Study of the Decays $\Lambda_c^+ \to \Xi^0 K^+$, $\Lambda_c^+ \to \Sigma^+ K^+ K^-$, and $\Lambda_c^+ \to \Xi^- K^+ \pi^+$

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We report the measurement of new modes of the charmed baryon Λ_c^+ using data recorded by the CLEO II detector at the Cornell Electron Storage Ring. We find branching ratios, relative to $\Lambda_c^+ \to pK^-\pi^+$, of $0.070 \pm 0.011 \pm 0.011$ for $\Lambda_c^+ \to \Sigma^+ K^+ K^-$, $0.069 \pm 0.023 \pm 0.016$ for $\Lambda_c^+ \to \Sigma\phi$, $0.078 \pm 0.013 \pm 0.013$ for $\Lambda_c^+ \to \Xi^0 K^+$, and $0.053 \pm 0.016 \pm 0.010$ for $\Lambda_c^+ \to \Xi^{*0} K^+$. These measurements indicate that W-exchange diagrams contribute to Λ_c^+ decay. We have also made a new measurement of the previously found mode $\Lambda_c^+ \to \Xi^- K^+ \pi^+$.

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Recent measurements [1] indicate a shorter Λ_c^+ lifetime than that of the charmed mesons. This suggests that Λ_c^+ decay mechanisms other than spectator diagrams [Fig. 1(a)] may be present. There are also indications [2,3] that the lifetime of the Ξ_c^0, where decays through W exchange [Fig. 1(b)] are allowed, may be less than that of the Ξ_c^+ where such decays are Cabibbo suppressed. Baryons offer a unique possibility to study the importance of W-exchange graphs in the weak decays of charm particles because, in contrast to meson decays, the amplitudes are expected to be neither color nor helicity suppressed. According to some models [4], the contribution from W-exchange diagrams is expected to be similar in magnitude to those of W decay. To date, the only direct evidence for W exchange in charmed baryon decays are weak signals $\Delta^{++}K^-$ in the resonant substructure of $\Lambda_c^+ \to pK^-\pi^+(\pi^0)$ [5], and 8.5 ± 3.0 events reported by CLEO [6] in the decays of $\Xi_c^0 \to \Omega^- K^+$. In this $\Sigma^+K^+K^-$, Ξ^0K^+ and $\Xi^{*0}K^+$ [7]. As these final states contain no d valence quarks, the simplest way for these decays to occur is through the W-exchange diagrams, although it is hard to rule out contributions from final state interactions [8]. We also present evidence of $\Lambda_c^+ \to \Sigma^+\phi \to \Sigma^+K^+K^-$ production, and new results on the previously measured [9] mode $\Lambda_c^+ \to \Xi^-K^+\pi^+$. The data sample used in the study was collected with the CLEO II detector [10]. It consists of 1.95 fb^{-1} from the $\Upsilon(4S)$ resonance, the $\Upsilon(3S)$ resonance, and from center-of-mass energies just below and above the $\Upsilon(4S)$. The main elements of the CLEO II detector are cylindrical precision vertex detectors, a wire drift chamber system, and a high resolution CsI electromagnetic shower calorimeter, all immersed in a 1.5 T axial magnetic field.

The Σ^+ is detected in the decay mode $p\pi^0$, for which the branching fraction is 51.6%. Charged particle identification is made by a combination of energy loss measurements in the drift chamber and time-of-flight measurements. For the case of the proton from the Σ^+, the proton candidate is required to be consistent with the proton hypothesis in the energy loss and time-of-flight measurements such that the efficiency for this requirement is $\approx 88\%$. The π^0's are reconstructed from a pair of photons detected in the CsI calorimeter. At least one photon is required to be in the "barrel" part of the calorimeter where the resolution is best (this corresponds to $|\cos\Theta| < 0.7$, where Θ is the angle with respect to the beam direction). The photons are required to have a minimum energy of 30 MeV and to not be matched to the projection of charged tracks into the calorimeter.

