Observation of Λ_c^+ decays to $\Lambda\pi^+\pi^0$, $\Sigma^0\pi^+$, $\Sigma^0\pi^+\pi^0$, and $\Sigma^0\pi^-\pi^+\pi^+$

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Abstract

We have observed the previously unseen decay modes $\Lambda\pi^+\pi^0$, $\Sigma^0\pi^+\pi^0$ and $\Sigma^0\pi^-\pi^+\pi^+$ of the charmed baryon Λ_c^+, as well as $\Lambda_c^+ \to \Sigma^0\pi^+$ observed previously by ARGUS. The branching ratios for these four decay modes relative to $\Lambda_c^+ \to pK^-\pi^+$ are measured to be $0.73 \pm 0.09 \pm 0.16$, $0.36 \pm 0.09 \pm 0.10$, $0.21 \pm 0.05 \pm 0.05$, and $0.21 \pm 0.02 \pm 0.04$, respectively. Using the world average branching ratio for $\Lambda_c^+ \to pK^-\pi^+$, these modes account for 5% of Λ_c^+ decays.

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Since the first observation of the charmed baryon Λ_c^+ in 1979, about 25% of its decays have been accounted for [1]. CLEO has previously reported results on continuum production of Λ_c^+ near the Υ(4S) resonance using 430 pb^{-1} of data collected with the CLEO I detector [2]. The ARGUS and ACCMOR collaborations have also recently provided a number of results [3,4] on the decays of the charmed baryon Λ_c^+. With a larger data sample and the new CLEO II detector it is now possible to improve the measurements of the branching fractions of Λ_c^+ decay modes previously observed, and to explore many new decay modes of the Λ_c^+, especially those which include neutral particles such as photons and π^0's. Herein are presented measurements of branching ratios, relative to $\Lambda_c^+ \to pK^-\pi^+$, for Λ_c^+ decays to the modes $\Lambda\pi^+\pi^0$, $\Sigma^0\pi^+\pi^0$, $\Sigma^0\pi^+\pi^+\pi^-$, and $\Sigma^0\pi^+$. [5]

The data were collected with the CLEO II detector located at the Cornell e^+e^- storage ring CESR. The sample consists of 1.9 fb^{-1} collected at the Υ(3S) and Υ(4S) resonances, and at energies just below and above the Υ(4S) resonance. The CLEO II detector is described in detail elsewhere [6].

The Λ candidates are identified through their decay to $p\pi^-$, for which the branching fraction is $64.1 \pm 0.5\%$ [1]. For each Λ candidate the secondary vertex is reconstructed from a pair of oppositely charged tracks which intersect at a radial distance of more than 1 mm from the primary vertex in the r-ϕ plane of the detector. The measured specific ionization (dE/dx) for the Λ daughter proton is required to be within 2.5σ of the expected value. A cut is also made on the vertex reconstruction χ^2, which measures the agreement of the extrapolated Λ flight line with the beam interaction point and the consistency of the z coordinates of the Λ daughter tracks when they cross in the r-ϕ plane.

The Σ^0 candidates are identified through their decay to $\Lambda\gamma$, for which the branching fraction is 100% [1]. In order to improve the signal-to-background ratio, the Σ^0 daughter photon is selected from showers which are separated by at least 8 cm from the projection of the nearest charged track and have deposited at least 40 MeV of energy in the barrel region of the CsI calorimeter ($|\cos\theta| < 0.707$). All combinations having reconstructed invariant mass within 2σ of the fitted Σ^0 mass are kept.

Charged pions which are not Λ daughters are required to be within 5 mm of the origin at the point of closest approach to the beam in the r-ϕ plane of the detector, and within 5 cm of the origin in z. Furthermore, each track is required to have dE/dx loss in the central drift chamber consistent within 3σ of the pion mass hypothesis. Analogous requirements are imposed on the charged kaons in the $\Lambda_c^+ \to pK^-\pi^+$ analysis. To identify the protons, χ^2 probabilities are formed for each hadron particle hypothesis using the candidate track's dE/dx loss and/or its time-of-flight measurement. For each proton candidate, the probability for a proton hypothesis must be at least 1%. Furthermore, the probability for a proton hypothesis normalized to the the sum of probabilities for proton, kaon and pion hypotheses must be at least 10%. This requirement for the protons is over 95% efficient below 0.5 GeV/c and falls smoothly to about 90% at 2.5 GeV/c.

