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PRODUCTION OF THE CHARMED BARYON Λ_c^+
IN π^- -Cu AND K^- -Cu INTERACTIONS AT 230 GeV

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ABSTRACT

We present results from the NA32 experiment at CERN on the production characteristics of the charmed baryon Λ_c^+ in 230 GeV π^- -Cu and K^- -Cu interactions. A high resolution vertex detector consisting of charge-coupled devices and silicon microstrip detectors allowed the selection of a very clean sample of $154 \Lambda_c^+ \rightarrow pK^- \pi^+$ (and charge conjugate) decays. Results on differential and integrated cross-sections are given.

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1. INTRODUCTION

The knowledge of the properties of the charmed baryon Λ_c^+ has improved greatly due to the new generation of experiments performed in the last five years. There have been precise measurements of the Λ_c^+ lifetime [1,2] and new results on the cross-section and production properties have been published [3,4], but the understanding of charm hadroproduction is still limited.

The physics of charm quark production represents an excellent laboratory to test several aspects of quantum chromodynamics (QCD). In this context, the relatively high mass charm quark should provide the high mass scale to make meaningful calculations in the framework of perturbative dynamics. The determination of the inclusive total and differential cross-sections of charm is essential when trying to establish the size of the contributions of the basic QCD subprocesses among the fundamental parton constituents, i.e. $q\bar{q}$ and gg . The knowledge of the dynamics behind the production of particles containing a heavy quark is also important, both to predict the production rate of new particles since the same dynamics is assumed, and to correctly evaluate the background they constitute in many rare processes.

The experiment described here was designed to measure $\Lambda_c^+ \rightarrow pK^-\pi^+$ and $D_s^+ \rightarrow K^+K^-\pi^+$ decays produced in hadronic interactions^{*)}. It was started in 1985 with the ACCMOR spectrometer at the CERN SPS. This continuation of the NA32 experiment [5] used a thin Cu target, an improved vertex detector and a dedicated trigger. This set-up allowed us to obtain a clean sample of Λ_c^+ decays on a small combinatorial background. For the first time charge-coupled devices, CCDs [6], were used as vertex detectors. They provide high resolution space points for secondary tracks close to the target. With this new technique, exclusive decay channels were detected with high statistics, comparable to that of e^+e^- colliders and photoproduction experiments. A modified version of the FAMP trigger [7] was used to trigger on events containing a pair of kaons and/or protons of opposite charge. During 1985 and 1986, a total of 17 million triggers have been recorded.

This letter is organized as follows : we describe the experimental set-up (section 2), the data analysis (section 3) and the Λ_c^+ signal obtained (section 4). We present the acceptance calculations (section 5) and finally, we discuss the results on differential and total cross-sections (sections 6,7).

^{*)} Throughout this paper particle symbols stand for particles and antiparticles.

2. THE EXPERIMENT

The experiment was situated in the H6 beam of the North Area at the CERN SPS. An unseparated and tagged negative hadron beam (96% pions and 4% kaons) with a momentum of 230 GeV was used.

Charm decays into charged particles have been fully reconstructed with the large acceptance spectrometer [8] and the vertex detector.

The spectrometer consisted of two magnets, 48 planes of drift chambers arranged in 4 groups, two hodoscope arrays and five planes of proportional chambers. Three multicellular Cerenkov counters allowed the identification of π , K and p in the momentum range 4-80 GeV.

The vertex detector [1] consisted of a beam telescope of 7 silicon microstrip detectors (MSDs) and a vertex telescope with 2 CCDs at 10 and 20 mm behind the 2.5 mm Cu target and 8 MSDs starting at 65 mm behind the target. Capacitive charge division readout was used for the MSDs. The precision of the space points measured by the 2 CCDs is $\approx 5 \mu\text{m}$ in the two orthogonal directions. The two track resolution is $40 \mu\text{m}$. CCDs have the advantage of providing space point information, which in comparison with a vertex telescope of only MSDs reduces reconstruction ambiguities significantly.

Triggering was performed at two levels in the experiment [1]. The first level trigger was based on fast digital signals from two scintillator hodoscope arrays and two multicell Cerenkov counters. Signals of fixed combinations of hodoscope and Cerenkov cells were correlated in order to select events with at least two particles of opposite charge having momenta below the Cerenkov threshold (π -thresholds were 6.5 and 12 GeV respectively). At the second trigger level three FAMP processors were used to combine the information of the first level trigger with the data from five multiwire proportional chambers in order to reject pions below the Cerenkov thresholds. A rough track reconstruction was performed where tracks were correlated with the hodoscope information and a cross-check was made between track momenta and the expected Cerenkov signals for kaon or proton. The enrichment factor of the recorded $\Lambda_c^+ \rightarrow pK^-\pi^+$ data sample compared to an interaction trigger is 7. The gain in sensitivity (defined as the number of events per unit time) for Λ_c^+ decays is a factor 5.

