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Observation of the Cabibbo-suppressed decay $\Xi_c^+ \rightarrow pK^-\pi^+$

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We report the first observation of the Cabibbo-suppressed charm baryon decay $\Xi_c^+ \rightarrow pK^-\pi^+$. We observe 150 ± 22 events for the signal. The data were accumulated using the SELEX spectrometer during the 1996–1997 fixed target run at Fermilab, chiefly from a 600 GeV/c Σ^- beam. The branching fractions of the decay relative to the Cabibbo-favored $\Xi_c^+ \rightarrow \Sigma^+K^-\pi^+$ and $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$ are measured to be $B(\Xi_c^+ \rightarrow pK^-\pi^+)/B(\Xi_c^+ \rightarrow \Sigma^+K^-\pi^+) = 0.22 \pm 0.06 \pm 0.03$ and $B(\Xi_c^+ \rightarrow pK^-\pi^+)/B(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+) = 0.20 \pm 0.04 \pm 0.02$, respectively.

The study of Cabibbo-suppressed (CS) charm decays can provide useful insights into the weak interaction mechanism for non-leptonic decays [1]. The observed final state may arise either from direct quark emission at the decay stage or, in some cases, from quark rearrangement due to final-state scattering. By comparing the strengths of CS decays to their Cabibbo-favored (CF) analogs, one can, in a systematic way, assess the contributions of the various mechanisms.

Modern methods for calculating non-leptonic decay rates of the charm hadrons employ heavy quark effective theory and the factorization approximation [2]. Nonetheless, the three-body decays of charm baryons are prohibitively difficult to calculate due to the complexity of associated final state interactions. Measurements of the relative branching fractions of charm baryon states, both CF and CS, give additional information about the structure of the decay amplitude and the validity of the factorization approximation.

Many CS hadronic decays of charm mesons have been measured by both e^+e^- collider and fixed target experiments. Until now the only CS charm baryon decay reported with significant statistics is $\Lambda_c^+ \rightarrow pK^-K^+$ and its resonant state, $\Lambda_c^+ \rightarrow p\phi$ [3,4]. This transition requires internal W -emission and may be inhibited by color-suppression effects. In this paper, we present the first observation of the CS decay $\Xi_c^+ \rightarrow pK^- \pi^+$ and determine the branching fractions of this decay relative to the CF $\Xi_c^+ \rightarrow \Sigma^+ K^- \pi^+$ and $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ modes. All three of these modes involve external W -emission.

Figure 1 shows a spectator diagram with external W -emission for Ξ_c^+ decaying into a CF and a CS mode. (The

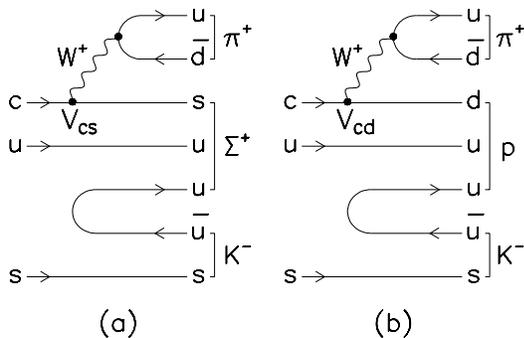


FIG. 1. An example of spectator diagrams for Ξ_c^+ decays, (a) CF $\Xi_c^+ \rightarrow \Sigma^+ K^- \pi^+$ and (b) CS $\Xi_c^+ \rightarrow pK^- \pi^+$

other CF Ξ^- mode interchanges s and u quark lines and produces a $d\bar{d}$ pair from the vacuum instead of a $u\bar{u}$ pair.) The decay process is similar in the two modes except for the flavor change in the weak decay Cabibbo-Kobayashi-Maskawa matrix element (V_{cs} vs. V_{cd}). Based on a simplified dimensional analysis, we would expect $B(\Xi_c^+ \rightarrow$

$pK^- \pi^+)/B(\Xi_c^+ \rightarrow \Sigma^+ K^- \pi^+) = 2.1 \times \alpha \times \tan^2 \theta_c$ where θ_c is the Cabibbo angle and α , of order unity, measures the ratio of the hadronic contributions to the weak decay matrix element. The factor 2.1 reflects the relative phase space of the two modes. By comparing the α factors for the entire family of CS non-leptonic charm baryon decays one may develop a picture of the dominant features of the amplitudes.