Neutral pion candidates are selected from pairs of well-defined showers with observed energies in excess of 30 MeV in the barrel region of the CsI calorimeter ($|\cos\theta| < 0.707$) and which are not associated with the projection of any charged tracks. The photons are kinematically fitted to the world average π^0 mass.

For each decay mode of the Λ_c^+ presented, in order to reduce the combinatoric background, two conditions are applied. First, only the combinations with the fragmentation variable x_p greater than 0.5 are kept. The fragmentation variable x_p is defined to be $x_p \equiv p/p_{\max}$, where E and p are the energy and momentum of the Λ_c^+, respectively, and $E_{\max} = E_{\rm beam}$ and $p_{\max} = (E_{\rm beam}^2 - m_{\Lambda_c^+}^2)^{1/2}$. The second requirement applied to all the modes is that the Λ_c^+ daughters (e.g. the Λ, the π^+ and the π^0 in the case of the $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ mode) must all be in the same hemisphere as the reconstructed Λ_c^+ when measured in the lab frame. This requirement typically removes about 40% of the background while retaining about 90% of the signal.

The $\Lambda\pi^+\pi^0$ invariant mass distribution is shown in Figure 1. The fit to the spectrum includes a second-order Chebyshev polynomial for the combinatoric background, the parametrized shape for the expected $\Sigma^0\pi^+\pi^0$ feed down (i.e. $\Lambda\gamma\pi^+\pi^0$ combinations with the γ not detected), and a Gaussian for the signal with the width fixed to the Monte Carlo prediction of 10.5 MeV/c^2 [7] [8]. The mean for the Gaussian as well as the normalization for the feed down shape are allowed to vary. The fit yields 464 ± 42 events for the $\Lambda\pi^+\pi^0$ signal with a mean mass of 2285.8 ± 1.1 MeV/c^2. The errors in this and subsequent mean masses are statistical only, as the systematic errors have not yet been evaluated. The fit also gives 270 ± 89 events for the $\Sigma^0\pi^+\pi^0$ feed down. As the difference in efficiency for the two modes is negligible in Figure 1, the ratio of the yields gives the ratio of branching ratios. The ratio of yields is 0.58 ± 0.20, in good agreement with the result from direct observation (Table I). No significant $\Lambda\rho^+$ resonant substructure is evident in the data. A search for $\Sigma(1385)\pi$ resonant substructure also yields no clear evidence for these possibilities. The systematic error in the detection efficiency due to the uncertainty in resonant substructure is estimated to be 11% using Monte Carlo.

In the case of the $\Sigma^0\pi^+\pi^0$ decay mode, in addition to the signal, an enhancement is observed in the 2.35 GeV/c^2 region, as seen in Figure 2. Examination of the corresponding invariant mass spectrum for $\Lambda\pi^+\pi^0$ combinations (with the photon from the candidate Σ^0 not included) suggests this enhancement is due to feed-up from the decay $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ combined with a random photon. Using the predicted efficiency for this feed-up and the corrected yield for $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ decays with $x_p > 0.5$ from Table I, approximately 41 ± 6 feed-up events are expected in the 2.35 GeV/c^2 region of Figure 2. Using Monte Carlo, the expected feed-up shape is parameterized and included in the fit to the observed $\Sigma^0\pi^+\pi^0$ mass spectrum in the data, along with a second-order Chebyshev polynomial for the combinatoric background and a Gaussian with a width of 10.6 MeV/c^2 from Monte Carlo for the signal. The true shape depends on the actual multiplicity and energy distribution of the extra photons in the data. If no feed-up is allowed in the background, the signal changes by 14%, and this variation is used as an estimate of the systematic error due to the feed-up. The fit yields 117 ± 24 signal events with a mean mass of 2286.6 ± 2.4 MeV/c^2. The fit also gives 74 ± 37 events for the feed-up which is consistent with the expected number.

