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MEASUREMENT OF ASSOCIATED PRODUCTION OF
 $(D^0\bar{D})$ IN (pp) INTERACTIONS AT $\sqrt{s} = 62$ GeV

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SUMMARY

The associated production of charm-meson pairs ($D^0\bar{D}$) has been studied in (pp) interactions at $\sqrt{s} = 62$ GeV. Total cross-section estimates are given for different hypotheses on the production distributions. The lowest cross-section estimate corresponds to a "central" production model, for both the D^0 and the $\bar{D}$.

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1. INTRODUCTION

The purpose of the present paper is to report evidence for the associated production of "open charm" mesons in (pp) interactions at $\sqrt{s} = 62$ GeV and to give cross-section estimates.

The reaction studied was

$$pp \rightarrow \bar{D} + D^0 + \text{anything} , \quad (1)$$

with the D^0 observed in the decay mode

$$D^0 \rightarrow K^- \pi^+ \quad (2)$$

and the associated $\bar{D}$ meson, used as a "trigger", via the decay mode

$$\bar{D} \rightarrow e^- + K^+ + \text{anything} . \quad (3)$$

So far, the production of $D^0 \bar{D}$ pairs has been observed in π , ν , or γ beam experiments¹⁾ at lower energy.

2. EXPERIMENTAL SET-UP

The experimental apparatus was a large-volume magnetic field, the Split Field Magnet (SFM) at the CERN Intersecting Storage Rings (ISR), with its powerful system of multiwire proportional chambers (MWPCs) to allow track reconstruction and momentum measurement. A hodoscope of time-of-flight counters (TOF)²⁾ was also used, providing particle identification up to about 2 GeV/c momentum. In addition, a system of electromagnetic shower detectors (EMSDs)³⁾, gas threshold Čerenkov counters, and a "dE/dx" chamber⁴⁾ (a small MWPC with analog read-out placed very close to the interaction region) was used for electron/positron detection at 90°.

A schematic view of the set-up is shown in Fig. 1. Details of detector performances and data-taking conditions have already been reported elsewhere⁵⁻⁹⁾.

The key points of the experiment were:

- i) the detection of a single electron, e^- , or of a single positron, e^+ (via EMSD, Čerenkov, and "dE/dx");
- ii) the identification of a negative or a positive K meson (via TOF);
- iii) the momentum measurement of all charged tracks, no matter whether they are identified as "e" or "K".

3. DATA ANALYSIS

The logic of the experiment, in order to study reaction (1), was as follows.

The $\bar{D}$ meson could be either a negatively charged D^- or a neutral $\bar{D}^0$. However, its decay mode had to follow the pattern illustrated below, in terms of antiquark transition states:

In terms of physical particles, reaction (4) produces the final state of reaction (3), i.e. an e^- and a K^+ . These particles were used as a "trigger". This means that the semileptonic decay mode of the $\bar{D}$ state was taken as a "signature" for the production of an anticharm particle.

The identification of the e^- was done via the study of the energy release in the EMSDs, of the Čerenkov counters' response, and of the pulse height in the "dE/dx" chamber⁵⁻⁹). Furthermore, the reconstructed e^- track was required to have a transverse momentum $p_T \geq 0.5$ GeV/c and a momentum uncertainty $\Delta p/p \leq 15\%$. The residual charged hadron contamination in the e^- sample was $\sim 2\%$, whilst the background from neutral hadron conversion amounted to $\leq 50\%$.

The K^+ identification was done by the TOF system with better than 90% C.L.²). The momentum cuts were: $p < 1.5$ GeV/c and $\Delta p/p \leq 30\%$. The π^+ and proton contamination in the K^+ sample was about 10%.

The charmed meson D^0 was searched for via its decay mode (2). For this purpose, the $(K^-\pi^+)$ invariant mass was studied, where the K^- was any negative track not identified by TOF as an $\bar{p}$ or a π^- , and the π^+ was any positive track not identified by TOF as a p or a K^+ . In addition, the π^+ had to satisfy the condition $|x_L| < 0.3$ (where $x_L = 2p_L/\sqrt{s}$), since above this value the "leading" proton contamination was not negligible¹⁰).

In order to enter the $(K^-\pi^+)$ mass plot, a track had to have a momentum error $\Delta p/p \leq 30\%$.

Finally, all e^- , K^+ , K^- , and π^+ tracks were required to fit the event vertex within ± 5 cm.

4. RESULTS

4.1 The mass spectrum

We have studied the $(K^-\pi^+)$ mass spectrum in two ways.

The first is shown in Fig. 2, where the D^0 enhancement is present with (47 ± 13) mass combinations and about 4 standard deviations significance. This result is obtained by means of the $(e^-K_{TOF}^+)$ trigger described above, without any further condition on the $(K^-\pi^+)$ system.

