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DIRECT EVIDENCE FOR ASSOCIATED CHARM PRODUCTION
IN 340 GeV π^-p INTERACTIONS

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ABSTRACT

In a 2.5 events/ μb exposure of a small 20 cm diameter, rapid cycling hydrogen bubble chamber equipped with high resolution optics, clear evidence is observed for the first time of the associated production of charmed particles, identified by their short decays. A significant excess of 12 events which we interpret as charm pairs corresponding to a total cross section of $\sim 40 \mu\text{b}$ is seen above the expected strange particle background. In addition, 8 charged 3-prong events consistent with $D^\pm$ decay are observed with an expected background of ~ 2 events.

Indirect evidence [1,2] indicates that hadronic charm production cross sections at SPS energies are in the region of 10-40 μb . The cross sections derived from the excess of ν events observed in the beam dump experiments are sensitive to both the assumed dependence of the cross section on atomic number A and the production distributions in Feynman x_F and transverse momentum p_t . It is of considerable interest to detect charmed particles produced in hydrogen by observing their decay and to study the dependence of both the cross section and the production distributions on the centre of mass energy $\sqrt{s}$ and the quark structure of the beam particles i.e. differences between π , K , p , $\bar{p}$, γ etc. Existing experimental measurements and limits of charmed particles lifetimes [3-6] give values in the 10^{-12} to 10^{-13} s range with recent data [4] supporting a significant difference in the measured lifetimes of neutral and charged D mesons.

For the purpose of directly detecting charmed particles and studying their production and decay properties, the high resolution hydrogen bubble chamber LEBC has been constructed. We report here the first attempt to use LEBC to search for topological evidence for charmed particles produced in 340 GeV π^-p interactions. The experiment was performed in a 10 day run in the North Area of the CERN SPS.

The chamber is described in detail in ref. [7]. LEBC is a "clean" cylindrical chamber constructed of Lexan, a material used successfully in the fabrication of the large volume track sensitive target for BEBC. The chamber is about one litre in volume, 20 cm diameter, 4 cm deep and has been operated for data taking at 40 Hz. The axis is horizontal, and perpendicular to the beam. There is no magnetic field. Tracks are photographed in bright field through a 25 mm Lexan window using a Schneider Componon S lens, 240 mm focal length at F/16, to give a limit on the resolution of $\sim 30 \mu\text{m}$ and a depth of field $\sim 5 \text{ mm}$. The demagnification from space to film was 2.14. The chamber was operated in a slow spill beam, with 1.2 s flat top, focused to give an $\sim 2 \text{ mm}$ horizontal image spread over 8 cm in height at the chamber. An interaction trigger was used to select events occurring within a sensitive gate of 1 ms around the pressure minimum and to start the timing of the bubble growth. The

trigger consisted of five scintillators, the smallest being $2 \text{ mm} \times 10 \text{ cm}$ to contain the focused beam and to ensure that triggered events fall within the depth of field of the high resolution optics. The flash delay was $200 \text{ } \mu\text{s}$, which, under the chamber operating conditions used, (temp. 28.7°K , static pressure 7.4 bar , $\Delta p \sim 4.1 \text{ bar}$) gave resolved bubbles of $40\text{--}50 \text{ } \mu\text{m}$ diameter. A typical picture has a number of early tracks with large bubble diameter and low bubble density together with the triggered event which has small bubbles and high ($\sim 70/\text{cm}$) bubble density. Approximately 50% of the pictures have a correctly timed event in hydrogen. The remaining triggers can be accounted for by interactions in the entrance and exit windows of the chamber. The run occurred in June/July 1979 and a total of 110 000 pictures containing 48 000 events, corresponding to a sensitivity of $2.5 \text{ events}/\mu\text{b}$, were taken with the chamber making 1.3×10^6 expansions. We report now on the results of scanning these events for topological evidence of charmed particle production.