The $\Sigma^0\pi^-\pi^+\pi^+$ mass distribution is shown in Figure 3. The fit to the spectrum includes a Gaussian for the signal and a second-order Chebyshev polynomial for the background. An enhancement from $\Lambda_c^+ \to \Lambda\pi^-\pi^+\pi^+$ combined with a random photon is expected here analogous to the $\Lambda_c^+ \to \Sigma^0\pi^+\pi^0$ case and is incorporated in the fit in exactly the same manner. In the fit the width of the signal peak is fixed to the Monte Carlo prediction of 6.4 MeV/c^2. The fit yields 90 ± 19 events for the $\Sigma^0\pi^-\pi^+\pi^+$ signal, with a mean mass of 2285.2 ± 1.5 MeV/c^2. The observed number of events in the enhancement is 86 ± 35, consistent with the expected number of 64 ± 7 which is based on the observed number of

$\Lambda_c^+ \to \Lambda\pi^-\pi^+\pi^+$ events and the Monte Carlo prediction for the feed-up efficiency. If no feed-up is allowed in the background, the signal changes by 14%, and this variation is used as an estimate of the systematic error due to the feed-up.

Figure 4 shows the invariant mass spectrum for the $\Sigma^0\pi^+$ combinations. In the fit to this mass spectrum an allowance is made as before for the feed-up due to the corresponding mode, $\Lambda_c^+ \to \Lambda\pi^+$ combined with a random photon, into the mass region above the signal. The shape of the enhancement is obtained from the Monte Carlo and used in the fit to the $\Sigma^0\pi^+$ mass spectrum with its normalization allowed to vary. The background is paramterized by a second-order Chebyshev polynomial and the signal by a Gaussian with a width of $\sigma = 9.6$ MeV/c^2 obtained from Monte Carlo. The fit yields 196 ± 18 events for the $\Sigma^0\pi^+$ signal with a mean mass of 2288.2 ± 1.1 MeV/c^2. Based on the number of $\Lambda_c^+ \to \Lambda\pi^+$ signal events observed in the data and the Monte Carlo efficiency for the feed-up, 48 ± 7 events are expected in the enhancement. The observed number of $\Lambda_c^+ \to \Lambda\pi^+$ feed-up events above the signal is 97 ± 27. This is somewhat (1.8σ) larger than the expectation. If no feed-up is included in the fit, the signal changes by 9%, and this variation is included in the estimate of the systematic error. This mode was previously observed by ARGUS [3] and a comparison of the results appears in Table II.

All the branching ratios are obtained relative to $\Lambda_c^+ \to pK^-\pi^+$. The fit to the $pK^-\pi^+$ mass spectrum yields 5103 ± 217 events with a mean mass of 2287.0 ± 0.4 MeV/c^2. The width of the Gaussian, as in the other modes, is fixed to the Monte Carlo prediction, which is 6.2 MeV/c^2 for this mode.

In order to minimize the dependence of the relative branching ratios on the modelling of the Λ_c^+ momentum spectrum, the yield for each mode is determined separately for each 0.1 unit bin in the fragmentation variable x_p from 0.5 to 1. The yields are obtained by maximum likelihood fits to the mass spectra observed in each x_p bin for each of the Λ_c^+ decay modes. In each of these fits, the feed-up bump is included and the mean and width of the signal are fixed to the values obtained for the entire $0.5 < x_p < 1.0$ region.