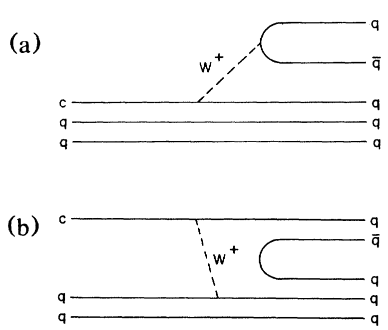

FIG. 1. Typical decays diagrams for (a) spectator decays and (b) W-exchange decays.

An event vertex position is found by a weighted average of the run-by-run beamspot position and the fitted vertex of all charged particles consistent with arising from the beamspot. This event vertex is then assumed to be the point of origin of the Σ^+. The Σ^+ travels a measurable distance from the event vertex before it decays. A first estimate of the Σ^+ momentum vector is made by the addition of the momentum vectors of the two photon candidates and the proton candidate. The point of intersection of this Σ^+ momentum vector with the proton track is then taken as the position of the Σ^+ decay vertex. We then require the measured flight path of the Σ^+'s to be greater than 3 mm. This requirement eliminates 70% of the background but retains 85% of the Σ^+'s. The two photons were kinematically fitted to the π^0 mass using the reconstructed Σ^+ decay point as their point of origin, and a cut of 9 placed on the χ^2 of this fit. The π^0 momentum was then required to be greater than 200 MeV/c. These cuts give a Σ^+ yield of $14\,100 \pm 390$. The Ξ^0 is formed using Λ and π^0 candidates. Λ candidates are made from a pair of oppositely charged tracks, the higher momentum track was taken as the proton and the lower momentum track as the π^-. The proton candidate is required to be loosely consistent with the proton hypothesis in the energy loss and time-of-flight measurements (efficiency $\approx 99\%$). The intersection of the two tracks is required to be displaced from the event vertex, and the invariant mass of the $p\pi^-$ pair was required to be within 5 MeV/c^2 of the Λ mass. These candidates are then combined with π^0 candidates in the same manner as in the case of the Σ^+, except in this case there was no cut placed on the momentum of the π^0, and a vertex position for the decay of the Ξ^0 is found. The Ξ^0 vertex is required to be displaced by at least 2.5 cm from the event vertex and to be consistent with being closer to the event vertex than the Λ decay vertex. These cuts give a Ξ^0 yield of 2500 ± 100.

The Ξ^- is detected using the decay into $\Lambda\pi^-$. Each Λ candidate found above was combined with all negatively charged tracks assumed to be π^-'s. The $\Lambda\pi^-$ vertex was required to be displaced by at least 2 mm from the event vertex and to be closer to the event vertex than the Λ decay vertex. The momentum vector of the reconstructed Ξ^- was required to be consistent with coming from the event vortex. These cuts give a Ξ^- yield of 3700 ± 80.

The Σ^+ candidates, selected by a cut of ± 9 MeV/c^2 ($\approx 2.5\sigma$) around the Σ^+ mass, were then combined with pairs of particles, taken to be kaons, each of which are required to be consistent with being from the event vertex and to be consistent with the kaon hypothesis. The

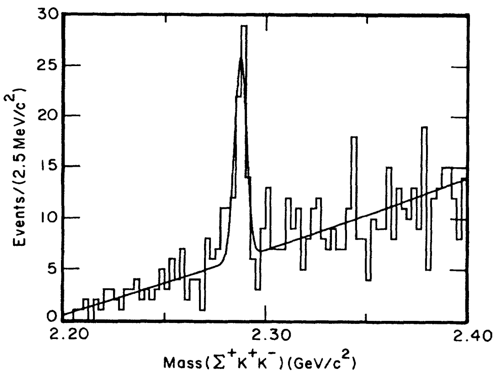

FIG. 2. Invariant mass distribution of $\Sigma^+K^+K^-$ with a cut of $x_p > 0.4$.

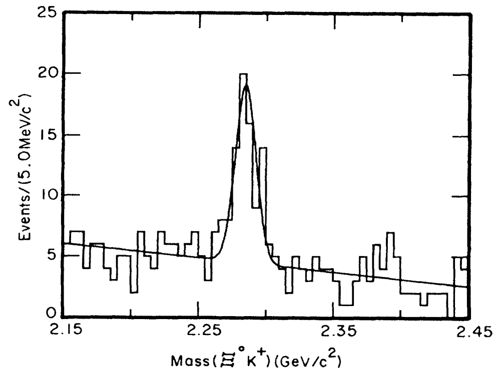

FIG. 4. Invariant mass distribution of Ξ^0K^+ combinations with a cut of $x_p > 0.4$.