The pictures were scanned for all in-time interactions, i.e. events photographed with bubbles in the $40\text{--}50 \text{ } \mu\text{m}$ range. On finding an event, the whole chamber was searched for secondary processes associated with the primary interaction. From a double scan of 70% of the film, the single scan efficiency for secondary processes was determined to be $\sim 90\%$.

The use of hydrogen as a chamber liquid is extremely important, not only because of the intrinsic physics interest in studying charm production off a single nucleon, but also for reasons of background rejection. The principal sources of background to the topological charm signal are the following:

- (a) Secondary interactions. In hydrogen, secondary interactions can in principle be completely removed by counting prongs. The residual contamination arising from the small probability of a prong being invisible in the single view available is small ($\sim 5\%$) and included in our background estimation.

- (b) Gamma conversions. The chance of having two gamma conversions within the charm search zone defined below is $\sim 10^{-4}$, corresponding to an effective cross section $\sim 2-3 \mu\text{b}$. This contamination is completely removed by requiring that any candidate for charm should have a non-zero opening angle.
- (c) Strange particles. This is the main source of background and is removed statistically as discussed later.

Selection of charm candidates. A charmed particle living for 10^{-12} s produced with $x_F \approx 0.5$ in a 340 GeV $\pi^- p$ interaction has decay length $L \sim 3$ cm. However, as discussed in ref. [8], the problem of detecting charm decays in complex final states is not related to the decay length L as such, but to the transverse decay lengths x and y indicated in fig 1(a). The quantity x determines whether the decay vertex can be seen outside the forward cone of particles and the quantity y determines whether the decay can be detected from the fact that the decay products do not point back to production vertex. The quantity x is related to $p_\perp$, the projected transverse momentum of the produced particle of mass m , and the time-of-flight, t : $x = p_\perp / m$ tc. For $p_\perp < m$, $t < 2\tau$ and $\tau = 10^{-12}$ s, $x < 0.06$ cm. We therefore expect that the decay vertices of long-lived D mesons will be within $\sim 600 \mu\text{m}$ of the forward direction even though the decay length may be several centimetres. A lifetime of 10^{-13} s would yield decay vertices within $\sim 60 \mu\text{m}$ of the forward direction with decay lengths of several millimetres.

The quantity y is related to the transverse momentum of the decay product with respect to the charmed particle line of flight. Because of the number of multiparticle decay modes and large branching ratios to leptonic decays, it is not possible to put a simple cut on y . However, y is very important, since the existence of a non-pointing track is often how the events are detected during scanning. A Monte-Carlo study of the distribution in y was made as a function of lifetime and used to estimate the detection efficiency and hence the production cross sections reported below.

We have defined a region which would contain charm decays as $L \leq 3$ cm; $x(= L \sin \theta_p) < 0.06$ cm. To identify the charm signal, we have selected:

- (a) Events having a pair of decay candidates within the charm region;
- (b) 3-prong decays, whether as part of a pair or as an apparent single decay.

Decays are classified in the following ways:

- (a) Clear charged or neutral particle decays in which the decay vertex is seen and the number n of decay prongs can be counted - labelled C_n , V_n , where n is odd for C and even for V ;
- (b) Decays not clearly resolved from the forward cone but where the total number of detected prongs in the event is even. If n secondaries, all inconsistent with production at the primary vertex, emerge from an obscured decay vertex, this vertex is labelled ambiguous C_n or ambiguous V_n for n odd or even respectively.

Division of the total sample according to label C or V will give subsamples rich in charged or neutral decays.

Analysis of candidates for pair production. The background within the charm region arises mainly from strange particle decays. The number of events with two strange particle decays in the charm region is estimated by counting the number of events with a single decay in the region, assumed strange, and evaluating the correlation between singles and doubles outside the region. For uncorrelated observations, or for correlations which do not change as a function of x , the quantity N_2/N_1^2 is constant, where N_1 is the number of singles in a given bin of x and N_2 is the number of doubles having each decay within the same bin of x . This ratio is evaluated in various bins outside of the charm region and is shown to be constant. It is then used to evaluate the background to the charm signal in the pairs. We note that although this background is calculated on the over-pessimistic assumption that all single decays are due to strange particles, the number is not changed significantly if corrected *a posteriori* for the number of apparent singles due to charm. The results are shown in table 1 for different cuts in L and x .