The second way is illustrated in Fig. 3, where a transverse momentum cut is applied to the $(K^-\pi^+)$ system, i.e. $p_T(K^-\pi^+) \geq 0.7$ GeV/c. The number of combinations is reduced to (34 ± 7) . However, the statistical significance increases: it is now at the 5 standard deviations level.

The D^0 is observed in the mass interval

$$(1.825 \leq m_{D^0} < 1.975) \text{ GeV}/c^2 ,$$

and its width is compatible with the expected mass resolution. The events/combinations ratio in the D^0 peak is $\sim 75\%$.

The background shape in Figs. 2 and 3 is obtained using the "event mixing" technique: take an $(e^-K_{TOF}^+)$ triggered event and combine the K^- from this event with the π^+ from the next one. The background shape follows quite well the natural background of the $(K^-\pi^+)$ mass spectrum.

Now comes a crucial test to check the validity of our starting hypothesis: Is the $(e^-K_{TOF}^+)$ trigger the signature of an anticharm semileptonic decay? In order to verify this point, we have studied the $(K^-\pi^+)$ mass plot using data with the following triggers:

$$\text{i) } e^-K_{TOF}^- ; \quad \text{ii) } e^+K_{TOF}^+ ; \quad \text{iii) } e^+K_{TOF}^- .$$

Trigger (i) has the "correct" e^- but the "wrong" K_{TOF}^- ; trigger (ii) has the "correct" K_{TOF}^+ but the "wrong" e^+ ; and trigger (iii) has both the e^+ and the K_{TOF}^- "wrong". The results are shown in Figs. 4a, 4b, and 4c, where there is clearly no evidence for any effect in the $(K^-\pi^+)$ invariant mass spectrum. Figure 4d is the sum of all the triggers.

4.2 Cross-section estimates

In order to evaluate the production cross-section for reaction (1), the following quantities are needed:

- a) the branching ratio

$$B(\bar{D} \rightarrow e^- K^+ + \text{anything}) = \frac{\bar{D} \rightarrow e^- K^+ + \text{anything}}{\bar{D} \rightarrow \text{all}} ; \quad (5)$$

- b) the branching ratio

$$B(D^0 \rightarrow K^-\pi^+) = \frac{D^0 \rightarrow K^-\pi^+}{D^0 \rightarrow \text{all}} ; \quad (6)$$

- c) the production distributions for the D^0 and the $\bar{D}$;
d) the acceptances and the efficiencies of the experimental apparatus;
e) the total luminosity.

The branching ratios are known, although with large uncertainties. In order to derive the semileptonic decay of the $\bar{D}(= \frac{1}{2}\bar{D}^0 + \frac{1}{2}\bar{D}^-)$, we have taken^{11,12}:

$$\begin{aligned} \text{i)} \quad & \frac{\bar{D} \rightarrow e^- + \text{anything}}{\bar{D} \rightarrow \text{all}} = (8.5 \pm 1.5)\% ; \\ \text{ii)} \quad & \frac{\bar{D} \rightarrow K e^- \bar{\nu}}{\bar{D} \rightarrow e^- + \text{anything}} = (60 \pm 15)\% \text{ (where } K = \frac{1}{2}K^0 + \frac{1}{2}K^+ \text{)} ; \\ \text{iii)} \quad & \frac{\bar{D} \rightarrow K^* e^- \bar{\nu}}{\bar{D} \rightarrow e^- + \text{anything}} = (40 \pm 15)\% \\ & \left(\text{with } K^* = \frac{1}{2}K^{*0} + \frac{1}{2}K^{*+} , \quad \frac{K^{*0} \rightarrow K^+\pi^-}{K^{*0} \rightarrow \text{all}} = \frac{2}{3} , \quad \text{and } \frac{K^{*+} \rightarrow K^+\pi^0}{K^{*+} \rightarrow \text{all}} = \frac{1}{3} \right) . \end{aligned}$$

The above values produce for the branching ratio (5), the result:

$$B(\bar{D} \rightarrow e^- K^+ + \text{anything}) = (4.3 \pm 1.2)\% .$$

For the D^0 decay, the branching ratio (6) is¹³)

$$B(D^0 \rightarrow K^-\pi^+) = (3.0 \pm 0.6)\% .$$

The inclusive charm production cross-section was assumed to follow the law:

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

where $b^{-1} = 0.5 \text{ GeV}/c$, and the function $f(y/y_{\max})$ gives the longitudinal momentum dependence. For this, the following three cases were considered*):

$$\text{model I ("central" production): } E \frac{d\sigma}{d|x_L|} \propto (1 - |x_L|)^3 ;$$

$$\text{model II ("flat-y" production): } \frac{d\sigma}{d|y|} = \text{const} ;$$

$$\text{model III ("flat-}x_L\text{" production): } \frac{d\sigma}{d|x_L|} = \text{const.}$$

A $K_{\ell 3}$ -like matrix was used to simulate the $\bar{D}$ decay (3).

