CERN-EP/79-100
17 September 1979

FIRST DIRECT OBSERVATION OF THE DECAY OF
NEUTRAL CHARMED PARTICLES PRODUCED BY NEUTRINOS IN EMULSION

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ABSTRACT

Three examples of the production in emulsion by neutrinos and subsequent decay of neutral short-lived particles are reported. The flight times are $\approx 10^{-13}$ s, similar in order of magnitude to those previously determined for charged charmed particles in the same experiment.

(Submitted to Physics Letters)

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Four examples of charged charmed particles produced in nuclear emulsion by high-energy neutrinos have so far been reported [1-3], with directly observed decay paths ranging from about 100 μm to 900 μm and corresponding decay times from 0.5 to 7×10^{-13} s. These lifetime values are well consistent with the mean lifetime of $\sim 5 \times 10^{-13}$ s [4] predicted from current theoretical models for charmed particles [4-6].

Three of the above-mentioned four events were obtained in an experiment in which large emulsion stacks were exposed, in front of the Big European Bubble Chamber (BEBC), to the wide-band neutrino beam at CERN. The apparatus used in this experiment has been briefly described in a previous paper [2]. The search for the neutrino interactions in the emulsion is still in progress, and to date some 150 charged current (CC) events have been found.

In a search for decays of neutral particles, a scan under high magnification was carried out downstream from each interaction vertex, over a volume defined by a cone of semi-opening angle 30° and length 2 mm, the interaction point being the apex of the cone.

In this paper, three events which are candidates for the decay of neutrino-induced neutral charmed particles are reported. The observed decay paths and the corresponding estimated decay times are similar in order of magnitude to those of the charged charmed particles reported previously [1-3].

In each case a "V" (two tracks of opposite sign, V_1 and V_2) is observed at a point B downstream with respect to the primary neutrino interaction vertex A. The distance AB is 182 μm , 54 μm , and 115 μm for the events shown in figs 1, 2 and 3, respectively. These V's are candidates for the decay at B of neutral short-lived particles produced at A.

A summary of the results of measurements at the decay vertex B is given in Table 1 for the three events.

In the first event (fig. 1) four particles of minimum ionization are emitted from the neutrino interaction vertex. Their tracks in the emulsion, as well as the two tracks of the "V", are all well associated with corresponding tracks seen

in BEBC. The event is of a CC type, since one of the particles (track 1) is unambiguously identified as a negative muon of 5.89 GeV/c momentum by the BEBC External Muon Identifier (EMI).

The opening angle of the V is 6° . The V plane does not contain the primary vertex A, the distance of A from the V line of flight being $(8 \pm 2) \mu\text{m}$. The kinematical analysis shows, furthermore, that the transverse momentum imbalance at the decay vertex is $(0.46 \pm 0.10) \text{ GeV/c}$. Hence the interpretation of the event as the decay at B of a neutral short-lived particle produced at A requires the emission of at least one neutral particle at vertex B *).

The following three-body decays, which satisfy the $\Delta C = \Delta S$ rule, are possible and give, for the momentum p_c (in GeV/c) and the proper decay time t_c (in units of 10^{-13} s) of the assumed charmed primary, two values (this is because of a kinematical ambiguity related to the presence of the unobserved neutral particle):

$$\begin{array}{lll} D^0 \rightarrow \pi^- \pi^+ K^0 & p_c = 13; 56 & t_c = 0.9; 0.2 \\ D^0 \rightarrow K^- \pi^+ \pi^0 & p_c = 13; 20 & t_c = 0.9; 0.6 \\ D^0 \rightarrow K^- \mu^+ \nu_\mu & p_c = 13; 21 & t_c = 0.9; 0.6 \end{array}$$

In the other two events the tracks V_1 and V_2 are not seen in BEBC, so that the analysis of the decay is based essentially on the information derivable from the emulsion alone.

In the second event (fig. 2), four minimum ionizing particles are emitted from the primary neutrino vertex. One (track 2) interacts in the emulsion. The other three leave the emulsion, but one of them (track 3) misses the BEBC window because of its large dip angle. Of the two remaining particles, which are both seen in BEBC, one (track 1) is positive, of momentum 3.3 GeV/c; the other is a negative muon of 13.7 GeV/c, identified by the EMI. The agreement between the angles observed in the emulsion and those extrapolated from the BEBC measurements is fully satisfactory.

The opening angle of the V is 23° . Multiple scattering measurements made in the emulsion on tracks V_1 and V_2 (unobserved in BEBC), lead to $p\beta$ values of

*) Moreover, the invariant mass M of the two-particle system is also incompatible with any two-body strange particle decay, since $M = (0.61 \pm 0.02) \text{ GeV/c}^2$ for a $\pi^+ \pi^-$ pair, $M = (1.21 \pm 0.01) \text{ GeV/c}^2$ for a $p \pi^-$ pair, and $M = (2.06 \pm 0.01) \text{ GeV/c}^2$ for a $\bar{p} \pi^+$ pair.

(0.9 ± 0.2) GeV/c for track V_1 and (0.20 ± 0.02) GeV/c for track V_2 . Curvature of the tracks in emulsion, which is measurable owing to the ~ 27 kG magnetic field present over the region of the stacks, indicates that track V_1 is due to a negative particle and V_2 to a positive one. Taking into account the emission angles of these particles and the curvature of their trajectories, neither would be expected to reach the sensitive volume of BEBC.

Differential scattering measurements made on track V_2 over a path of ~ 30 mm show no variation within errors of $p\beta$ with the distance from the decay vertex. By comparison with the expected radiative energy loss in traversing 30 mm of emulsion, it is concluded that the probability of track V_2 being due to a positron is 15 times smaller than that for a muon or heavier particle.