The SELEX(E781) experiment at Fermilab is particularly well-suited for studying CS charm baryon decays because of its excellent particle identification capabilities. SELEX is a high energy hadroproduction experiment using a 3-stage spectrometer designed for high acceptance for forward interactions ($x_F = 2p_{\parallel}^{CM}/\sqrt{s} > 0.1$). The experiment emphasizes understanding charm production in the forward hemisphere and the study of charm baryon decays. Using both a negative beam ($\simeq 50\% \Sigma^-, \simeq 50\% \pi^-$) and positive beam ($\simeq 92\% p, \simeq 8\% \pi^+$), SELEX recorded 15.2 billion interaction events during the 1996–1997 fixed target run. The majority particles (Σ^-, π^-) in the 600 GeV/c negative beam and the protons in the 540 GeV/c positive beam were tagged by a beam transition radiation detector. The data were accumulated from a segmented target (5 foils: 2 Cu, 3 C, each separated by 1.5 cm) whose total thickness was 5% of an interaction length for protons.

The spectrometer had silicon strip detectors to measure the beam and outgoing tracks, giving precision primary and secondary vertex reconstruction. Transverse position resolution (σ) was $4 \mu\text{m}$ for the 600 GeV/c beam tracks. The average longitudinal vertex position resolution was $270 \mu\text{m}$ for primary and $560 \mu\text{m}$ for secondaries, respectively. Momenta of particles deflected by the analyzing magnets were measured by a system of proportional wire chambers (PWCs), drift chambers and silicon strip detectors. Momentum resolution for a typical 100 GeV/c track was $\sigma_p/p \approx 0.5\%$. The absolute momentum scale was calibrated using the K_S^0 mass. For $D^0 \rightarrow K^- \pi^+$ decays the average mass resolution was $9 \text{ MeV}/c^2$ independent of D^0 momenta from 100–450 GeV/c. Charged particle identification was done with a Ring Imaging Čerenkov detector (RICH) [5], which distinguished K^\pm from π^\pm up to 165 GeV/c. The proton identification efficiency was greater than 95% above proton threshold ($\approx 90 \text{ GeV}/c$). For pions the total mis-identification probability due to all sources of confusion was less than 4%.

Interactions were selected by a scintillator trigger. The trigger for charm required at least 4 charged tracks after the targets as indicated by an interaction counter and at least 2 hits in a scintillator hodoscope after the second analyzing magnet. It accepted about 1/3 of all inelastic interactions. Triggered events were further tested in an on-line computational filter based on downstream tracking and particle identification information. The on-line filter selected events that had evidence of a secondary

vertex from tracks completely reconstructed using the forward PWC spectrometer and the vertex silicon. This filter reduced the data size by a factor of nearly 8 at a cost of about a factor of 2 in charm written to tape (as determined from a study of unfiltered K_S^0 , Λ and $D^0 \rightarrow K^-\pi^+ + c.c.$ decays). Most of the charm loss came from selection cuts that were independent of charm species or kinematic variables and which improved the signal/noise in the final sample.

Results presented here come from the first processing pass through all data. In this analysis, secondary vertex reconstruction was attempted when the χ^2 per degree of freedom (χ^2/dof) for the fit of the ensemble of tracks to a single primary vertex exceeded 5. All combinations of tracks were formed for secondary vertices with as many as 5 prongs. Secondary vertices were tested against a reconstruction table that specified selection criteria for each charm decay mode. Secondary vertices which occurred inside the volume of a target or after the first plane of the silicon vertex detector were rejected.