3. DATA ANALYSIS

The first step consists of reconstructing all tracks in an event and then fitting the primary vertex [1]. Events are selected if they have at least two tracks not originating from the primary vertex (impact parameter larger than 3 standard deviations) giving a data reduction factor of approximately 7.

The very precise track reconstruction in the vertex detector allows the charm search to be based on a purely topological search for secondary vertices [1]. This approach has the advantage of being restricted neither to a limited number of prechosen decay channels, nor to any mass window for a specific decay mode. Hence, the next step is to select events containing at least one good secondary vertex. This vertex is constructed from the tracks which are not originating from the primary vertex. Tracks which are consistent with both the primary and secondary vertices are then added to the secondary vertex. All such ambiguous interpretations are used in the following analysis. The secondary vertex is required to be outside the Cu target to remove secondary interactions. To select fully reconstructed charm decays with no missing neutral particles the total momentum vector of the decay tracks has to point to the primary vertex (χ^2 probability $> 1\%$). Finally, for each accepted secondary vertex all the possible charged decay channels of charmed particles are considered which are consistent with the particle identification.

4. Λ_c^+ SIGNAL

The invariant mass distribution for the $\Lambda_c^+ \rightarrow pK^-\pi^+$ events is presented in Fig. 1. The reflections due to D_s^+ , $D^+ \rightarrow K^-K^+\pi^+$ and $D^+ \rightarrow K^-\pi^+\pi^+$ decays have been removed. The number of fitted events after background subtraction is 154; 147 produced by a π^- beam particle and 7 (all of them antibaryons) by a K^- particle. A search was made for $\Sigma_c^0 \rightarrow \Lambda_c^+\pi^-$ and $\Sigma_c^{++} \rightarrow \Lambda_c^+\pi^+$ decays. Figures 2a and 2b show the mass differences $m(pK^-\pi^+\pi^-) - m(pK^-\pi^+)$ and $m(pK^-\pi^+\pi^+) - m(pK^-\pi^+)$ respectively. No significant signal is observed at the expected mass difference of ~ 167 MeV [9]. Correcting these events for the background outside the expected mass difference, we derive an upper limit to the fraction of Λ_c^+ produced via the decay of Σ_c^0 of 5.3% (90% C.L.) and from Σ_c^{++} of 5.2% (90% C.L.) in π^- production.

5. ACCEPTANCE CALCULATIONS

Many of the $\Lambda_c^+ \rightarrow pK^-\pi^+$ decays will not be observed because of the limited geometrical acceptance of the spectrometer. Decays will also be lost because of secondary interactions or decays of the decay particles, the inefficiencies of the detectors and the acceptance of the trigger and the selection criteria.

In order to study the production characteristics of Λ_c^+ , we have to correct the observed differential cross-sections (x_F and p_t^2 distributions) for their respective acceptances. Here, the Feynman variable x_F is defined as the longitudinal momentum of the Λ_c^+ in the centre of mass system divided by the maximum possible value and p_t^2 is the transverse momentum squared of the Λ_c^+ relative to the incident beam. We assume the absence of correlations between x_F and p_t^2 in the production process.

Acceptance curves are determined by a Monte-Carlo calculation for the $\Lambda_c^+ \rightarrow pK^-\pi^+$ decay mode [10]. Only losses which depend on the aforementioned variables are incorporated in the Monte-Carlo program. Table 1 shows the corresponding acceptance factors. Losses which do not depend upon the event kinematics or for which the dependence is known to be small, like track and vertex reconstruction efficiencies, are taken into account as global factors when calculating the cross-section and are listed in Table 2.

The Monte-Carlo program generates an uncorrelated pair of charmed particles

$$\pi^- p \rightarrow C \bar{D} X$$

where C is the particle being studied, in this case a Λ_c^+ , and $\bar{D}$ is its associated partner, assumed to be a $\bar{D}$ meson. The distribution of the generated primary vertices is uniform in the direction of the beam and corresponds to the beam shape in the transverse directions. Only the charmed particles are generated. The other tracks (X) are chosen from a real minimum bias event, making sure that the total momentum is not exceeded.

