MEASUREMENT OF ASSOCIATED CHARM PRODUCTION

IN pp INTERACTIONS AT $\sqrt{s} = 62$ GeV

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ABSTRACT

The associated charm production has been studied in pp interactions at $\sqrt{s} = 62$ GeV. The comparison of the measured production cross-section and e^-/π^- ratio with various theoretical models and with existing inclusive e/π measurements, allows to conclude that the most likely interpretation of the associated production is in terms of a charmed baryon Λ_c^+ produced forward, plus the $\bar{D}$ meson produced centrally.

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1. INTRODUCTION

The study of associated production of charmed particles (c , $\bar{c}$) in proton-proton interactions has been and still is very difficult. The experiments have so far been centred on the inclusive production¹⁻⁴⁾ of a single charmed particle, D^+ or Λ_c^+ . Only preliminary data^{5,6)} have been reported for the associated production of charmed pairs in hadronic interactions.

In this paper, the associated production of a charmed baryon plus the anti-charmed particle is studied, together with an estimate of the cross-section. The reaction investigated in proton-proton collisions at $\sqrt{s} = 62$ GeV is

$$pp \rightarrow \Lambda_c^+ + e^- + \text{anything} , \quad (1)$$

where the Λ_c^+ is identified via its decay mode $\Lambda_c^+ \rightarrow K^- p \pi^+$. The negative electron is the signature for the semileptonic decay of an anticharmed particle, where the antiquark transition follows the expected generalized Cabibbo dominance⁷⁾, as illustrated by the diagram:

The results, as in previous experiments²⁻⁶⁾, obviously depend on the production mechanism chosen. A comparison of all experimental results with various theoretical predictions suggests that the most likely mechanism is the forward production of a charmed baryon associated with a centrally produced anticharmed meson.

2. EXPERIMENTAL PROCEDURE

The experiment was performed using the Split-Field Magnet (SFM) detector of the CERN Intersecting Storage Rings (ISR), with the addition of gas threshold Čerenkov counters and electromagnetic shower detectors, to trigger on electrons produced at 90° . The apparatus is shown in fig. 1. The trigger electron was

detected by the coincidence of the two Čerenkov counters (C_0C_3 or C_0C_4) and by the condition of a minimum energy deposited in the corresponding electromagnetic shower detector (EMSD)⁸⁾: $E_{\min}^e \geq 500$ MeV.

A small multiwire proportional chamber (MWPC) with analog read-out ("dE/dx" chamber)⁹⁾, placed near the intersection region, provided the necessary pulse-height information to reject the background electrons from Dalitz π^0 and η decays and from external γ conversions.

The software analysis allows reduction of both charged and neutral hadron contaminations, via the off-line refinement of the triggering conditions and the rejection of the electron pairs originating from internal and external conversions.

Data collected during test runs and Monte Carlo simulations have been used to determine these contaminations in the final sample of e^+ and e^- events. The contamination due to charged hadrons is reduced to the 2% level. The neutral hadrons constitute a source of background that is much more difficult to reject, and the contamination level in the final sample is $\lesssim 50\%$.

The SFM, with its MWPC system, provided the momentum measurement for the charged secondaries. A fraction of these particles could be identified, in a momentum interval up to ~ 2 GeV/c¹⁰⁾, using the time information provided by a large time-of-flight system.

3. DATA ANALYSIS AND MASS SPECTRA

Using the procedure described above, we obtained a sample of $\sim 60,000$ events, corresponding to an integrated luminosity $\mathcal{L} = 4.39 \times 10^{36}$ cm⁻². From this sample, we have selected events with at least one positive particle with $x = 2p_L/\sqrt{s} \geq 0.3$ and an error on the measured momentum $\Delta p/p \leq 30\%$. In these events the positive particle with the highest x has been assumed to be a proton^{*)}.

The final sample of events has been studied in two ways, with reference to the hemisphere opposite to that of the detected proton:

*) The p/π^+ ratio at $x = 0.3$ is already 1.5 and increases rapidly as a function of x .

