CHARM D-MESON PRODUCTION IN 360 GeV π^- p INTERACTIONS;EVIDENCE FOR LEADING QUARKS

LEBC EHS Collaboration

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ABSTRACT

Charm D-meson production in 360 GeV π^-p interactions has been studied using the high resolution hydrogen bubble chamber LEBC and the European Hybrid Spectrometer. The data show evidence for leading quark effects both in the number of D-meson types and in the Feynman x distributions. The production cross section is of the form

$$d^2\sigma/dx dp_T^2 \propto (1-x)^n \exp(-ap_T^2)$$

with $n = 2.8 \pm 0.8$ and $a = 1.1 \pm 0.3 \text{ (GeV/c)}^{-2}$. The x distribution is, however, compatible with the presence of both central ($n = 6$) and leading ($n = 1$) $D/\bar{D}$ production. The fraction of D-mesons in the leading component is estimated to be $\sim 30\%$. The rapidity gap between members of reconstructed charm pairs is small compared to the available rapidity range. The inclusive cross section for single D-mesons in the forward direction is

$$\sigma(D/\bar{D}) = 40^{+15}_{-8} \text{ } \mu\text{b (for } x > 0\text{)}.$$

The high resolution hydrogen bubble chamber, LEBC, has been used to detect directly the decay vertices of charm particles produced in negative pion and proton interactions at 360 GeV/c. In this letter the production of D-mesons in π^-p interactions is analyzed in terms of the Feynman variable x and transverse momentum p_T . In the data taking, a minimum bias interaction trigger was used. A study of the multiplicity distribution of all inelastic events showed that some trigger losses occurred in the simple topologies (2, 4 and 6 prong final states), however, because of the high charged particle multiplicities from a pair of charm particle decays and the high transverse momenta involved in addition to the charged particle multiplicity at production, these trigger losses are unimportant.

The direct observation of the production and decay vertices removes, to a large extent, the combinatorial problem in the reconstruction of charm decays in complex hadronic events; in addition it provides an important geometrical constraint to be satisfied by the correct decay interpretation. Details of the bubble chamber LEBC have been published elsewhere [1]. A typical event showing the production and decay of a $D^0\bar{D}^0$ pair is shown in ref. [2].

The charged and neutral decay products were analysed downstream of LEBC using a preliminary version of the European Hybrid Spectrometer [3]. The essential features of the LEBC-EHS arrangement are as follows:

- The geometrical acceptance, as a function of the Feynman x of the D-mesons produced in LEBC, is shown in fig. 1. Fig. 1(a) applies to decays involving only charged particles in the final state and fig. 1(b) to decays with a single reconstructed π^0 . In both cases we require a kinematic fit of 3 or 2 constraints: either all decay products completely measured (3C) or only one charged particle momentum lost (2C). Note that 1C and 0C fits are usually not used for D-meson cross section calculations because they are often ambiguous between charm interpretations. The spectrometer acceptance in the forward direction is high and approximately independent of x .
- Charged particle momenta are measured to $\lesssim 1\%$ with angle errors ~ 0.1 mr. The gamma detectors provide reconstructed π^0 momenta to $\lesssim 2\%$. The

effective mass resolution, checked using strange particle decays visible in the bubble chamber and reconstructed using the spectrometer information is $\sim 2.6 \text{ MeV}/c^2$ for $K^0 \rightarrow \pi^+ \pi^-$ decays and $\sim 1.1 \text{ MeV}/c^2$ for $\Lambda^0 \rightarrow p \pi^-$ decays. The resolution on the reconstructed D-meson mass is in the range $10\text{--}20 \text{ MeV}/c^2$ depending on decay mode.

- Charged particle identification is not available except via the gamma detectors, which can be used to identify electrons, and crude ionization measurements from the ISIS 1 pictorial drift chamber, which occasionally provides useful supporting evidence to kinematic fits. The general absence of particle identification results in ambiguities in the interpretation of the charm decays.

In the cases where ambiguous kinematic fits exist, we have applied the following simple rules:

- We prefer Cabibbo favoured over Cabibbo unfavoured solutions.
- We prefer Cabibbo favoured D solutions to F or Λ_c solutions.

To calculate relevant production distributions, each decay is assigned a weight corresponding to the probability for detection. The overall weight is made up from two factors: (a) the spectrometer acceptance weight derived from the curves shown in fig. 1 and (b) a scanning weight representing the probability that the event be detected at the scanning stage on the bubble chamber film. This procedure is described in more detail in the paper on the evaluation of lifetimes [4]. The scanning weight is evaluated for each event and automatically takes account of the visibility problems associated with the complexity at production in a given event. It should, however, be noted that the scanning weight depends mainly on transverse geometrical parameters and therefore is, to a good approximation, independent of x .

For the 0 and $1 \pi^0$ events used in the following analysis the average weights are not large (~ 1.7 for all charged modes and ~ 3.0 for $1 \pi^0$ modes) and the features relevant to the production mechanism analysis are already apparent in the unweighted data.