There is a clear excess of pairs above the estimated background which appears to be independent of the cuts for $L > 2$ cm and $x > 0.06$ cm. We conclude that in the charm region (as chosen *a priori*) we see 20 events where we expect 8. This excess of 12 events is evidence for charm pair production. This interpretation is supported by the fact that a further selection of events with $y(= L \sin \theta_d) < 0.1$ cm gives 14 events with an estimated background of 3.9. A Monte-Carlo study shows that for charged D decays this cut would remove 5% of the events.

This signal seen in the charm region corresponds to an observed cross section of $4.8^{+2.2}_{-1.4}$ μb .

In table 2 we show the observed number of pairs and the computed background separately for the CC, CV and VV categories. Although this selection according to the label V or C is not unique because some events are ambiguous, it certainly enriches the sample with neutral or charged particle decays, respectively. As a consequence the background for the CC category is much smaller since the major contribution to it comes from hyperon/antihyperon decays (charged kaons are too long-lived to contribute significantly). This small background makes the CC signal the most significant; however, the limited statistics prevents us from drawing any conclusion about the relative production rate or detection efficiency between the charged and neutral components of the signal.

The detection efficiency has been estimated by generating D mesons by a Monte-Carlo method and allowing them to decay with mean charged multiplicity given by the SPEAR data [9], $n_{\text{ch}}(D^0) = n_{\text{ch}}(D^\pm) = 2.3$ and a mean total decay multiplicity of 4.2. The decay distributions follow phase space. In this way distributions in the quantity y were generated as a function of the assumed mean lifetime. A study of the scanning techniques employed showed that events were unambiguously accepted if $y \geq 100$ μm . The efficiency was thus estimated by requiring that for detection the maximum y associated with a charged secondary from a decay should exceed 100 μm .

For 3-prong events we computed also the probability that the minimum y exceeds $100 \mu\text{m}$, this being a measure of the efficiency to identify a 3-prong decay with certainty.

In the model used in the Monte-Carlo calculation the D's were generated according to:

$$(a) \quad \frac{dN}{d x_F dp_t} \propto (1 - |x_F|)^3 \exp[-2p_t];$$

$$(b) \quad \frac{dN}{d x_F dp_t} \propto (1 - |x_F|)^3 \exp[-p_t^2];$$

$$(c) \quad \text{No } x_F \text{ or } p_t \text{ dependence.}$$

However, since y is a transverse distance determined by the decay kinematics, the efficiency is a very weak function of the assumed production distribution in x_F or p_t .

The results of this calculation are shown in fig. 1(b). The efficiency to detect a single decay varies approximately linearly with lifetime between $\sim 65\%$ at 10^{-12} s and $\sim 10\%$ at 10^{-13} s.

A consequence of the approximate linear dependence of the detection efficiency on particle lifetime is that, in the presence of a mixture of particles of different mean lifetimes within the above range, the efficiency depends only on the average mean lifetime. This is true also for the detection efficiency of pairs provided that there is no correlation between the mean lifetimes of the two members of the pair. In the following all our efficiencies are estimated with this assumption.

Fig. 2 shows the cross section versus average mean lifetime derived from the pairs data. For the canonical 5×10^{-13} s we find a cross section of $\sim 40 \mu\text{b}$. For comparison the cross sections derived from the CERN beam dump experiments vary from 10 to $30 \mu\text{b}$ per nucleon [2] for 400 GeV incident protons. The interpretation of this data is discussed in [10]. The FNAL beam dump experiment [1]

yields a cross section of 22 ± 9 $\mu\text{b}/\text{nucleon}$ from a study of prompt muon production from 350 GeV p-Fe interactions. A recent experiment using a high pressure streamer chamber [11] gives an estimate of 30-50 $\mu\text{b}/\text{nucleon}$ from p-neon interactions at 350 GeV/c. The above results using incident protons all assume a linear dependence of the cross section on the atomic number A, however, if the dependence on A is in fact like the proton absorption cross section, all of these results would be revised upwards by a factor between 2 and 3.