The required decay mode of the Λ_c^+ ($pK\pi$) is then generated assuming a phase space distribution of its decay tracks whereas the associated $\bar{D}$ (66.7% $\bar{D}^0$ and 33.3% D^- , since the neutral D cross-section is about a factor 2 higher than the charged D cross-section [3]) decays according to the branching fractions given in [11]. The total acceptance for the channel $pK\pi$ is not very sensitive to the presence of a kaon from the decay of the charmed partner. By varying the branching fraction of $\bar{D} \rightarrow K^+ + X$ from 0 to 100% the acceptance changes relatively by $\pm 6\%$.

The lifetime of the Λ_c^+ is generated from an exponential distribution with a mean lifetime value as measured in this experiment [1].

The Λ_c^+ decay tracks and the K of the associated charmed particle (if any) are traced through the spectrometer. At this point, the geometrical event selection is done as follows :

- All the decay tracks have to be seen in at least the first five or six planes of the MSDs, depending on the number of CCD hits.

- All tracks are traced through the spectrometer magnets. They have to traverse at least the first group of drift chambers.
- Any kaon or proton among the decay tracks must traverse the second magnet and be seen in the drift chambers downstream. The kaon decay and the kaon and proton interaction probabilities are also taken into account.

The main features of the trigger simulation are as follows :

- Hardware trigger signals for all decay/interaction tracks are generated and the first level trigger condition has to be fulfilled.
- The FAMP algorithm is simulated and at least one pair of kaon and/or proton candidates of opposite charge has to be found within the momentum range used by FAMP.

To reproduce the topological cuts applied during the data selection, a measurement error has to be assigned to the generated decay tracks. This error depends on the number of hits in the vertex detector. Multiple scattering is also taken into account.

The requirements on the impact parameter of the decay tracks and on the position of the decay vertex outside the copper target are the same as in the real event selection. Finally, we simulated the particle identification of the decay tracks using the selection as in real data.

The impact parameter and momentum distributions (Fig. 3) of the Λ_c^+ decay tracks that fulfil the selection criteria in the Monte-Carlo simulation agree well with the corresponding distributions of the real data sample.

Figure 4 shows the total acceptance for $\Lambda_c^+ \rightarrow pK^-\pi^+$ as a function of x_F and p_t^2 . We have checked that there is no correlation between the x_F and p_t^2 acceptances.

6. DIFFERENTIAL CROSS-SECTIONS

The differential cross-section for charm production is usually parametrized by :

$$\frac{d^2\sigma}{dx_F dp_t^2} \approx (1 - x_F)^n e^{-bp_t^2}$$

The x_F and p_t^2 distributions for the $pK\pi$ channel corrected for their acceptances are shown in Fig. 5. The background contribution, estimated from the events in side bands around the Λ_c^+ mass peak, has been subtracted.

The parameters n and b are determined by a combined maximum likelihood fit to the invariant mass spectrum and the x_F and p_t^2 distributions. For the mass spectrum we assumed a Gaussian signal on a linear background. For the x_F and p_t^2 distributions we used respectively $A(x_F)(1-x_F)^n$ and $B(p_t^2)e^{-bp_t^2}$ where $A(x_F)$ is the x_F acceptance and $B(p_t^2)$ is the p_t^2 acceptance. The background is quite well represented by a similar parametrization of the x_F and p_t^2 distributions. Due to some differences in the geometry of the detector set-up between the 1985 and 1986 run, we corrected each sample of data for their respective acceptance (Fig. 4). Table 3 summarizes the results of the fit for both the signal and the background produced in π^- -Cu interactions. The statistical errors come from the errors on the numbers of observed events. The systematic errors are mainly due to the method for adding interaction tracks. This gives a systematic effect of about 10% in the value of n and 3% in the value of b .

No significant difference is observed between the x_F and p_t^2 distributions for Λ_c^+ and for $\bar{\Lambda}_c^-$ with the π^- beam. The fitted values of n and b for Λ_c^+ and $\bar{\Lambda}_c^-$ together are $n = 3.52^{+0.51}_{-0.49}$ and $b = 0.84^{+0.09}_{-0.08} \text{ GeV}^{-2}$. The production characteristics are similar to the ones of D mesons as measured in our experiment, $n = 3.74 \pm 0.23$ and $b = 0.83 \pm 0.03 \text{ GeV}^{-2}$ [12].