$\Sigma^+K^+K^-$ mass plot is shown in Fig. 2 for $x_p > 0.4$ (where $x_p = p/p_{\max}$, where $p_{\max}$ is the maximum momentum possible). The distribution is fitted to the sum of a Gaussian function and polynomial background, where the width of the Gaussian ($\sigma = 2.8$ MeV/c^2) is fixed at the value obtained from a Monte Carlo simulation program. A clear peak is found with a total of 59 ± 10 in the signal, and a mass of 2287.4 ± 0.5 MeV/c^2 (statistical errors only). A similar plot using sidebands to the Σ^+ peak shows no such structure.

A search was made for the two-body decay $\Lambda_c \to \Sigma^+\phi$ by looking at the resonant substructure of the $\Sigma^+K^+K^-$ mode. A signal region was defined by those combinations with $\Sigma^+K^+K^-$ masses of 2.275–2.295 GeV/c^2, with two sideband regions to represent background, 2.22–2.25 and 2.32–2.35 GeV/c^2. Figure 3 shows the invariant mass of the K^+K^- pair for those $\Sigma^+K^+K^-$ combinations in the signal region, with a subtraction made using the sample of K^+K^- pairs from $\Sigma^+K^+K^-$ combinations in the sidebands. A ϕ signal is apparent which is fitted to a Breit-Wigner convoluted with a Gaussian, plus polynomial background shape to give a yield of 26 ± 9 events.

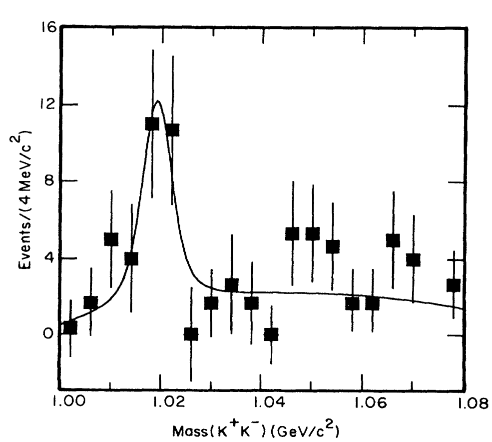

FIG. 3. K^+K^- invariant mass distribution for $\Lambda_c^+ \to \Sigma^+K^+K^-$ candidates.

This implies that $(49 \pm 17)\%$ of the $\Lambda_c^+ \to \Sigma^+K^+K^-$ decays are due to the two-body decay $\Lambda_c^+ \to \Sigma^+\phi$.

The Ξ^0 candidates were selected by a cut of ± 6 MeV/c^2 ($\approx 2.5\sigma$) around the Ξ^0 mass and then combined with a K^+ using the same kaon criteria as in the $\Sigma^+K^+K^-$ case. The Ξ^0K^+ invariant mass plot for combinations with $x_p > 0.4$ is shown in Fig. 4; a clear peak in the Λ_c^+ region is observed. This peak is then fitted with a Gaussian function and polynomial background, where the width of the Gaussian ($\sigma = 7$ MeV/c^2) is fixed at the value found by Monte Carlo simulation program. The fit yields a total of 56 ± 10 Λ_c^+'s with a mass of 2285.0 ± 1.7 MeV/c^2 (statistical errors only). A plot of Ξ^0K^- invariant mass shows no such enhancement.