For each decay mode, the central values for the relative branching ratios are obtained by dividing the total efficiency-corrected yield by that for the $\Lambda_c^+ \to pK^-\pi^+$ reference mode. The efficiencies are averages over the region $0.5 < x_p < 1.0$ and include all applicable branching ratios. They exclude particle identification efficiencies because the proton identification efficiency is virtually equal for all the modes and the identification efficiency for the other particles is near 1. In Table I the relative branching ratios are listed relative to $\Lambda_c^+ \to pK^-\pi^+$. The major contributions to the systematic error are due to signal widths in the fits to the mass spectra (10–15%), resonant substructure in the modes $\Lambda_c^+ \to \Lambda\pi^+\pi^0$, $\Lambda_c^+ \to \Sigma^0\pi^+\pi^0$, and $\Lambda_c^+ \to \Sigma^0\pi^-\pi^+\pi^+$(10–11%), the enhancement in each mass plot due to feed-in (1–14%), Λ reconstruction (10%), fit to the $pK^-\pi^+$ mass spectrum (8%), particle identification (2–3%), Monte Carlo statistics (3–5%), fits to the Monte Carlo spectra for determining the efficiencies (5–7%), and tracking (1–8%).

In summary, we have observed three new decay modes of the Λ_c^+ totalling 1.5 ± 0.2 times the branching fraction for $pK^-\pi^+$. Using the current average value of $B(\Lambda_c^+ \to pK^-\pi^+) = (3.2 \pm 0.7)\%$ [1], this accounts for 5 ± 1 % of all Λ_c^+ decays. In Table II are listed the branching ratios relative to $pK^-\pi^+$ for $\Lambda_c^+ \to \Sigma^0\pi^+$ and $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ along with the ARGUS result on $\Lambda_c^+ \to \Sigma^0\pi^+$. Also listed are a number of theoretical predictions for $\Lambda_c^+ \to \Sigma^0\pi^+$ and $\Lambda_c^+ \to \Lambda\rho^+$, the latter being listed for comparison with our $\Lambda\pi^+\pi^0$ result. The $\Lambda_c^+ \to \Sigma^0\pi^+$

decay mode is required to have the same amplitude as $\Lambda_c^+ \to \Sigma^+\pi^0$ by an isospin sum rule [12]. The only measurement of $\Lambda_c^+ \to \Sigma^+\pi^0$ is from CLEO, where the branching ratio relative to $\Lambda_c^+ \to pK^-\pi^+$ is found to be $B(\Lambda_c^+ \to \Sigma^+\pi^0)/B(\Lambda_c^+ \to pK^-\pi^+) = 0.20 \pm 0.03 \pm 0.03$ [13]. There is good agreement with the isospin sum rule. We can set a conservative upper limit on the $\Lambda_c^+ \to \Lambda\rho^+$ relative branching ratio by assuming that all our $\Lambda\pi^+\pi^0$ events are from $\Lambda\rho^+$. This yields $B(\Lambda_c^+ \to \Lambda\rho^+)/B(\Lambda_c^+ \to pK^-\pi^+) < 0.95$ at 95% confidence level. This disagrees with the model in reference [9]. Our result for the two-body mode $\Sigma^0\pi^+$ is in closest agreement with Cheng and Tseng's predictions [11]. Our result for the $\Lambda_c^+ \to \Sigma^0\pi^+$ mode is consistent with the result from ARGUS.

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TABLES

TABLE I. Total efficiency-corrected yields, average efficiencies excluding particle ID (see text), and measured branching ratios relative to $\Lambda_c^+ \to pK^-\pi^+$.

Decay Mode	Corrected Yield	Average Efficiency	$\frac{B}{B(pK^-\pi^+)}$
$pK^-\pi^+$	11201 ± 511	0.46	1.0
$\Lambda\pi^+\pi^0$	8160 ± 883	0.057	$0.73 \pm 0.09 \pm 0.16$
$\Sigma^0\pi^+\pi^0$	3972 ± 946	0.030	$0.36 \pm 0.09 \pm 0.10$
$\Sigma^0\pi^-\pi^+\pi^+$	2386 ± 531	0.038	$0.21 \pm 0.05 \pm 0.05$
$\Sigma^0\pi^+$	2303 ± 227	0.085	$0.21 \pm 0.02 \pm 0.04$

TABLE II. Comparison of measured and predicted Λ_c^+ branching ratios relative to the reference mode $\Lambda_c^+ \to pK^-\pi^+$.