Since both tracks are of minimum ionization, it can be stated that the particle producing track V_1 is not heavier than a kaon, and that producing track V_2 is not heavier than a pion. Hence the decay cannot be that of Λ^0 or $\bar{\Lambda}^0$ hyperons. Interpreting both decay particles as pions, the invariant mass of the two-particle system is (0.38 ± 0.03) GeV/c². Thus the V cannot be due to a $K_S^0 \rightarrow \pi^+\pi^-$ decay.

The resultant vector momentum of the secondary particles (see table 1) is inconsistent with the two-body decay of a particle produced at vertex A, the line of flight passing at (12 ± 1) μ m from the primary vertex. Thus the interpretation of this as the decay of a neutral particle produced at A, requires the emission of at least one neutral particle at vertex B.

The possible three-body decays of the D^0 meson already considered for the previous event now give the following results (same units as before):

$D^0 \rightarrow \pi^-\pi^+K^0$	$p_c = 0.6;$	17	$t_c = 5.5;$	0.2
$D^0 \rightarrow K^-\pi^+\pi^0$	$p_c = 0.7;$	8.5	$t_c = 5.0;$	0.4
$D^0 \rightarrow K^-\mu^+\nu_\mu$	$p_c = 0.6;$	9.0	$t_c = 5.5;$	0.4

A photomicrograph of the last event is given in fig. 3, accompanied by an explanatory drawing. This event was found while searching for another prediction, but no satisfactory correlation with BEBC photos has been established for it.

The opening angle of the V is 20° . Multiple scattering measurements performed on the two prongs, V_1 and V_2 , give $p\beta$ values of (1.15 ± 0.25) GeV/c and (1.75 ± 0.45) GeV/c, respectively. Curvature of the tracks in emulsion indicates they have opposite sign, V_1 being positive. The opening angle and $p\beta$ values given above rule out the possibility that the V is due to a $\Lambda^0 \rightarrow p\pi^-$ decay. The V plane does not contain the primary vertex A, the distance of A from the V plane being (11 ± 2) μm . This again implies that if the event is indeed due to the decay of a neutral particle produced at A, at least one neutral particle has to be present among the decay products. The possible three-body decays of the D^0 meson, considered already for the two previous events, now yield the results given below (same units as before):

$$\begin{array}{lll} D^0 \rightarrow \pi^-\pi^+K^0 & p_c = 3.1; \quad 17 & t_c = 2.3; \quad 0.4 \\ D^0 \rightarrow K^-\pi^+\pi^0 & p_c = 3.0; \quad 11 & t_c = 2.4; \quad 0.7 \\ D^0 \rightarrow K^-\mu^+\nu_\mu & p_c = 2.9; \quad 11 & t_c = 2.5; \quad 0.7 \end{array}$$

The probability that the three observed V's are not correlated with the primary neutrino interaction is estimated to be less than 10^{-9} on the basis of the experimental fact that no such V's, other than e^+e^- pairs, were observed in the scanning, under high magnification, of 500 mm^3 of emulsion. The further possibility that the events represent the interactions at point B of neutral particles produced in the primary interaction can be shown to be negligible on the basis of arguments analogous to those applied for the background to charged charmed hadron decays [2,3].

In conclusion, three events have been found, which are most readily interpreted as decays of neutral charmed particles created in neutrino interactions. The flight times are $\approx 10^{-13}$ s, namely similar in order of magnitude to those observed for charged charmed particles in the same experiment [2,3]. There is an indication of a shorter mean life in the present case, but some bias is expected for the detection of neutral decays with long paths.

We wish to thank the members of the CERN staff and the technicians and scanners of our groups who contributed with skilfulness and devotion the various stages of preparation, running, and analysis of this experiment.

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Table 1

Summary of the results of measurements at the decay vertex B
for the three neutral charmed candidates

Event No.	Track	Azimuthal angle ($\pm 0.3^\circ$) (degrees)	Dip angle ($\pm 0.5^\circ$) (degrees)	Charge	p β emulsion (GeV/c)	p BEBC (GeV/c)
1	V ₁	- 1.5	2.8	-		2.36 $\pm$ 0.01
	V ₂	4.5	4.2	+		8.60 $\pm$ 0.02
	AB	2.0	1.8			
2	V ₁	-22.4	1.1	-	0.9 $\pm$ 0.2	
	V ₂	0.5	0.0	+	0.20 $\pm$ 0.02	
	AB	- 5.4	3.7			
3	V ₁	-18.5	-4.1	+	1.15 $\pm$ 0.25	
	V ₂	1.4	-6.3	-	1.75 $\pm$ 0.45	
	AB	- 0.9	0.3			

Figure captions

- Fig. 1 : Schematic drawing of event 1. This is a CC neutrino event (track 1 being identified as a μ^- of 5.89 GeV/c momentum) interpretable by the creation at A of a neutral short-lived particle which decays at B after travelling a distance $AB = (182 \pm 3) \mu\text{m}$.
- Fig. 2 : Schematic drawing of event 2. This is also a CC neutrino event (track 4 being due to a μ^- of 13.7 GeV/c) again interpretable by the creation at A of a neutral short-lived particle which decays after travelling a distance $AB = (54 \pm 3) \mu\text{m}$.
- Fig. 3 : Photomicrograph of event 3 (left) with explanatory diagram (right). Some tracks do not appear in the photomicrograph owing to their large dip angles in the emulsion. The distance between production and decay points of the neutral short-lived particle is in this case $AB = (115 \pm 3) \mu\text{m}$.

Fig. 1

Fig. 2

Fig. 3