

Measurement of Exclusive Λ_c Decays with a Σ^+ in the Final State

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We have measured branching ratios for three Λ_c decay modes that have a Σ^+ in the final state. Two of the observed decay modes, $\Lambda_c \rightarrow \Sigma^+\pi^0$ and $\Lambda_c^+ \rightarrow \Sigma^+\omega$, have no external W -emission amplitudes. Their branching ratios relative to the $pK^-\pi^+$ mode are $0.20 \pm 0.03 \pm 0.03$ and $0.54 \pm 0.13 \pm 0.06$, respectively. We have also significantly improved the measurement of the branching ratio for the previously observed decay mode $\Lambda_c^+ \rightarrow \Sigma^+\pi^+\pi^-$. We find its branching ratio relative to $pK^-\pi^+$ to be $0.74 \pm 0.07 \pm 0.09$.

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Our current knowledge of Λ_c decay is dominated by decays where the daughter baryon is either a proton or a Λ hyperon. Decays where another Σ hyperon is the daughter baryon are allowed, but have not been very accurately measured, since all their decay modes include neutral particles [1]. The two-body decays with a Σ^+ are particularly interesting, since they are only possible through W exchange or internal W emission. W -exchange decays are never factorizable, and the internal W -emission decay of a Λ_c is not factorizable unless the final state meson includes the strange quark [2]. Both decay mechanisms are expected to be suppressed in B meson and to a lesser degree charm meson decays, due to helicity and color suppression. The measurement of decay rates comparable to rates that include the factorizable external W -emission amplitude would confirm the importance of nonfactorizing amplitudes in charm baryon decays [3]. For example, the decay $\Lambda_c^+ \rightarrow \Lambda\pi^+$ has amplitudes due to all the mechanisms in $\Lambda_c^+ \rightarrow \Sigma^+\pi^0$ plus the additional external W -emission amplitude. We have therefore studied Λ_c decay modes including a Σ^+ .

The data were collected with the CLEO II detector at the Cornell Electron Storage Ring (CESR), which ran above, below, and at the $\Upsilon(4S)$ resonance. The CLEO II detector is a solenoidal-magnet spectrometer and electromagnetic calorimeter. The central drift chamber measures a charged particle's momentum and its specific ionization, which is used for particle identification. The time-of-flight system provides additional particle identification information. The calorimeter consists of 7800 CsI(Tl) crystals located inside the magnet. It has high efficiency, fine segmentation, and excellent energy resolution, allowing us to reconstruct Σ^+ hyperons through their decay to $p\pi^0$. A complete description of the detector can be found elsewhere [4].

The total integrated luminosity for the data sample is 1.9 fb^{-1} . The hadronic event selection requires at least three charged tracks, visible energy greater than 0.15 of E_{cm} , and a distance less than 5.0 cm along the beam direction between the reconstructed primary vertex and the interaction point. To discriminate against beam-wall and beam-gas backgrounds we require all charged tracks to have impact parameters in the plane perpendicular to the beam (r, ϕ) of less than 2.0 cm and to have a distance of closest approach to the primary vertex along the beam direction of less than 3.0 cm.

We search for Σ^+ candidates in the $p\pi^0$ decay mode where the π^0 subsequently decays to $\gamma\gamma$. (Throughout this paper the charge conjugate state is implied.) Proton candidates can be identified by either their ionization loss in the central drift chamber or their time of flight. Both types of information are combined to form a probability that the particle is consistent with either the proton, kaon, or pion hypothesis. We require that the probability of a proton hypothesis be at least 1% and that it be at least 10% of the sum of three probabilities.

This requirement is over 95% efficient below $0.5 \text{ GeV}/c$ and falls smoothly to about 90% at $2.5 \text{ GeV}/c$. The Σ^+ is relatively long lived ($c\tau = 2.40 \text{ cm}$), and it decays a measurable distance from the primary interaction vertex. Hence protons from the Σ^+ decay have large impact parameters with respect to the primary vertex. We require that the proton impact parameter in the (r, ϕ) plane be greater than 0.6 mm .