The sensitivity of the pion exposure reported here was 7.8 events/ μb based on 350,000 pictures containing 117,277 interactions. We have 27 examples of D-meson decays and one decay best interpreted as $F^+ \rightarrow \eta\pi^+$. Fourteen of the D-mesons come from fully reconstructed pairs and a further eight come from topological pairs in which the other decay cannot be reconstructed because too many decay particles are outside of the spectrometer acceptance.

The mean primary charged multiplicity for observed events containing charm is 8.8 ± 0.9 ; the mean multiplicity for all inelastic events at this energy [5] being 8.7.

Cross sections have been evaluated from the weighted number of $D/\bar{D}$ decays and the known branching ratios. The branching ratios have been measured [6] for $D^\pm \rightarrow K^\mp \pi^\pm \pi^\pm$ ($4.6 \pm 1.1\%$), $D^0/\bar{D}^0 \rightarrow K^\pm \pi^\mp \pi^0$ ($9.3 \pm 2.8\%$), $D^0/\bar{D}^0 \rightarrow K^\mp \pi^\pm \pi^+ \pi^-$ ($4.5 \pm 1.3\%$) and $D^0/\bar{D}^0 \rightarrow K^\mp \pi^\pm$ ($2.4 \pm 0.4\%$). The acceptance cut at $x \sim 0$ (fig. 1) is such that we only quote cross sections for x positive. The inclusive single charm cross section for $x > 0$ is found to be

$$\sigma(D/\bar{D}) = 40^{+15}_{-8} \mu\text{b} \quad (13 \text{ decays})$$

The individual cross sections are: $\sigma(D^-) = 24^{+16}_{-7} \mu\text{b}$ (5 decays), $\sigma(D^0) = 5^{+5}_{-2} \mu\text{b}$ (3 decays), $\sigma(\bar{D}^0) = 7^{+5}_{-2} \mu\text{b}$ (4 decays). For the D^+ we have no event in any channel with known branching ratio but one event is observed in the $K^- \pi^+ \pi^+ \pi^0$ channel. From the total sample of D^+ from both this and the proton exposure we can derive a branching ratio for this mode:

$$\frac{D^+ \rightarrow K^- \pi^+ \pi^+ \pi^0}{D^+ \rightarrow \text{all}} = (0.57^{+.65}_{-.17}) \times \frac{D^+ \rightarrow K^- \pi^+ \pi^+}{D^+ \rightarrow \text{all}} = 2.6^{+3}_{-1}\%$$

This can be used to estimate the D^+ cross section: $\sigma(D^+) = 4^{+8}_{-1} \mu\text{b}$.

The numbers of reconstructed decays summed over all decay modes are $9D^-$, $2D^+$, $8D^0$ and $5\bar{D}^0$. One event is ambiguous $D^-/\bar{D}^+$ and two are ambiguous $D^0/\bar{D}^0$. Care has to be taken in assigning the correct quark content at production corresponding to the observed particles because of the D^* decays. We observe 5 events in the D^* signal above a negligible background

($\lesssim 1$ event). Three of these D^{*-} 's decay to $D\pi^0$ and therefore the charge and hence quark content of the produced charm is not changed. We observe one example of $D^{*-} \rightarrow \bar{D}^0 \pi^-$ and this decay $\bar{D}^0$ is considered in the following discussion as an example of $(\bar{c}d)$ production.

The cross sections can be grouped according to whether the D 's contain one of the quarks of the incident $\pi^-(\bar{u}d)$ or not, i.e. (D^0, D^-, D^{*-}) or ($D^+, \bar{D}^0$). We obtain

$$\sigma(c\bar{u}/\bar{c}d) = 31^{+14}_{-7} \text{ } \mu\text{b} \quad (9 \text{ decays})$$

$$\sigma(c\bar{d}/\bar{c}u) = 9^{+7}_{-3} \text{ } \mu\text{b} \quad (4 \text{ decays})$$

This result is reflected in the observation of 18 leading states to 6 non-leading states. Although the statistics are small the data clearly suggest the presence of a leading particle effect.

In fig. 2 the weighted and unweighted Feynman $x(= 2p_L^*/\sqrt{s})$ distribution for $x > 0$ is shown for the potentially leading quark states (fig. 2(a)) and non-leading states (fig. 2(b)). The unweighted events are shown as crosses on these distributions. The leading states have a tail extending to high x whilst the non-leading states are centrally produced. Fig. 2(c) shows a weighted integral plot for all states. In this plot the abscissa is logarithmic in $(1 - x)$ and a differential distribution of the form $(1 - x)^n$ will yield a line having slope $(n + 1)$. A maximum likelihood fit to all events for a single slope gives a value of $n = 2.8 \pm 0.8$. In all likelihood fits the error corresponds to a change in the normalized log likelihood function of 0.5.

