**THE DOUBLE ASSOCIATED PRODUCTION OF CHARMED PARTICLES
BY THE INTERACTION OF 350 GeV/c π^- MESONS WITH EMULSION NUCLEI^{*)}**

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- Abstract -

Evidence is reported for the simultaneous production of four charmed particles in interactions induced by 350 GeV/c π^- mesons in stacks of nuclear emulsions. The events were found during a search for beauty particles in CERN experiment WA75 among a sample of about 200 interactions with candidates for charmed particles. The events selected required the presence of at least one muon with a high component of momentum transverse to the beam direction.

- Introduction -

The present experiment, WA75 at CERN¹⁾, was designed to observe directly the decay of beauty particles and to measure their lifetimes, using a hybrid apparatus consisting of emulsions and electronic detectors. The first event with a pair of beauty particles B^- and $\bar{B}^0$ has already been reported²⁾.

In the course of the beauty search about 200 events have been found with charmed particles candidates, most of them as an associated pair. Within this sample two primary interactions have been also found, each of which contain four charmed particles which subsequently decay in the emulsion. This is the first direct observation of that type of event.

- Description of the experiment -

The hybrid apparatus, exposed to a 350 GeV/c π^- meson beam at the CERN-SPS, was described in previous papers^{1,2)}. A total of 80 litres of emulsion in the form of stacks was irradiated with the pellicles either perpendicular or parallel to the beam direction. During the spill the stacks were moved across the beam at a rate depending upon the incident intensity to obtain a uniform irradiation over the whole area of 3×10^3 particles/mm² (1.5×10^3 particles/mm²) for perpendicular (parallel) stacks respectively. The thicknesses of the emulsion target were 18.5 and 40 mm along the beam direction in the two cases. The apparatus also included a beam hodoscope (BH), a vertex detector (VD), an iron/tungsten dump and a magnetic spectrometer (SPC), whose detailed performances will be described elsewhere.

The on-line trigger selected 1.5×10^6 interactions from a total of 3×10^8 by requiring that at least one charged particle be detected in the spectrometer beyond the dump outside of a small angle to the beam, in coincidence with a beam particle and more than three particles of minimum

ionization just beyond the emulsions. The off-line selection required the presence of at least one reconstructed track of a muon with the component of momentum transverse to the beam, $p_{\perp} \gtrsim 1 \text{ GeV}/c$ ($\gtrsim 0.6 \text{ GeV}/c$ for a subsample), and a good association between this track and one of those reconstructed in the vertex detector. This procedure reduced the number of events to be studied to less than 10^4 .

- Analysis -

At present about 5000 interactions have been located in emulsion and in 92% of these the track reconstructed as that of the muon was found to originate from the primary vertex. Most of these events can be explained by the direct production of muons or by pions and kaons decaying into muons almost along the same line of flight. These events were not considered further.

The remaining events were further analysed to search for decays. Events in which secondary tracks in emulsion were not observed in the vertex detector or vice-versa were investigated by a variety of methods, including the following of tracks from the primary interaction, a volume scanning to seek neutral decay topologies and a scanning back from the exit face within a restricted fiducial zone for tracks with defined directions. Both scanning and measurements, especially in the pellicles exposed perpendicular to the beam direction, were performed with largely automated devices³⁾, which allow a greater reliability and productivity of the experiment.

About one half of the events with the muon track not originating at the primary vertex showed one or more decay topologies, at least one of which compatible with the semileptonic muon decay of a charmed particle. Twelve events were found with more than two decay topologies, among them four with four independent secondary vertices. In the two cases reported here all the decay vertices are compatible with the decays of charmed particles.

- Description of the events -

Both events were observed in emulsions exposed perpendicularly to the beam. Fig.1 and Table 1 show a sketch and the main features of the events with regard to the production and decay of the short lived particles.

The first event was found 13.0 mm from the exit edge of the stack and the primary interaction consisted of four evaporation and nineteen minimum ionization prongs. Of these, none matched the negative muon track reconstructed in both the SPC and VD, six were emitted outside the VD acceptance and all but two of the remainder matched, well within the combined errors, the corresponding tracks reconstructed in the VD. Both the unmatched prongs were observed to have a sudden change in direction (kinks at vertices 1 and 4) and after that, there was a good agreement with a predicted track; in particular, the one deflected by 17 mr after a path of 3.97 mm agreed with the μ^- of momentum 20.5 GeV/c observed in the SPC. The transverse momentum with respect to its parent's line of flight was (0.35 ± 0.02) GeV/c and this rules out any possibility of a strange particle decay.