The π^0 candidates are formed by pairing energy clusters in the calorimeter that are not matched to charged tracks, have at least 30 MeV of energy, and have at least one of the clusters in the highest resolution portion of the calorimeter ($|\cos\theta| < 0.71$). We also require the cluster's lateral shower shape to be consistent with that expected for a photon [5]. The photon momenta are then adjusted by a kinematic fit constrained by the known π^0 mass and by the assumption that the photons originate at the primary vertex.

The Σ^+ candidates are found with an iterative method that finds an estimated decay point and calculates the Σ^+ four-momentum assuming the decay occurred there [6]. This procedure improves our Σ^+ mass resolution, and only one iteration is necessary. We are able to reject random background combinations by requiring that the Σ^+ decay distance be greater than zero, and that the proton trajectory be within 1 cm in z of the Σ^+ trajectory at the estimated decay point in the (r, ϕ) plane. These requirements reject 70% of the background. The size of the Σ^+ signal after the decay point estimation is accurately predicted by the Monte Carlo (MC) simulation to be 10% lower than the initial Σ^+ signal. The $p\pi^0$ invariant mass distribution is shown in Fig. 1. The fit yields $12900 \pm 300 \Sigma^+$'s. We choose those $p\pi^0$ combinations within $15 \text{ MeV}/c^2$ of the nominal Σ^+ mass to be our Σ^+ candidates.

The production of charm baryons in e^+e^- collisions is peaked at high momentum, so we can reduce our combinatoric background by requiring that all Λ_c candidates have $x_p > 0.5$ (where $x_p = p/\sqrt{E_{\text{beam}}^2 - m^2}$). In the $\Sigma^+\pi^0$ decay mode there is a combinatoric background that the x_p requirement does not eliminate, and this background peaks near the Λ_c mass. It occurs when a

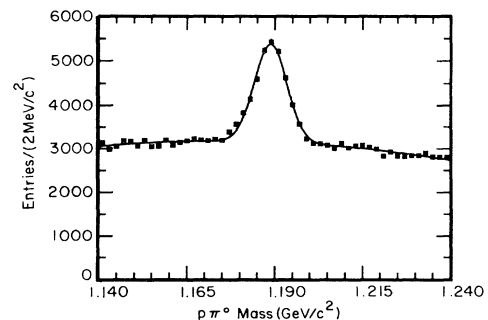
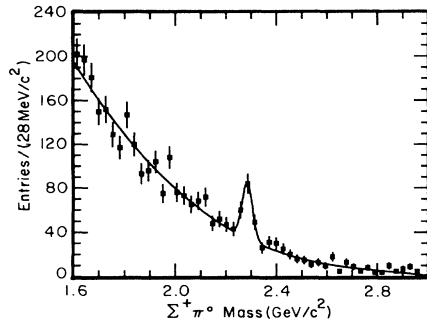


FIG. 1. The $p\pi^0$ invariant mass distribution.

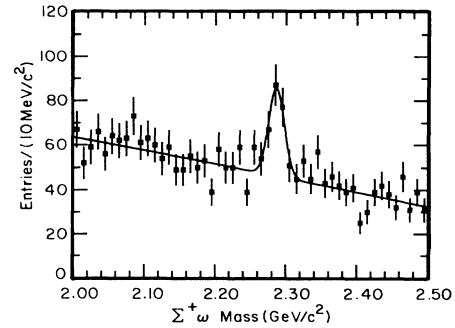
FIG. 2. The $\Sigma^+\pi^0$ invariant mass distribution.

fast Σ^+ in one jet combines with a slow π^0 in the other jet. We therefore require that $p_{\pi^0} > 500$ MeV/c, and that the angle between the π^0 and the Λ_c momentum vectors in the lab frame be less than 90° . These requirements reject only 9% of the signal, while rejecting about 50% of the background and eliminating any peaking of the background near the Λ_c . The $\Sigma^+\pi^0$ invariant mass is fitted with a fourth-order Chebyshev polynomial for the background and a Gaussian fixed to the MC predicted width for the signal, which yields 93 ± 15 events. The data and fit are shown in Fig. 2.