The Ξ^- candidates were selected by a cut of ± 5 MeV/c^2 ($\approx 2.5\sigma$) around the Ξ^- mass and then combined with a K^+ and a π^+ using the same kaon criteria as above. The $\Xi^-K^+\pi^+$ invariant mass plot for combinations with $x_p > 0.4$ is shown in Fig. 5; a clear peak in the Λ_c^+ region is observed. This peak is then fitted with a Gaussian function and polynomial background, where the width of the Gaussian ($\sigma = 5$ MeV/c^2) is fixed at the value found from Monte Carlo simulation program. The fit yields a total of 60 ± 9 Λ_c^+'s with a mass of

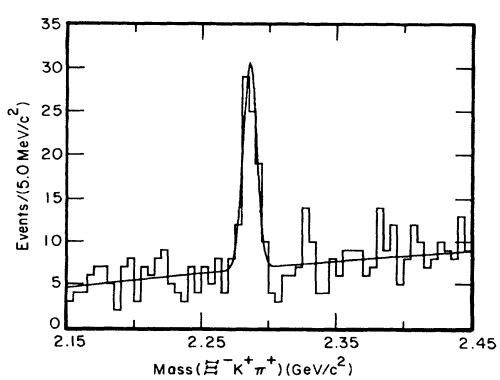

FIG. 5. Invariant mass distribution of $\Xi^-K^+\pi^+$ combinations with a cut of $x_p > 0.4$.

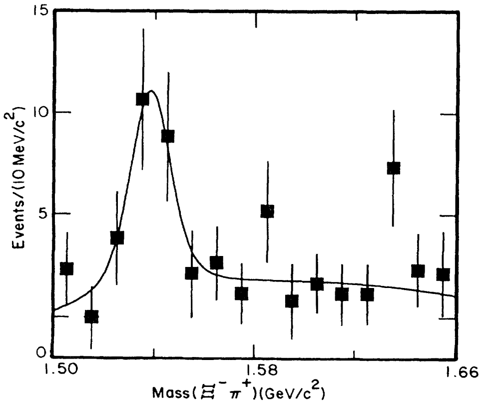

FIG. 6. $\Xi^-\pi^+$ invariant mass distribution for $\Lambda_c^+ \to \Xi^- K^+ \pi^+$ candidates.

2285.5 ± 1.0 MeV/c^2 (statistical errors only).

A search was made for the two-body decay $\Lambda_c^+ \to \Xi^{*0} K^+$ by looking at the resonant substructure of the $\Xi^- K^+ \pi^+$ mode. A signal region was defined by those combinations with $\Xi^- K^+ \pi^+$ masses of 2.275–2.295 GeV/c^2, with two sideband regions to represent background, 2.205–2.265 and 2.305–2.365 GeV/c^2. Figure 6 shows the invariant mass of the $\Xi^-\pi^+$ pair for those $\Xi^- K^+ \pi^+$ combinations in the signal region, with a subtraction made using the sample of $\Xi^-\pi^+$ pairs from $\Xi^- K^+ \pi^+$ combinations in the sidebands. A Ξ^{*0} signal is apparent which is fitted to a Breit-Wigner convoluted with a Gaussian, plus polynomial background shape. The fit gives a yield of 24 ± 7 events. This implies that $(42 \pm 12)\%$ of the $\Lambda_c^+ \to \Xi^- K^+ \pi^+$ decays are due to the two-body decay $\Lambda_c^+ \to \Xi^{*0} K^+$.

Using the same data sample we obtain the yield of Λ_c^+'s decaying into $pK^-\pi^+$. This mode is generally used as a reference for measuring the branching fractions of Λ_c^+'s into less common modes. It also has the same number of charged particles in its final state as $\Sigma^+ K^+ K^-$ and $\Xi^0 K^+$ so the systematic uncertainties in the ratios of branching fractions of these modes tend to cancel. The particle identification used for the proton and K^- candidates were the same as in $\Sigma^+ K^+ K^-$. To suppress combinatorial background the π^+ candidate was required to have a momentum of greater than 300 MeV/c^2. A fit to the $pK^-\pi^+$ spectrum with a cut of $x_p > 0.4$ gives a total number of $\Lambda_c \to pK^-\pi^+$ decays detected of 5670 ± 210.

Table I shows the branching fractions for these modes relative to $\Lambda_c^+ \to pK^-\pi^+$ calculated using efficiencies determined primarily from Monte Carlo simulation. The efficiency of the particle identity cuts were found using the large samples of $\Lambda \to p\pi^-$ and $\phi \to K^+K^-$ in the data. The total efficiencies were averaged over the momentum range and include all branching fractions such as $\Lambda \to p\pi^-$.