	$\Lambda_c^+ \to \Sigma^0\pi^+$	$\Lambda_c^+ \to \Lambda\pi^+\pi^0$	$\Lambda_c^+ \to \Lambda\rho^+$
CLEO[a]	0.21 ± 0.04	0.73 ± 0.18	< 0.95 @ 95%C.L.
ARGUS[b]	0.17 ± 0.07		
K&K [9]	0.07 ± 0.02		4.2 ± 1.0
C&T [11][c]	0.17 ± 0.04		0.5 ± 0.1
X&K [10]	0.08 ± 0.02		

[a]This experiment.

[b]Ref. [3].

[c]Pole model results; $\beta = \frac{3}{4}$ result for the $\Lambda\rho^+$ prediction.

FIGURES

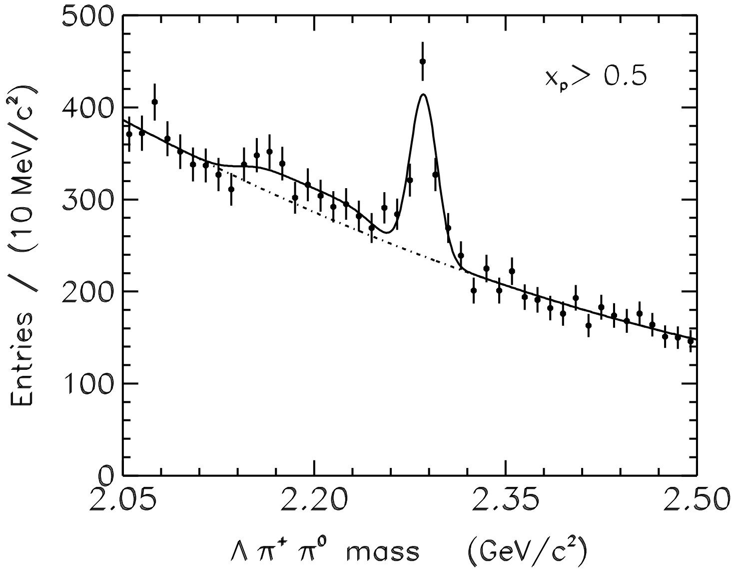

FIG. 1. The $\Lambda\pi^+\pi^0$ invariant mass distribution. The feature in the 2.2 GeV/c^2 region is due to $\Lambda_c^+ \to \Sigma^0\pi^+\pi^0$ where the photon from the Σ^0 decay is not detected.

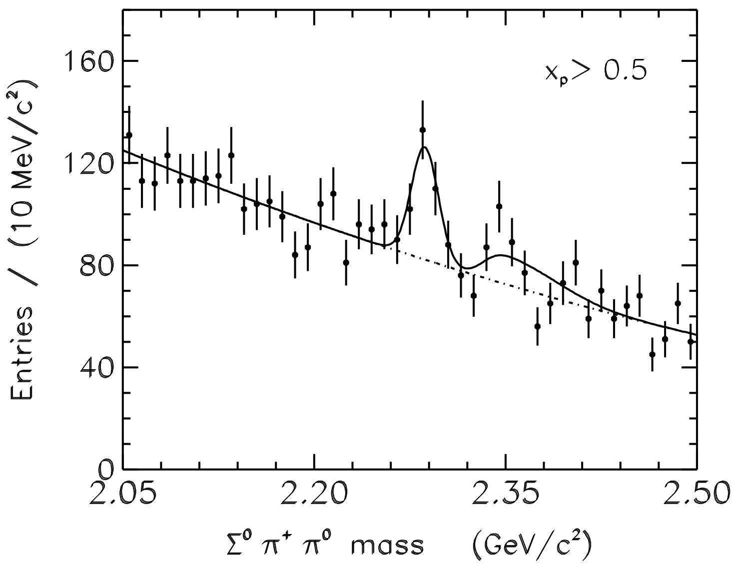

FIG. 2. The $\Sigma^0\pi^+\pi^0$ invariant mass distribution. The feature in the 2.35 GeV/c^2 region is due to $\Lambda_c^+ \to \Lambda\pi^+\pi^0$ events where the Λ combines with a random photon in the event to fake a Σ^0.