The $pK^-\pi^+$ sample was selected by the following requirements: (i) primary and secondary vertex fits each have $\chi^2/\text{dof} < 5$; (ii) vertex separation significance $L/\sigma \geq 8$, where L is the longitudinal separation between primary and secondary vertices and σ is the error on L ; (iii) the reconstructed momentum vector from the secondary vertex points back to the primary vertex with $\chi^2/\text{dof} < 4$; (iv) the momentum of the $\pi^+ \geq 5 \text{ GeV}/c$; (v) $\mathcal{L}(K)/\mathcal{L}(\pi) > 1$ for K identification and $\mathcal{L}(p)/\mathcal{L}(\pi) > 1$ for p identification, where \mathcal{L} is the mass-selection likelihood function for the RICH; and (vi) the sum of the squared transverse momenta of the three daughter particles with respect to the parent direction, $\Sigma p_T^2 > 0.3 (\text{GeV}/c)^2$.

Figure 2 shows the first observation of the CS $\Xi_c^+ \rightarrow pK^-\pi^+$ decay mode. The inset of the figure shows the invariant mass distribution from the entire selected mass range of reconstructed $pK^-\pi^+$ candidates. The large peak in the inset is the decay $\Lambda_c^+ \rightarrow pK^-\pi^+$. The bump at the right is the CS $\Xi_c^+ \rightarrow pK^-\pi^+$ decay. The distribution has an artificial high-mass cutoff because of a maximum mass cut imposed in this first-pass analysis. Monte Carlo simulations show that the observed number of signal events is systematically reduced only by $(2 \pm 3)\%$ due to this cutoff. The background characteristics are very similar both in the number per mass bin and lifetime through the entire mass region, so that the background subtraction under the Ξ_c^+ peak is stable. The lifetime both of background and signal events for the Ξ_c^+ region has been investigated. The background apparent lifetime is quite short, while the Ξ_c^+ lifetime is consistent with the Particle Data Group average [6]. A detailed lifetime analysis is underway and will be reported elsewhere. The mass is determined using a Gaussian of variable centroid, width and area. The number of signal events is determined by a sideband subtraction method.

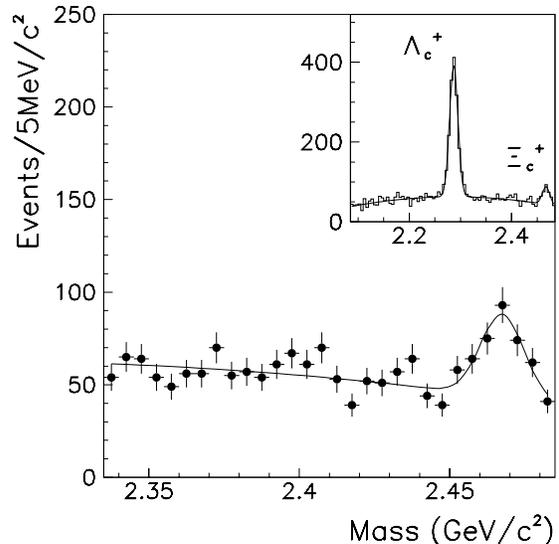


FIG. 2. The invariant mass distribution of $pK^-\pi^+$.

The signal window is determined from the Λ_c^+ data and is set at $45 \text{ MeV}/c^2$. The background is a second order polynomial fit to the entire mass region excluding a $65 \text{ MeV}/c^2$ wide window centered at each mass peak. The Ξ_c^+ yield is the difference between the summed events in the $45 \text{ MeV}/c^2$ signal window centered at $2.467 \text{ GeV}/c^2$ and the extrapolated background. Variations in the exclusion window size change the extrapolated background by fewer than 2 events. There are 150 ± 22 events for $\Xi_c^+ \rightarrow pK^-\pi^+$ at a Ξ_c^+ mass of $2467.4 \pm 1.3 \text{ MeV}/c^2$. The statistical significance for the signal, $S/\sqrt{S+B}$, is 6.9 ± 0.6 in which S is the number of signal events and B is the number of background events in the signal region.