The cross-section for associated $D^0\bar{D}$ production was then computed for different combinations of D^0 and $\bar{D}$ models, with the further assumption that the two mesons were produced in an uncorrelated way. More precisely, the production cross-sections were estimated in the following five hypotheses:

- 1) both D^0 and $\bar{D}$ are produced in a "central" way;
- 2) both D^0 and $\bar{D}$ are produced "flat" in the rapidity variable y ;
- 3) both D^0 and $\bar{D}$ are produced "flat" in the longitudinal fractional momentum variable x_L ;
- 4) the D^0 is produced "flat" in x_L , whilst the $\bar{D}$ is produced in a "central" way;
- 5) the D^0 is produced "centrally", whilst the $\bar{D}$ is produced "flat" in x_L .

The efficiencies for e^- and K_{TOF}^+ detection, $\sim 45\%$ and $\sim 70\%$ respectively, and the acceptances of the apparatus corresponding to the various production mechanisms listed above, were calculated by Monte Carlo simulation.

The total integrated luminosity, relative to an initial sample of about 1.5×10^6 collected events, was $4.4 \times 10^{36} \text{ cm}^{-2}$.

Table 1 contains the cross-section estimates for $D^0\bar{D}$ pair production. The overall uncertainty is $\sim 50\%$.

*) $x_L = 2p_L/\sqrt{s}$ and $y = \frac{1}{2}\ln [(E + p_L)/(E - p_L)]$.

5. CONCLUSION

We have observed the pair production of D^0 and $\bar{D}$ charmed mesons. The D^0 was detected via the hadronic decay mode ($K^-\pi^+$); the associated anticharm meson, $\bar{D}^0$ or D^- , was identified via its semileptonic decay into an e^- and a K^+ .

Even though the total cross-section estimates are affected by large errors, the case where both the D^0 and the $\bar{D}$ are produced "centrally" provides the lowest cross-section value. This, even if higher, is the closest to present theoretical predictions¹⁴⁾. However, as previously observed for the $\Lambda_c^+\bar{D}$ associated production study⁵⁾, charm cross-sections, as measured at the ISR, tend to be larger than any theoretical expectation.

The hypothesis of a "central" charm meson production is supported by the experimental x_L distribution of the D^0 , measured in the same experiment. This will be reported elsewhere¹⁵⁾.

Our present results on $D^0\bar{D}$ pair production are further evidence for associated charm production at the ISR and provide a deeper knowledge of this phenomenon in high-energy proton-proton interactions.

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Table 1

Production cross-sections for $D^0\bar{D}$ in (pp) interactions
at $\sqrt{s} = 62$ GeV versus different models

	D^0 production distribution	$\bar{D}$ production distribution	σ_{tot} (μb)
1	$E \frac{d\sigma}{d x_L } \propto (1 - x_L)^3$ (I)	$E \frac{d\sigma}{d x_L } \propto (1 - x_L)^3$ (I)	575
2	$\frac{d\sigma}{d y } = \text{const.}$ (II)	$\frac{d\sigma}{d y } = \text{const.}$ (II)	1290
3	$\frac{d\sigma}{d x_L } = \text{const.}$ (III)	$\frac{d\sigma}{d x_L } = \text{const.}$ (III)	> 5000
4	$\frac{d\sigma}{d x_L } = \text{const.}$ (III)	$E \frac{d\sigma}{d x_L } \propto (1 - x_L)^3$ (I)	1000
5	$E \frac{d\sigma}{d x_L } \propto (1 - x_L)^3$ (I)	$\frac{d\sigma}{d x_L } = \text{const.}$ (III)	3610

Figure captions

Fig. 1 : Top view of the apparatus showing the SFM and the MWPC system; the Čerenkov counters (C0 to C5); the electromagnetic shower detectors (EMSDs) (lead-glass array: LG3 and LG4; and lead/scintillator sandwich: SW2 to SW5); the time-of-flight counters hodoscopes (TOF) and the "dE/dx" chamber (numbered as 209).

Fig. 2 : $(K^-\pi^+)$ invariant mass spectrum obtained with $(e^-K_{TOF}^+)$ trigger. The circles and the dashed-line curve superimposed show the "event mixing" background spectrum and fit, respectively.

Fig. 3 : Same as Fig. 2 with the further high- p_T requirement:

$$p_T(K^-\pi^+) \geq 0.7 \text{ GeV/c} .$$

Fig. 4a-d: $(K^-\pi^+)$ mass spectra obtained when $p_T(K^-\pi^+) \geq 0.7 \text{ GeV/c}$ with the following triggers: 4a) $(e^-K_{TOF}^-)$; 4b) $(e^+K_{TOF}^+)$; 4c) $(e^+K_{TOF}^-)$. Figure 4d is the sum of all triggers. The dashed-line curves are fits to these spectra.

Fig. 2

Fig. 3

Fig. 4 a)

Fig. 4 b)

Fig. 4 c)

Fig. 4 d)