The corrected average value of x_F for the total sample of Λ_c^+ in the forward hemisphere is 0.06 and the corrected average of p_t^2 is 1.19 GeV^2 .

The 7 $\bar{\Lambda}_c^-$ produced by an incoming K^- beam are not sufficient to determine a differential cross-section.

7. TOTAL CROSS-SECTION

From the number of observed events and the total acceptance we can determine for the forward hemisphere the product of the inclusive Λ_c^+ production cross-section and the corresponding branching fraction.

To estimate the total acceptance we use the values of n and b as determined in the previous section.

The evaluation of the total cross-section has been done assuming an A^1 dependence of the charm cross-section. An $A^{0.8}$ dependence would yield values larger by a factor 2.3 than the ones we quote.

The resulting cross-section value for Λ_c^+ produced by π^- having positive x_F is :

$$\sigma(\pi^- N \rightarrow \Lambda_c^+ X) \times BR(\Lambda_c^+ \rightarrow pK\pi) = 0.18 \pm 0.02 \pm 0.03 \text{ } \mu\text{b/nucl.}$$

where the first error is statistical and the second is systematic. This second error comes mainly from the total acceptance calculation which includes the contribution of the errors in n and b

(4% with π^- beam and 20% with K^- beam), the uncertainty in the lifetime value (9%), the contribution of the associated charm partner in the generation (6%) and the change in the acceptance due to the chosen method for adding interaction tracks (10%). This introduces a 15% (25% with K^- beam) uncertainty in the total cross-section.

For $\bar{\Lambda}_c^-$ produced by K^- ($x_F > 0$) we obtain :

$$\sigma(K^- N \rightarrow \bar{\Lambda}_c^- X) \times BR(\Lambda_c^+ \rightarrow pK\pi) = 0.16 \pm 0.06 \pm 0.04 \text{ } \mu\text{b/nucl.}$$

If we take the branching fraction of $\Lambda_c^+ \rightarrow pK\pi$ to be $4.1 \pm 2.4\%$ as given by the ARGUS collaboration [14] we measure a production cross-section of Λ_c^+ by pions to be

$$\sigma(\pi^- N \rightarrow \Lambda_c^+ X) = 4.4 \pm 2.6 \pm 0.6 \text{ } \mu\text{b/nucleon.}$$

Another interesting determination of the branching fraction of $\Lambda_c^+ \rightarrow pK\pi$ has been obtained from an analysis of ARGUS and CLEO data [15]. It starts from the average value of $BR(\bar{B} \rightarrow \Lambda_c^+ X)$. $BR(\Lambda_c^+ \rightarrow pK\pi) = (0.29 \pm 0.07)\%$. Using a few plausible assumptions and measurements of inclusive baryon decay fractions of B mesons, a fit yields values for these baryon decay fractions and

$$BR(\Lambda_c^+ \rightarrow pK^- \pi^+) = (3.7 \pm 1.0)\%.$$

Using this value, we obtain

$$\sigma(\pi^- N \rightarrow \Lambda_c^+ X) = 4.9 \pm 1.4 \pm 0.7 \text{ } \mu\text{b/nucleon.}$$

These values are comparable in size to the D production cross-section obtained in our experiment $\sigma(\pi^- N \rightarrow D/\bar{D}+X) = 9.5 \pm 0.4 \pm 1.9 \text{ } \mu\text{b/nucleon}$ [12,13].

An almost equal number of Λ_c^+ and $\bar{\Lambda}_c^-$ are produced with the π^- beam and we measure the ratio to be :

$$\frac{\sigma\left(\pi^- Cu \rightarrow \Lambda_c^+\right)}{\sigma\left(\pi^- Cu \rightarrow \bar{\Lambda}_c^-\right)} = 0.99 \pm 0.16$$

In contrast, with the K^- beam we find only the antibaryon (7 $\bar{\Lambda}_c^-$ have been found).

8. CONCLUSIONS

A large and clean sample of Λ_c^+ has been obtained in 230 GeV π^- Cu interactions due to a selective trigger and the introduction of charge-coupled devices for vertex reconstruction.

A study of 147 Λ_c^+ produced with a π^- beam led to the following results for $x_F > 0$ (assuming A^1 dependence) :

$$\sigma(\pi^- N \rightarrow \Lambda_c^+ / \bar{\Lambda}_c^- X) \times BR(\Lambda_c^+ \rightarrow pK\pi) = 0.18 \pm 0.02 \pm 0.03 \text{ } \mu\text{b/nucl.}$$

Λ_c^+ and $\bar{\Lambda}_c^-$ are produced at equal rates in a π^- beam and have similar x_F and p_t^2 distributions.