- i) no conditions on the system of charged particles in this hemisphere;
- ii) the requirement of either a leading system of charged particles with $x_{\text{opp}} \geq 0.5$, or a system with $x_{\text{opp}} \leq 0.1$ as a signature of a leading system escaping detection. [Notice that $x_{\text{opp}} = \sum_{i=1}^n (x_{\text{opp}}^i)$, where the sum is extended to all particles fitted to the vertex and with $\Delta p/p \leq 30\%$.]

In the invariant mass $pK^-\pi^+$, K^- (π^+) is any negative (positive) track, not identified as a $\bar{p}$ or π^- (K^+ or p) by the time of flight. All possible combinations are entered into the mass plot, provided they satisfy the following conditions:

- a) all particles are fitted to the vertex and have $\Delta p/p \leq 30\%$;
- b) both the K^- and the π^+ are in the same rapidity hemisphere as that of the proton;
- c) the rapidity of both the K^- and the π^+ is greater than 1.0.

Figure 2a shows the $pK^-\pi^+$ mass spectrum for the e^- triggered events when condition (ii) is applied. A clear peak is observed at $m \approx 2330 \text{ MeV}/c^2$. Its width is compatible with the expected mass resolution. This peak is not present in the case of the e^+ triggered events (see fig. 2b). In fact the associated $\Lambda_c^+\bar{D}$ production needs an e^- , not an e^+ , in the final state [reaction (2)].

The mass shift of $\sim 55 \text{ MeV}/c^2$ from the weighted world average value of the Λ_c^+ mass¹¹⁾ ($2273 \pm 6 \text{ MeV}/c^2$) is due to local systematic effects in the SFM detector.

Note that, as shown in fig. 3, a clear improvement in the signal-to-background ratio is obtained when condition (ii) is applied for the particles in the hemisphere opposite to that of the detected proton. This is evidence for a long-range correlation in charmed particle production associated with a "leading" system in the opposite hemisphere.

4. RESULTS

4.1 Cross-sections

In order to compute the cross-section for reaction (1), an assumption must be made on the mass of the anticharmed particle, which could be either a meson $\bar{D}$

or a baryon $\bar{C}$. Since in the framework of the recombination or diffraction models -- which seem to be the more likely processes for charm production in pp collisions -- the production of a $\bar{D}C$ pair is much more natural than that of a $\bar{C}C$ pair, we have assumed that all the electrons come from the decay of the $\bar{D}$ meson.

The cross-section for the associated production of a $\bar{D}\Lambda_c^+$ pair has been computed assuming the standard scaling law for the inclusive charm cross-section:

$$E \frac{d^3\sigma}{dp^3} = f(y/y_{\max}) \exp(-\alpha p_T) ,$$

where $\alpha^{-1} = 0.5 \text{ GeV}/c$.

The function $f(y/y_{\max})$ gives the dependence from the longitudinal momentum and is parametrized as listed below:

$$\begin{aligned} \text{Model I)} \quad & \frac{d\sigma}{dx} \propto (1-x)^3 \\ \text{Model II)} \quad & \frac{d\sigma}{dy} = \text{const} \\ \text{Model III)} \quad & \frac{d\sigma}{dx} = \text{const} . \end{aligned}$$

The detection efficiency for the electron and the over-all acceptance of the apparatus were determined via Monte Carlo simulation. Table 1 summarizes the results obtained for different combinations of the longitudinal momentum distributions of $\bar{D}$ and Λ_c^+ .

In order to compute the total cross-section, we have used the following values for the branching ratios¹²⁻¹³):

$$\begin{aligned} \frac{(\bar{D} \rightarrow e^- \bar{\nu}_e + \text{anything})}{(\bar{D} \rightarrow \text{all})} &= 8.5\% \\ \frac{(\Lambda_c^+ \rightarrow p K^- \pi^+)}{(\Lambda_c^+ \rightarrow \text{all})} &= 2.2\% . \end{aligned}$$

The cross-section values given in table 1 have an over-all uncertainty of no more than 40%.

4.2 The e/π ratio

The rapidity range covered by the apparatus for e^- detection is $-0.55 \leq y \leq 0.55$, while the transverse momentum acceptance is determined by the EMSD energy thresholds mentioned above and discussed elsewhere⁸⁾.