A search for the remaining predicted tracks downstream of the primary interaction succeeded in locating two neutral four-prong decay topologies, 1.30 and 2.70 mm away (vertices 2 and 3), respectively. Six out of these eight prongs show a very good association with the corresponding predicted tracks, one is outside the acceptance, the last lies in an angular region where the efficiency of the vertex detector is decreasing rapidly. Thus an unambiguous time correlation between the neutral topologies, the "kinks" and the primary event has been established.

Multiple scattering measurements using as a reference incident primaries (350 GeV/c π^-) were performed on the interesting tracks, providing either a lower limit or an interval of values for $p\beta$. In one case, where $p\beta$ turned out to be low (0.12 GeV/c), an ionization measurement permitted the assignment for the corresponding particle to be restricted to either a pion or a muon.

The second event was also found in the upstream part of the stack, 13.3 mm from the exit edge, and the primary interaction consisted of 21 evaporation and 17 minimum ionization prongs. As in the previous event, six of them were emitted in directions outside the acceptance of the VD and all but two of the rest were directly associated to predicted tracks. Again, the remaining two showed sudden changes in direction (vertices 3 and 4) and the reconstructed μ^- corresponds to that track deflected by 34 mr at a distance from the primary interaction of 4.22 mm. As the muon momentum was determined to be 23.6 GeV/c, the resulting $p_{\perp}$ of the muon is (0.81 ± 0.02) GeV/c with respect to the parent's line of flight.

A scanning for neutral decay topologies succeeded in locating a four prong vertex, 361 μ m downstream, and a two prong one, 2.02 mm away (vertices 1 and 2, respectively). In the first, one track is associated, two are outside the VD acceptance and the last is observed to undergo a nuclear interaction after a path of 5.1 mm. In the second, one track is associated and the other, with a low but rather uncertain measurement of p_{β} , gives rise after 1.70 mm to a knock-on electron ($p_{\beta} \sim 50$ MeV/c) and a track that, on the basis of ionization and multiple scattering [$p_{\beta} = (.17 \pm .38 - .07)$ GeV/c] is also compatible with being that of an electron, though assignment as muon or pion cannot be ruled out entirely.

- Discussion and conclusions -

For both the events reported above the most natural interpretation is the simultaneous emission and the subsequent decay of four charmed particles. In both cases a rather energetic D^- is seen to decay semileptonically into a μ^- and neutrals, whereas in the second one there is some evidence that a neutral D also decays into an electron.

Any alternative explanation is very improbable, the most likely one being that only two of the decay topologies

are due to decays of charmed particles (more precisely, that associated with the muon and one of the neutrals into four charged prongs) and the remaining two are due to secondary interactions or to early decays of strange particles. However, the probability of such a background within this sample is estimated to be of the order of 10^{-3} for each event separately.

Table 2 shows a summary of a kinematical analysis of the events performed⁽²⁾ by using the available data and plausible decay schemes. Errors have been evaluated from the average of the possible energy of the decaying particles with weights given by a phase space calculation and taking into account the observed configurations. The proper decay times are well within the range expected for charmed particles⁽⁴⁾. On the other hand, an estimate of the energies released in the primary interactions, including that of the decaying particles interpreted as charms, sum up roughly to the nominal beam energy. Finally, any attempt to interpret as chains of the sort beauty into charm those topologically possible gave unsatisfactory results when the kinematical constraints were included.

In the present experimental situation the rate of double to single charmed pair production turns out to be around 10^{-2} . In fact, the experimental figure (2 events in 200) remains almost unchanged when taking into account the larger acceptance of the apparatus for events containing four charmed particles (and at least one of them must decay into a muon) and the lower chance that all of them be detected.

An interpretation suggested recently⁽⁵⁾ could be in terms of the formation of multiple pairs of heavy flavours in diffractive central clusters, according to a double pomeron exchange process. At these energies, however, this process is expected to contribute at the level of 10^{-3} or less with respect to single pairs.

The features of the primary interactions, namely angular distribution and number of minimum ionization and evaporation prongs, suggest that for both events (surely for

the second) the struck nucleus is a heavy constituent of the emulsion, presumably Ag or Br, and that the interaction is central in character. It seems somewhat difficult, however, to explain such large production of two pairs of charmed particles by two successive acts of the intranuclear cascade induced by a primary particle on to a heavy nucleus.

It is a pleasure to thank our technicians and scanners warmly for their considerable contribution to the experiment.