Parametrizing the differential cross-section as $(1-x_F)^n e^{-bp_t^2}$, we have determined for $x_F > 0$, $n = 3.52 \pm_{0.49}^{0.51}$ and $b = 0.84 \pm_{0.08}^{0.09} \text{ GeV}^{-2}$.

The production characteristics of Λ_c^+ are similar to the production characteristics of D mesons.

Less than 5.3% (90% C.L.) of the Λ_c^+ decays come from Σ_c^0 and less than 5.2% (90% C.L.) from Σ_c^{++} decays, in π^- production.

For K^- production of Λ_c^+ ($x_F > 0$) we find only the antibaryon (7 events) and the cross-section times branching fraction quoted is :

$$\sigma(K^- N \rightarrow \bar{\Lambda}_c^- X) \times BR(\Lambda_c^+ \rightarrow pK\pi) = 0.16 \pm 0.06 \pm 0.04 \text{ } \mu\text{b/nucl.}$$

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Table 1

Effect of the various cuts applied in the Monte-Carlo calculation and total acceptance for the decay channel $\Lambda_c^+ \rightarrow pK\pi$. The quoted errors are statistical only. The systematic errors in the total acceptance are estimated to be 15% for the π^- beam and 25% for the K^- beam.

Beam	π^-	K^-
Geometrical cuts	0.362 ± 0.005	0.456 ± 0.005
Trigger simulation	0.494 ± 0.009	0.450 ± 0.009
Topological cuts	0.348 ± 0.011	0.335 ± 0.011
Total acceptance ($x_F > 0$)	0.062 ± 0.002	0.069 ± 0.002

Table 2

Global correction factors for the decay channel $\Lambda_c^+ \rightarrow pK\pi$.

The decoding correction entry includes the losses due to undecodable events, interactions upstream of the target and events where no beam track is reconstructed.

Decoding correction	0.75 ± 0.02
Reconstruction efficiency	0.84 ± 0.03

Table 3

Fit results for Λ_c^+ produced by π^- . The quoted errors are statistical only.

The systematic errors are estimated to be 10% for n and 3% for b .

The background includes events with masses between 2.1 and 2.5 GeV using a linear fit.

	Particle	n	b (GeV ⁻²)
Signal	$\Lambda_c^+ + \bar{\Lambda}_c^-$	$3.52^{+0.51}_{-0.49}$	$0.84^{+0.09}_{-0.08}$
	Λ_c^+	$3.69^{+0.74}_{-0.71}$	$1.02^{+0.15}_{-0.14}$
	$\bar{\Lambda}_c^-$	$3.37^{+0.70}_{-0.66}$	$0.73^{+0.11}_{-0.11}$
Background	$\Lambda_c^+ + \bar{\Lambda}_c^-$	$6.65^{+0.79}_{-0.76}$	$1.98^{+0.25}_{-0.23}$
	Λ_c^+	$6.45^{+1.11}_{-1.04}$	$2.02^{+0.33}_{-0.30}$
	$\bar{\Lambda}_c^-$	$6.86^{+1.14}_{-1.08}$	$1.86^{+0.41}_{-0.32}$

Figure Captions

Fig. 1 : $pK\pi$ invariant mass spectrum.

Fig. 2 : Mass difference.

a) $m(pK^-\pi^+\pi^-)-m(pK^-\pi^+)$.

b) $m(pK^-\pi^+\pi^+)-m(pK^-\pi^+)$.

Fig. 3 : Momentum and impact parameter distributions of p, K and π from the decay of the Λ_c^+ . The solid line corresponds to the experimental data and the dashed line is the result of the Monte-Carlo simulation.

Fig. 4 : Acceptance as a function of a) x_F and b) p_t^2 for the decay mode $pK\pi$ of the Λ_c^+ . The solid line corresponds to the acceptance using the 1986 experimental set-up and the dashed line using the 1985 set-up.

Fig. 5 : x_F and p_t^2 distributions corrected for acceptance for :

a) Λ_c^+ and $\bar{\Lambda}_c^-$

b) Λ_c^+

c) $\bar{\Lambda}_c^-$

The solid line is the result of a maximum likelihood fit where $d\sigma/dx_F$ is parametrized by $(1 - x_F)^n$ and $d\sigma/dp_t^2$ by $e^{-bp_t^2}$.

Fig.1

Fig.2

Fig.3

Fig.4

Fig.5