A study of direct electrons coming from 70 GeV/c π^-p interactions [12] finds a value of 19 ± 11 μb for charm production.

Fig. 3 shows two examples of charm pair candidates. The first, fig. 3(a), is a clear example of a pair of single-prong charged decays in a 4-prong interaction. The absence of high multiplicity makes the detection simple. The second is an example of a less clear but potentially very interesting candidate. Two decay points are clearly seen, the first a single-prong decay at 1.3 mm and the second at 3.4 mm has at least four tracks emerging. The overall multiplicity of the event is even so that it is very improbable that the second vertex is an interaction. The most probable interpretation therefore, is that the second vertex is either a 4-prong neutral decay or a 5-prong charged decay. The topological D branching ratios [4] are such that we might expect at least 1 such decay in our sample. Unfortunately the absence of kinematic information prevents unique identification of any single event. A candidate for charm pair production has also been reported in a 400 GeV/c proton emulsion experiment [13].

Evidence for the detection of charm 3-prong decays. The signal for the 3-prong charged charm decays has a much reduced physical background because of the long lifetime and small branching ratios for $K_T^\pm$. All 3-prong decays were scrutinised and measured to remove topological background; the principal background being the superposition of a V^0 on a charged particle track from the origin. To remove this background, it was required that the central track of the 3-prong did not point back

to the origin, i.e. was not continuous with the candidate charm track. Table 3 gives a summary of the eight "golden" 3-prong candidates found within the $x < 0.06$ cm cut with no decay length cut. A further seven events are outside the cut. We have estimated the expected ratios of events inside, to events outside the cut for the following sources of background:

- (a) $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$, assuming that the $K^\pm$ have the same x distribution as the observed V2 events.
- (b) $\Sigma^+ \rightarrow p e^+ e^- \gamma$ decays, assuming the Σ^+ to have the same x distribution as the observed C1 events.
- (c) 4-prong secondary interactions with a lost prong, using the observed x distribution for secondary interactions.

The dependence on x is the same for all sources of background and predicts that for every event outside of the cut there will be 0.3 background events within the cut. This gives a prediction of two background events inside the charm region where we observe eight events.

We conclude therefore that there is an observed signal of $2.4_{-0.8}^{+1.6}$ μb in the charm 3-prong category corresponding to an estimate for the inclusive $D^\pm$ cross section of ~ 35 μb , assuming the detection efficiency corresponding to a mean lifetime of 10^{-12} s and a 3-prong branching ratio of 0.4 similar to that measured for $D^\pm$ decays. This is to be compared with the ~ 40 μb obtained from the doubles for the inclusive pair production cross section.

The distributions of L and $L \sin \theta_p$ for the "golden" 3-prong candidates can be used, assuming a mean lifetime for the charged decays of 10^{-12} s, to give an idea of the $\langle x_F \rangle$, $\langle p \rangle$, $\langle p_\perp \rangle$ of the sample. This yields $\langle p \rangle \simeq 50-60$ GeV/c, $\langle x_F \rangle \sim 0.1 - 0.2$, and $\langle p_\perp \rangle \simeq 1.2 - 1.4$ GeV/c. Note that some models e.g. quark fusion [14] predict a small positive $\langle x_F \rangle$ for charmed particles produced in $\pi^- p$ interactions.

Fig. 3(c) shows an example of a 3-prong candidate. A notable feature of the 3-prongs is the absence of a clean "golden" candidate as part of a pair. The pairs include several probable 3-prong decays but none satisfying the stringent criteria applied to select the "golden" sample. However, due to the reduced detection efficiency for acceptable 3-prong events we would expect one "golden" 3-prong in the pair sample.