- References -

- 1) J.P.Albanese et al.: CERN-SPSC/81-69 SPSC/P-166.
- 2) J.P.Albanese et al.: Phys.Lett. 158B (1985) 186.
- 3) K.Niu: Proc. Int. Cosmic Ray Sympo. on HE Phenom. (Cosmic Ray Lab., Univ. of Tokyo) (1974) 149.
K.Niu: Proc. Phys. in Coll. & Workshop, Search for Heavy Flavours (Como, Italy) (1983) 475.
S.Aoki et al.: Nucl. Track & Rad. Meas., 11 (1986) in press.
- 4) Particle data group, Phys.Lett. 170B (1986) 14-17;
N.Ushida et al.: Phys.Rev.Lett. 56 (1986) 1767 and 1771.
- 5) K.H.Streng: Phys.Lett. B171 (1986) 313.

TABLE 1

Geometrical and kinematical data of the four charmed particles events.

EV	(VT)	particle	production α (mr) δ		L (mm)	decay α (mr) δ		VD	ID	Notes
1	(1)	$D^\pm$	22	11	.180	16	47	Y		$p\beta > 2.6$ GeV/c
	(2)	$D^0/\bar{D}^0$	-71	-28	1.30	81	-19	Y		$p\beta = (1.5^{+1.0}_{-.3})$ GeV/c
						-211	-7	N		$p\beta = (1.7^{+1.5}_{-.4})$ GeV/c
						-163	-32	Y		$p\beta = (2.0^{+1.2}_{-.4})$ GeV/c
						-294	-400	N	π/μ	$p\beta = (.12^{+.4}_{-.1})$ GeV/c
										$I/I_0 = 1.23^{+.16}_{-.14}$
	(3)	$D^0/\bar{D}^0$	12	50	2.70	43	39	Y		$p\beta > 4.2$ GeV/c
						37	40	Y		$p\beta > 4.7$ GeV/c
						101	152	Y		$p\beta > 5.4$ GeV/c
						-40	39	Y		$p\beta > 3.9$ GeV/c
	(4)	D^-	12	-24	3.97	24	-37	Y	μ^-	$p = 20.5$ GeV/c
2	(1)	$D^0/\bar{D}^0$	-91	39	.361	29	64	Y		$p\beta > 2.6$ GeV/c
						-9	53	-		Nucl. int. at 5.11 mm
						-543	-73	N		$p\beta = (.7^{+.7}_{-.15})$ GeV/c
						-335	34	N		$p\beta = (.7^{+.5}_{-.14})$ GeV/c
	(2)	$D^0/\bar{D}^0$	34	-27	2.02	-4	-10	Y		$p\beta > 6.3$ GeV/c
						27	-117	-	a)	$p\beta = (.2^{+.5}_{-.1})$ GeV/c
	(3)	D^-	-12	-27	4.22	8	-55	Y	μ^-	$p = 23.6$ GeV/c
	(4)	$D^\pm$	-20	-9	6.22	-34	-2	Y		$p\beta > 4.6$ GeV/c

Notes: VT: decay vertex number. See fig.1

 α, δ : projection angles w.r. to the beam

VD: matching with VD track

ID: particle identification

 μ^- : measured in the spectrometer

a) probable electron : gives rise to a knock-on electron after 1.70 mm

 $p\beta$: measured in emulsion (multiple scattering) I/I_0 : relative ionization in emulsion

TABLE 2

Summary of the kinematical analysis.
Momenta computed assuming D-meson masses.

Event	Decay vertex (mm)	Decay length	Momentum (GeV/c)	Production $P_{\perp}$ (GeV/c)	Life-time (10^{-13} s)	Notes
n°1	1 (C1)	0.180	90^{+90}_{-50}	2.3	$0.14^{+.15}_{-.07}$	
	2 (N4)	1.30	$7.7 \pm .4$	0.6	$10.4^{+.5}_{-.4}$	
	3 (N4)	2.70	20^{+3}_{-6}	1.0	$7.6^{+3.0}_{-1.1}$	
	4 (C1)	3.97	180^{+120}_{-110}	5.2	$1.3^{+1.9}_{-.5}$	$\mu^- p = 20.5 \text{ GeV/c}$ $p_{\perp} = .35 \text{ GeV/c}$
n°2	1 (N4)	0.361	$6.9 \pm .2$	0.7	$3.3 \pm .1$	
	2 (N2)	2.02	25 ± 9	1.1	$5.7^{+3.3}_{-1.4}$	$e^+ (?)$
	3 (C1)	4.22	57 ± 12	1.7	$4.6^{+1.1}_{-.8}$	$\mu^- p = 23.6 \text{ GeV/c}$ $p_{\perp} = .81 \text{ GeV/c}$
	4 (C1)	6.22	170^{+120}_{-60}	3.9	$2.4^{+1.2}_{-1.0}$

Fig.1 Sketch of the events.