In the decay $\Lambda_c \rightarrow \Sigma^+\omega$, the Λ_c decays to a spin one-half baryon and a vector meson, like the decay $\Lambda_c \rightarrow \Sigma^+\rho^0$. However, the $\Sigma^+\omega$ is much easier to measure experimentally since the ω is much narrower than the ρ^0 . We search for $\Sigma^+\omega$ where the ω decays into $\pi^+\pi^-\pi^0$. Since the ω does not decay according to phase space, we can preferentially select $\pi^+\pi^-\pi^0$ combinations that are ω 's by selecting only those in the interior of the Dalitz plot. The requirement is very loose and more than 99% of true ω 's are kept. Figure 3 shows the $\Sigma^+\omega$ invariant mass distribution for combinations with $x_p > 0.5$. The invariant mass distribution is fitted with a second-order Chebyshev polynomial for the background and a Gaussian fixed to the MC predicted width for the signal, which yields 108 ± 19 events. Any contributions from nonresonant $\Sigma^+\pi^+\pi^-\pi^0$ or involving wide resonances like $\Sigma^+\rho\pi$ will appear in the ω sidebands, so we attempted to fit a Λ_c signal in the ω sidebands and found 1 ± 15 events, which we subtract from our yield.

The decay $\Sigma^+\pi^+\pi^-$ is searched for by adding a pair of oppositely charged tracks to a Σ^+ candidate. Figure 4 shows the invariant mass distribution for candidates with $x_p > 0.5$. The invariant mass distribution is fitted with a second-order Chebyshev polynomial for the background and a Gaussian fixed to the MC predicted width for the signal, which yields 487 ± 37 events. The efficiency is relatively flat over the Dalitz plot, and we find that the efficiency varies by less than 5% for $\Sigma^+\rho^0$, $\Sigma^*\pi^+$, and phase space. This range of efficiencies is included in the systematic error.

The decay mode $\Sigma^+\rho^0$ is predicted to be large in some models, and an upper limit on its branching fraction

FIG. 3. The $\Sigma^+\omega$ invariant mass distribution.

would be interesting. We extract the Λ_c yield as a function of the invariant mass of the two pions, by dividing the data into bins according to $m_{\pi^+\pi^-}$. The number of Λ_c 's is found by fitting the $\Sigma^+\pi^+\pi^-$ invariant mass to a Gaussian fixed to the same width and mean as in Fig. 4. The resulting spectrum of Λ_c 's as a function of $m_{\pi^+\pi^-}$ is barely consistent with phase space (C.L. = 2.0%) and inconsistent (C.L. = $0.6 \times 10^{-5}\%$) with coming entirely from $\Sigma^+\rho^0$. Neither fit has a large confidence level, which is probably due to the presence of other resonances that we are not sensitive enough to resolve. A full Dalitz plot analysis is not feasible with our high background.

A fit to the spectrum using only phase space and $\Sigma^+\rho^0$ contributions yields 100 ± 43 events from the $\Sigma^+\rho^0$. We estimate the systematic error on the $\Sigma^+\rho^0$ yield to be ± 20 events. This is not a significant measurement of $\Sigma^+\rho$ and we will use it to set an upper limit on the branching ratio relative to $pK^-\pi^+$.

We will calculate our branching ratios relative to the well known decay, $\Lambda_c \rightarrow pK^-\pi^+$. To reduce systematic errors, the same proton identification is required in this mode as was used for the Σ^+ modes. For kaon candidates we form a particle identification probability in the same way as for the proton. The kaon candidate is required to be consistent with the kaon hypothesis. The observed number of decays is 4114 ± 187 .

The efficiencies are evaluated by MC simulation using the GEANT [7] package, except for particle identification efficiencies, which were evaluated from samples of $\Lambda \rightarrow p\pi^-$, $\phi \rightarrow K^+K^-$, and $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\pi^+$.

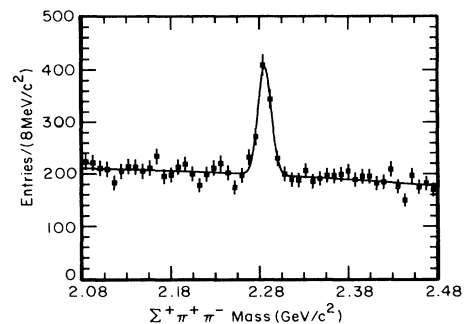
FIG. 4. The $\Sigma^+\pi^+\pi^-$ invariant mass distribution.