From the observed number of $e^- \Lambda_c^+$, it is possible to derive important information on the longitudinal momentum distribution of the associated $\Lambda_c^+ \bar{D}$ production. We have considered two cases:

- i) The longitudinal momentum distribution of Λ_c^+ is totally independent from the source which produces the e^- .

The acceptance of the apparatus changes with the production mechanism for Λ_c^+ . Thus, if Λ_c^+ production follows model I, the observed number of $e^- \Lambda_c^+$ events corresponds to a production rate which is about 24 times higher than that following model III.

In order to obtain for the ratio e^-/π^- a value consistent with well-established measurements^{14,15)}, the only possible model for Λ_c^+ production is model III. Table 2 shows all results.

- ii) The longitudinal momentum distribution of Λ_c^+ is correlated with the source of e^- .

As previously stated, we assume that the e^- source is the $\bar{D}$ meson.

Table 3 shows the corresponding values of e^-/π^- for the cases where Λ_c^+ and $\bar{D}$ have the same longitudinal momentum distributions (I, II, III) and for the case where the $\bar{D}$ is produced "centrally" (model I), i.e.

$$\frac{d\sigma}{dx} \propto (1-x)^3 ,$$

while the Λ_c^+ is produced "flat" in x (model III), i.e.

$$\frac{d\sigma}{dx} = \text{const.} .$$

This last model seems to be the best one for producing a ratio e^-/π^- that is nearest to expectations.

Other evidence supporting this choice is provided by the study of the p_T distribution for the e^- .

Figure 4 shows the experimental transverse momentum distribution of the electrons associated with Λ_c^+ . This distribution is determined by the difference between the p_T distribution of the electrons associated with a Λ_c^+ [$2.28 \leq m(K^- p \pi^+) \leq 2.38 \text{ GeV}/c^2$], and the p_T distribution of the electrons associated with $K^- p \pi^+$ masses outside the Λ_c^+ mass range, these distributions being normalized to the same number of events. The expected p_T distribution of the electrons from $\bar{D}$ decay using model I-III is shown by the dashed line in fig. 4. The experimental results are in good agreement with expectations.

5. CONCLUSIONS

The experimental status of the charmed baryon Λ_c^+ production cross-section, as measured at the ISR, is summarized in fig. 5. Also shown are some theoretical predictions for

- a) diffractive-like $\Lambda_c^+ \bar{D}$ production¹⁶⁾;
- b) $c\bar{c}$ pair creation by quark and gluon fusion models^{17,18)} ($q\bar{q} \rightarrow c\bar{c}$, $gg \rightarrow c\bar{c}$);
- c) flavour excitation via gluon and quark scattering¹⁷⁾ ($gc \rightarrow gc$, $qc \rightarrow qc$);
- d) $c\bar{c}$ pair production via gluons, computed by scaling the charm photoproduction cross-section¹⁹⁾ ($\gamma p \rightarrow c\bar{c} + \text{anything}$).

Even though the data points show large uncertainties, it seems possible to conclude that all theoretical predictions tend to give limits smaller than the experimental results²⁰⁾. This is even more true if we consider that, with the exception of the diffractive case, all the models predict the total charm cross-section. The measurements reported in fig. 6 refer only to Λ_c^+ inclusive production cross-section²¹⁾. For example, it has been measured that the total cross-section for $pp \rightarrow D^+ + X$ is of the same order of magnitude^{1,4,5)} as for $pp \rightarrow \Lambda_c^+ + X$.

The results of our experiment are further evidence for associated charm production, and provide a measurement of the cross-section (table 1 and fig. 5) for $\Lambda_c^+ \bar{D}$, in proton-proton interactions at $\sqrt{s} = 62 \text{ GeV}$.

A comparison of the results obtained with the various models allows us to contribute to the understanding of an important detail in the associated production of $\Lambda_c^+ \bar{D}$. In fact, the most likely interpretation of the $e^- \Lambda_c^+$ associated production is that the charmed baryon Λ_c^+ is produced forward, while the anticharmed meson $\bar{D}$ is produced centrally.