Conclusions. From this purely topological study we can conclude the following:

- (a) There is a significant signal in events having a pair of decays. This represents experimental evidence for pair production of short-lived particles, which can be identified with charm.
- (b) The derived cross sections are shown as a function of lifetime and in comparison with other data on hadronic charm production in fig. 2. If we assume either a common lifetime of $5 \cdot 10^{-13}$ s for all contributing charm particle decays, or we assume that the two lifetimes 10^{-13} and 10^{-12} s are present with equal production cross sections, we obtain essentially the same estimate for the total charm pair cross section of $\sim 40 \mu\text{b}$.
- (c) A significant signal is seen in the charged 3-prong topology which can be interpreted as charmed particle decay. Assuming that this signal is due to $D^\pm$ production an estimate of the inclusive $D^\pm$ cross section from these events is $\sigma_{D^\pm \text{inc}} \sim 35 \mu\text{b}$ for $\tau = 10^{-12}$ s.
- (d) It is shown that it is possible to detect charmed particles directly in a fast cycling high resolution hydrogen bubble chamber. Both the chamber performance and the cross sections and lifetimes are such that the technique is applicable to charm physics. Detailed kinematic information, particle identification and photon detection are required to give a complete analysis of hadronic charm production.

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TABLE 1

Number of pairs of decays observed for different cuts in the decay length L and the transverse decay length $x = L \sin \theta_p$. The numbers in parentheses give the predicted strange particle backgrounds.

$\begin{array}{c} L \text{ (cm)} \\ x \text{ (cm)} \end{array}$	< 1.0	< 2.0	< 3.0
< 0.03	5(1.1)	9(2.0)	10(2.9)
< 0.06	9(2.6)	17(5.4)	20(8.2)
< 0.10	9(4.3)	21(9.7)	25(15.3)

TABLE 2

Number of pairs of decays observed with $L < 3$ cm and $x < 0.06$ cm divided into CC, CV and VV categories (C = charged; V = neutral decay).

Event Type	Observed pairs	Predicted background	Signal
All	20	8.2	11.8
CC	5	0.8	4.2
CV	10	4.0	6.0
VV	5	3.4	1.6

TABLE 3

Summary of the eight 3-prong candidates. n_{ch} is
the primary charged multiplicity

Length (cm)	$L\sin\theta_p$ (cm)	n_{ch}	Length (cm)	$L\sin\theta_p$ (cm)	n_{ch}
1.23	0.012	10	1.52	0.005	12
0.32	0.015	6	1.06	0.01	8
0.07	0.002	16	3.5	0.018	8
0.15	0.025	6	5.87	0.05	16

FIGURE CAPTIONS

- Fig. 1 (a) Definition of the transverse distances x and y and the production and decay angles θ_p and θ_d : $x = L\sin\theta_p$; $y = L\sin\theta_d$.
- (b) Estimated detection efficiency for D mesons as a function of mean lifetime. Curve (a) gives the efficiency for V2 and the mean of C1 and C3 decays, where it is required that, for detection, the maximum value of the projected transverse distance y exceeds $100\text{ }\mu\text{m}$. The linear approximation is also shown. Curve (b) shows the estimated detection efficiency for "golden" 3-prongs with the requirement that all 3 decay tracks have $y > 100\text{ }\mu\text{m}$ (i.e. $y_{\min} > 100\text{ }\mu\text{m}$).
- Fig. 2 The charmed particle pair cross sections derived from this experiment under the assumptions given in the text. The results of the CERN and FNAL beam dump experiments for 350 GeV/c and 400 GeV/c proton interactions derived using the assumptions given in refs [1,2] are indicated as is the limit derived from the emulsion experiment on 300 GeV/c proton interactions [3].
- Fig. 3 (a), (b) Two examples of charm pair candidates as described in the text.
- (c) An example of a 3-prong candidate.

FIG.1

FIG. 2

Fig. 3(a)

Fig. 3(b)

3-prong vertex
at 3.2 mm

Fig. 3(c)