TABLE I. Number of events, efficiencies, and branching ratios relative to the $pK^-\pi^+$ decay mode. The upper limit is at 95% confidence level.

Decay mode	Number of events	Efficiency	Branching ratio
$pK^-\pi^+$	4114 ± 187	38.4%	1.0
$\Sigma^+\pi^0$	93 ± 15	4.3%	$0.20 \pm 0.03 \pm 0.03$
$\Sigma^+\omega$	107 ± 24	1.8%	$0.54 \pm 0.13 \pm 0.06$
$\Sigma^+\pi^+\pi^-$	487 ± 37	6.1%	$0.74 \pm 0.07 \pm 0.09$
$\Sigma^+\rho^0$	$100 \pm 43 \pm 20$	6.0%	< 0.27

The efficiencies for all modes are nearly flat with Λ_c momentum, so we use the average value over the momentum range. The efficiencies also include all branching ratios. The yields, efficiencies, and resultant branching ratios for all decay modes are shown in Table I. The dominant systematic errors are due to the Σ^+ reconstruction (6%), fitting of the mass distributions (5–10% depending on mode), and various possible resonant substructures in the $\Sigma^+\pi^+\pi^-$ mode (5%).

The $\Sigma^+\pi^+\pi^-$ branching ratio of $0.74 \pm 0.07 \pm 0.09$ can be compared with the recent result from ACCMOR, which is $0.54^{+0.18}_{-0.15}$ (statistical error only) [8]. The $\Sigma^+\pi^0$ mode has not been observed before, but it is required to have the same amplitude as $\Sigma^0\pi^+$ by an isospin sum rule [9]. The $B(\Lambda_c \rightarrow \Sigma^0\pi^+)/B(\Lambda_c \rightarrow pK^-\pi^+)$ has been measured by ARGUS and CLEO II to be 0.17 ± 0.07 and 0.18 ± 0.05 [10], respectively. Both values are consistent with our value for $B(\Lambda_c \rightarrow \Sigma^+\pi^0)/B(\Lambda_c \rightarrow pK^-\pi^+)$ of $0.20 \pm 0.03 \pm 0.03$.

The two-body decays, $\Sigma^+\pi^0$ and $\Sigma^+\omega$, can be compared with a variety of theoretical predictions. We convert our branching ratios into decay rates using the particle data group values for the Λ_c lifetime and $B(\Lambda_c \rightarrow pK^-\pi^+)$. The comparison is shown in Table II. The $\Sigma^+\pi^0$ measurement is compatible with some of the theoretical predictions. The $\Sigma^+\omega$ measurement and the $\Sigma^+\rho^0$ upper limit both fall below the predictions of Körner and Krämer [11]. The $\Sigma^+\rho^0$ prediction of Cheng and Tseng [12] is much smaller and is compatible with our upper limit.

In summary, two Λ_c decays ($\Sigma^+\pi^0$ and $\Sigma^+\omega$) that have no external W -emission contributions have been measured. Their branching ratios relative to the $pK^-\pi^+$ decay mode range from 0.20 to 0.54. Two similar Λ_c decay modes ($\Lambda\pi^+$ and $\Lambda\pi^+\pi^-\pi^+$) that do have external spectator contributions have branching ratios from 0.18 to 0.64 [13]. The similarity of these rates implies that nonfactorizable effects are important in charm baryon decays.

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TABLE II. Comparison of Λ_c decay rates between theory and experiment. The units are 10^{-11} s^{-1} . The first error on the experimental decay rate is due to our branching ratio measurement; the second is due the $pK^-\pi^+$ branching fraction. The upper limit is at 95% C.L.

	$\Sigma^+\pi^0$	$\Sigma^+\omega$	$\Sigma^+\rho^0$
This work	$0.33 \pm 0.08 \pm 0.07$	$0.88 \pm 0.24 \pm 0.19$	< 0.5
Ref. [11]	0.16	2.01	1.56
Ref. [12]	0.37		0.02–0.10
Ref. [14]	0.17		
Ref. [15]	2.20		
Ref. [16]	5.84		

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