The data show evidence that two components might be present with different values of n . A likelihood fit with two exponents yields a "central" component with $n = 6 \pm 3$, accounting for $70 \pm 30\%$ of the events, and a "leading" component with $n = 1 \pm 1$. Separating the events according to their quark content we find that the leading component is associated only with D 's containing a π^- valence quark (see figs 2(a) and (b)).

Single D^- or $\bar{D}^0$ could, in principle, be accounted for by $\Lambda_c \bar{D}$ production. Interpreted thus, we would obtain an estimate of Λ_c production

cross section in association with a forward $\bar{D}$ of $\sim 20 \mu\text{b}$. However, Λ_c^+ production cannot easily account for the observation of D^- mesons at large x ; this effect can be understood in terms of a leading d quark from the π^- .

Fig. 3 shows the integral distribution in transverse momentum squared of all the D events. The weight due to the spectrometer acceptance does not depend in any significant way on the value of p_T and therefore only the visibility weight has been used. The distribution is well represented by the form

$$\frac{d\sigma}{dp_T^2} \propto \exp(-ap_T^2)$$

with $a = 1.1 \pm 0.3 (\text{GeV}/c)^{-2}$ and with no significant difference between leading and non-leading states.

In fig. 4 the centre of mass rapidities of charm particles from reconstructed $D\bar{D}$ states are shown. A strong correlation exists with a mean rapidity gap of $\langle \Delta y^* \rangle = 0.5 \pm 0.1$ for events in which both members of a pair are reconstructed. It is difficult to quote a mean gap for all pairs because the spectrometer acceptance is such that a pair can only be reconstructed if both members are in the forward direction. The value 0.5 is therefore a lower estimate for $\langle \Delta y^* \rangle$. It is interesting to note that R.J.N. Phillips [8] predicts a mean gap in the range 0.8-0.9 for $c\bar{c}$ pairs produced in the parton processes $q\bar{q} \rightarrow c\bar{c}$ and $gg \rightarrow c\bar{c}$ with $m_c = 1.2-1.5 \text{ GeV}$.

In summary, therefore, we observe the following features of D -meson production in $360 \text{ GeV}/c \pi^- p$ interactions:

- An inclusive single $D/\bar{D}$ cross section for $x > 0$

$$\sigma(D/\bar{D}) = 40^{+15}_{-8} \mu\text{b}$$

- A production cross section of the form

$$\frac{d^2\sigma}{dx dp_T^2} \propto (1-x)^n \exp(-ap_T^2)$$

with $n = 2.8 \pm 0.8$ and $a = 1.1 \pm 0.3 \text{ (GeV/c)}^{-2}$ for a fit to a single value of n . This value of n is different from the value of $n = 5$ expected for central production of $D\bar{D}$ pairs or from $n = 1$ expected for leading production.

- A fit with two components gives exponents $n = 6 \pm 3$ and $n = 1 \pm 1$ consistent with a mixture of central and leading production. The fraction of the leading component is $\sim 30\%$ and it contains D^- , D^{*-} and D^0 mesons. The D^+ and $\bar{D}^0$ are centrally produced. This is given as evidence for the production of D-mesons containing leading π^- valence quarks.
- A strong correlation in rapidity is observed between members of reconstructed $D\bar{D}$ pairs.

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REFERENCES

- [1] J.L. Benichou et al., Nucl. Instr. & meth. 190 (1981) 48.
- [2] B. Adeva et al., Phys. Lett. 102B (1981) 285.
- [3] M. Aguilar-Benitez et al., The European Hybrid Spectrometer, CERN/EP 82-75, to appear in Nucl. Instr. & Meth.
- [4] LEBC-EHS Collaboration, Lifetime measurement of charm mesons produced in π^-p and pp interactions at 360 GeV/c, submitted to Phys. Lett.
- [5] A. Firestone et al., Phys. Rev. D14 (1976) 2902.
- [6] Review of Particle Properties, Phys. Lett. 111B (1982).
- [7] F. Halzen, Production of heavy quarks, Rapporteur's Talk, XXI Int. Conf. on High Energy Physics, Paris (1982).
- [8] R.J.N. Phillips, Leading particles in charm production around 350 GeV, Proc. Moriond Workshop on New Flavours (1982) 467, Ed. by J. Tran Than Van and L. Montanet.

FIGURE CAPTIONS

- Fig. 1 The geometrical acceptance as a function of Feynman
 $x (= 2p_L^*/\sqrt{s})$.
- Fig. 2 The weighted and unweighted (crosses) distribution of x for (a)
 D^{*-} , D^- , D^0 , (b) D^+ , $\bar{D}^0$, (c) integral, weighted distribution
 for all events.
- Fig. 3 The integral, weighted distribution of transverse momentum
 squared.
- Fig. 4 The centre of mass rapidities of D-mesons for (a) pairs, (b)
 singles.

Fig 1

Fig. 2

Fig. 2(c)

Fig. 3

Fig. 4