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Table 1

Model	$\bar{D}$	Λ_c^+	σ_{tot} (μb)
I	$\frac{d\sigma}{dx} \propto (1-x)^3$	$\frac{d\sigma}{dx} \propto (1-x)^3$	4200
II	$\frac{d\sigma}{dy} = \text{const}$	$\frac{d\sigma}{dy} = \text{const}$	750
III	$\frac{d\sigma}{dx} = \text{const}$	$\frac{d\sigma}{dx} = \text{const}$	1125
I-III	$\frac{d\sigma}{dx} \propto (1-x)^3$	$\frac{d\sigma}{dx} = \text{const}$	184

Table 2

Model	Λ_c^+	e^-/π^-
I	$\frac{d\sigma}{dx} \propto (1-x)^3$	$(3.0 \pm 0.9) \times 10^{-3}$
II	$\frac{d\sigma}{dy} = \text{const.}$	$(3.5 \pm 1.0) \times 10^{-4}$
III	$\frac{d\sigma}{dx} = \text{const.}$	$(1.25 \pm 0.40) \times 10^{-4}$

Table 3

Model	$\bar{D}$	Λ_c^+	e^-/π^-
I	$\frac{d\sigma}{dx} \propto (1-x)^3$	$\frac{d\sigma}{dx} \propto (1-x)^3$	$(6.5 \pm 2.6) \times 10^{-3}$
II	$\frac{d\sigma}{dy} = \text{const.}$	$\frac{d\sigma}{dy} = \text{const.}$	$(9.5 \pm 3.8) \times 10^{-4}$
III	$\frac{d\sigma}{dx} = \text{const.}$	$\frac{d\sigma}{dx} = \text{const.}$	$(8.8 \pm 3.5) \times 10^{-4}$
I-III	$\frac{d\sigma}{dx} \propto (1-x)^3$	$\frac{d\sigma}{dx} = \text{const.}$	$(2.5 \pm 1.0) \times 10^{-4}$

Figure captions

Fig. 1 : Top view of the SFM detector, showing the MWPCs and the external apparatus for particle identification:

- i) C_i ($i = 0,5$) are gas threshold Cerenkov counters;
- ii) SW_i ($i = 2,5$) are lead/scintillator sandwiches;
- iii) LG_i ($i = 3,4$) are lead-glass arrays;
- iv) TOF is the time-of-flight system.

Fig. 2 : Mass distribution of $K^-p\pi^+$ combinations selected as described in the text:

- a) trigger particle = e^- ;
- b) trigger particle = e^+ .

Fig. 3 : The $K^-p\pi^+$ invariant mass distribution for e^- triggered events when, relative to the particles in the hemisphere opposite to that of the detected proton,

- i) no conditions are required ($\square$);
- ii) the condition $\sum_{i=1}^n x_{opp}^i \geq 0.5$ or $\sum_{i=1}^n x_{opp}^i \leq 0.1$ is requested (hatched).

The lines are the fit to the background, i.e. the same mass spectra for e^+ triggered events.

Fig. 4 : Experimental distribution of the transverse momentum of the electrons from the $\bar{D}$ decay. The dashed line represents the expected p_T distribution for electrons from $\bar{D}$ decay using model I-III. The relative fractions of three- and four-body decays of the $\bar{D}$ have been taken from Ref. 11.

Fig. 5 : The Λ_c^+ charmed baryon production cross-sections as measured by various ISR experiments. The dotted lines are unpublished results. Notice that ref. [5b] is a recent, unpublished, updated reanalysis of the measurement published in ref. [4].

The circles are the measurements obtained triggering on the hadronic decay of the Λ_c^+ . The squares are the experiments where the trigger

was the electron from the semileptonic decay of the associated anti-charmed particle. The data are all relative to the following model: $d\sigma/dx = \text{const.}$ for the Λ_c^+ , plus, for the case where the electron was detected, $d\sigma/dx \propto (1 - x)^3$ for the $\bar{D}$. The curves are the theoretical predictions according to the models specified in the text.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5