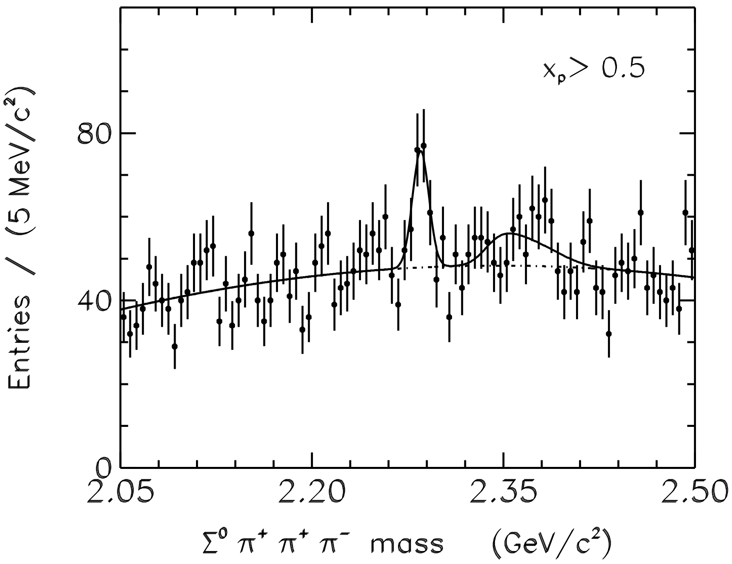

FIG. 3. The $\Sigma^0\pi^+\pi^-\pi^+$ invariant mass distribution. The feature in the 2.35 GeV/c^2 region is due to $\Lambda_c^+ \to \Lambda\pi^-\pi^+\pi^+$ events where the Λ combines with a random photon in the event to fake a Σ^0.

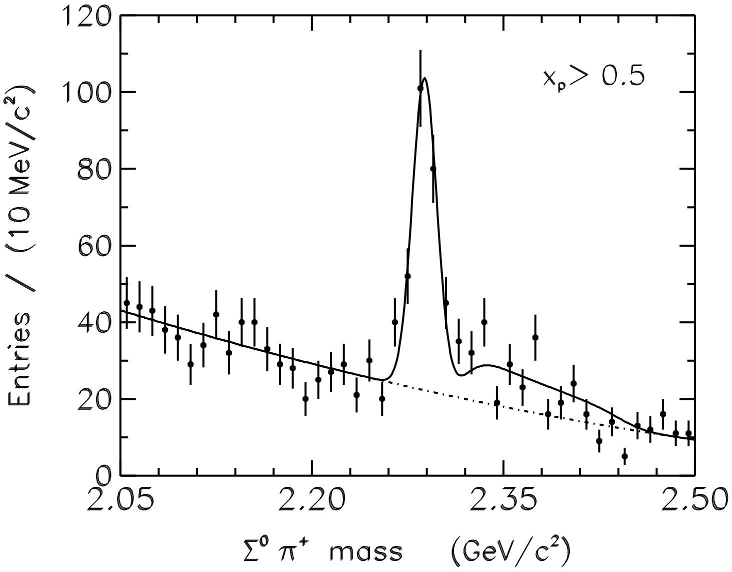

FIG. 4. The $\Sigma^0\pi^+$ invariant mass distribution. The feature above the signal region is due to $\Lambda_c^+ \to \Lambda\pi^+$ events where the Λ combines with a random photon in the event to fake a Σ^0.