Background contributions from charm baryon (Ξ_c^0 and Ω_c^0) decay to the CS decay are expected to be negligible; they produce an even number of secondary vertex tracks and their decay lengths are short compared to the minimum Ξ_c^+ flight path cut. Excellent proton identification strongly suppresses background from charm meson decays (three-body D^+ and D_s^+).

One normalizes the CS mode by comparing it to CF modes that have a hyperon in the final state. In the first reconstruction pass, hyperons (Σ^\pm, Ξ^\pm) were identified only inclusively in a limited decay interval (5 – 12 m downstream from the target): candidates had $p > 40 \text{ GeV}/c$ and no hits assigned along the trajectory in the 14 chambers after the second analyzing magnet. This category of tracks gives unique Σ^+ identification but is ambiguous between Σ^- and Ξ^- . Figure 3 shows two CF Ξ_c^+ modes decaying to $\Xi^-\pi^+\pi^+$ and $\Sigma^+K^-\pi^+$, respectively. The shaded areas in Fig. 3(a) and 3(b) are the estimated reflection from $\Lambda_c^+ \rightarrow \Sigma^-\pi^+\pi^+$ and $\Lambda_c^+ \rightarrow \Sigma^+\pi^-\pi^+$, respectively. The shapes are determined by a Monte Carlo simulation and the areas are normalized to the observed

number of signal events in the Λ_c^+ data. For this part of the analysis, additional cuts were applied to all data. The pion momentum threshold was raised from 5 to 10 GeV/c and the transverse component of the Ξ_c^+ momentum with respect to its line of flight was required to be less than 0.3 GeV/c.

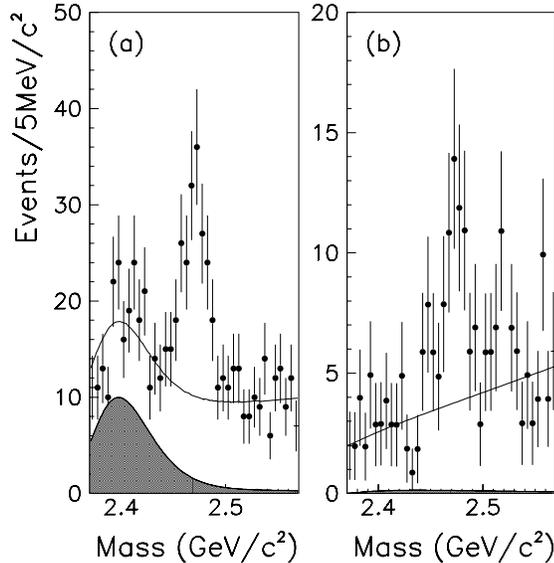


FIG. 3. Charm baryon Ξ_c^+ signals with hyperon partial reconstruction, (a) $\Xi^- \pi^+ \pi^+$ and (b) $\Sigma^+ K^- \pi^+$. The solid line is the background fit.

The total acceptance (geometrical acceptance and reconstruction efficiency) for decay modes of interest was estimated by embedding Monte Carlo charm decay tracks into data events. Momentum and energy were not conserved in the process, but studies indicate this has little effect on the single-charm acceptance calculation. Events were generated with an average transverse momentum $\langle p_T \rangle = 1.0$ GeV/c and longitudinal momentum distributions as observed for the data. Detector hits, including resolution and multiple Coulomb scattering smearing effects, produced by these embedded tracks were folded into the hit banks of the underlying data event. The new ensemble of hits was passed through the SELEX off-line software. The acceptance is the ratio of the number of events in the signal to the number of embedded events in a particular mode.