The systematic errors quoted include an estimate of the uncertainties in the efficiency calculations and fitting procedures. The quoted value for the branching ratio for $\Lambda_c^+ \to \Sigma^+ K^+ K^-$ includes the contribution from $\Lambda_c^+ \to \Sigma^+\phi$, and that for $\Lambda_c^+ \to \Xi^- K^+ \pi^+$ includes the contribution from $\Lambda_c^+ \to \Xi^{*0}\pi^+$. The result for $\Lambda_c^+ \to \Xi^- K^+ \pi^+$ is smaller than that obtained with the CLEO 1.5 detector [9], but not inconsistent with it. It can be seen that the branching fractions into all the measured modes are considerably smaller than that of $\Lambda_c^+ \to pK^-\pi^+$. This is not surprising as all the modes here include the popping of a $s\bar{s}$ pair, and thus does not imply that the widths of decays due to W exchange are in general any smaller than those due to spectator diagrams. Recent theoretical models [11–14] have produced predictions for the widths of Λ_c^+ decays into two-body states. Taking the results for branching ratios above, together with the world average lifetime of the Λ_c^+ [2] and the world average measurement of the branching fraction for $\Lambda_c^+ \to pK^-\pi^+$ [15], we obtain the measured widths for these decays given in Table II.

It is clear from this comparison that these models, which predict these final states purely from W-exchange diagrams, predict widths similar to those we measure. These measurements thus give further evidence that W exchange is an important contributor to the decays of the Λ_c^+.

We thank the CERN computer staff for maintaining the GEANT detector simulation (version 3.14, CERN DD/EE/84-1, R. Brun *et al.*) code. We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. This

TABLE I. Measured yield, calculated efficiency, and measured branching ratios for six decay modes of the Λ_c^+.

Mode	Yield	Efficiency	Branching ratio
$pK^-\pi^+$	5670 ± 210	0.35	1.0
$\Sigma^+K^+K^-$	59 ± 10	0.052	$0.070 \pm 0.011 \pm 0.011$
$\Sigma^+\phi$	26 ± 9	0.023	$0.069 \pm 0.023 \pm 0.016$
Ξ^0K^+	56 ± 10	0.044	$0.078 \pm 0.013 \pm 0.013$
$\Xi^-K^+\pi^+$	60 ± 9	0.046	$0.079 \pm 0.013 \pm 0.014$
$\Xi^{*0}K^+$	24 ± 7	0.028	$0.053 \pm 0.016 \pm 0.010$

TABLE II. Measurements and theoretical predictions for two-body decay modes of the Λ_c^+.

Model	Width (experimental) (10^{11} s^{-1})	Width (theory) (10^{11} s^{-1})
$\Sigma^+\phi$	0.12 ± 0.04	0.13 [11]
Σ^0K^+	0.13 ± 0.04	0.13 [11]
		0.05 [12]
		0.83 [13]
		0.157 [13]
$\Xi^{*0}K^+$	0.09 ± 0.03	0.25 [11]
		0.04 [14]

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[1] Particle Data Group, K. Hikusa *et al.*, Phys. Rev. D **45**, S1 (1992) gives $\tau(\Lambda_c^+)=(1.91^{+0.15}_{-0.12})\times 10^{-13}$ s, compared with $\tau(D^+)=(10.66\pm 0.23)\times 10^{-13}$ s, $\tau(D^0)=(4.77\pm 0.08)\times 10^{-13}$ s, and $\tau(D_s^+)=(4.50^{+0.30}_{-0.26})\times 10^{-13}$ s.

[2] Particle Data Group (Ref. [1]) gives $\tau(\Xi_c^+)=(3.0^{+1.0}_{-0.6})\times 10^{-13}$ s.

[3] S. Barlag *et al.*, Phys. Lett. B **236**, 495 (1990) gives $\tau(\Xi_c^0)=(0.82^{+0.59}_{-0.30})\times 10^{-13}$ s.

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[15] Particle Data Group (Ref. [1]) gives $B(\Lambda_c\rightarrow pK^-\pi^+)$ of 0.032 ± 0.007.