc⁺π⁺)−Mass(Λc⁺) (GeV/c²)