The method was checked by measuring two well-determined relative branching fractions, $B(D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-)/B(D^0 \rightarrow K^- \pi^+) = 1.94 \pm 0.07 \pm_{0.11}^{0.09}$ and $B(D^+ \rightarrow K^- K^+ \pi^+)/B(D^+ \rightarrow K^- \pi^+ \pi^+) = 0.093 \pm 0.010 \pm_{0.006}^{0.008}$ where the first error is statistical and the second is systematic. Systematic errors include the difference of the ratio for charge-conjugate states, and uncertainties of signal yields and acceptance estimations. The results agree well with the world average [6]. For the D^+ decays, the vertex significance cut (L/σ) was increased to

	Acceptance(%)	Events
$\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$	2.46 ± 0.04	130 ± 15
$\Xi_c^+ \rightarrow \Sigma^+ K^- \pi^+$	1.09 ± 0.02	53 ± 10
$\Xi_c^+ \rightarrow p K^- \pi^+$	7.08 ± 0.06	76 ± 13

TABLE I. Summary of observed events and estimated acceptance for Ξ_c^+ modes using the tighter cuts. The errors are statistical only.

20 to suppress background from $D_s^+ \rightarrow K^- K^+ \pi^+$. This costs little signal, since the lifetime of D^+ is 2.4 times longer than that of D_s^+ .

Using this procedure, we measure the relative branching fraction for $\Xi_c^+ \rightarrow \Sigma^+ K^- \pi^+$ and $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ to be $(0.92 \pm 0.20 \pm 0.07)$. The systematic error is due to uncertainties in the background subtraction and relative acceptance estimation. This result is comparable to the CLEO measurement, $(1.18 \pm 0.26 \pm 0.17)$ [7]. The number of events and estimated acceptance for the three observed Ξ_c^+ modes with the common set of cuts are summarized in table I.

The branching fraction of the CS decay $\Xi_c^+ \rightarrow p K^- \pi^+$ relative to the CF $\Xi_c^+ \rightarrow \Sigma^+ K^- \pi^+$ is measured to be $0.22 \pm 0.06 \pm 0.03$ which corresponds to $(4.2 \pm 1.1 \pm 0.5) \times \tan^2 \theta_c$. The α factor is $2.0 \pm 0.5 \pm 0.2$. To put this in some perspective, the corresponding α factor for the CS decay $\Lambda_c^+ \rightarrow p K^- K^+$ relative to the CF mode $\Lambda_c^+ \rightarrow p K^- \pi^+$ is 2.5 ± 0.6 , using the world average for the branching fraction and correcting for phase space. Thus, the factors for these two different baryons are similar. In contrast, the CS ratios of D mesons depend strongly on final state multiplicity, suggestive of sizable final state interactions. For the $\Xi^- \pi^+ \pi^+$ mode, $B(\Xi_c^+ \rightarrow p K^- \pi^+)/B(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+)$ is measured to be $0.20 \pm 0.04 \pm 0.02$. Systematic errors include uncertainties in (i) the relative acceptance estimation, (ii) background subtractions due to the reflection from other hyperon modes, and (iii) the $p K^- \pi^+$ yield due to the imposed mass cutoff.

In summary, we observe the CS decay $\Xi_c^+ \rightarrow p K^- \pi^+$ at a mass of 2467.4 ± 1.3 MeV/c² with 150 ± 22 signal events. The relative branching fractions of the decay $\Xi_c^+ \rightarrow p K^- \pi^+$ to the CF $\Xi_c^+ \rightarrow \Sigma^+ K^- \pi^+$ and $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ are measured to be $B(\Xi_c^+ \rightarrow p K^- \pi^+)/B(\Xi_c^+ \rightarrow \Sigma^+ K^- \pi^+) = 0.22 \pm 0.06 \pm 0.03$ and $B(\Xi_c^+ \rightarrow p K^- \pi^+)/B(\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+) = 0.20 \pm 0.04 \pm 0.02$, respectively.

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