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LIFETIME OF CHARMED HADRONS PRODUCED IN NEUTRINO INTERACTIONS

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LIFETIME OF CHARMED HADRONS PRODUCED IN NEUTRINO INTERACTIONS

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ABSTRACT

Examples of the decay of charmed hadrons produced by high-energy neutrinos in an emulsion hybrid experiment (WA17, CERN) and in a bubble chamber exposure (E546, Fermilab) have been directly observed.

The decay paths of the five charmed candidates found in experiment WA17 (three positively charged and two neutral range from about 50 to 900 μm, giving charmed hadron proper decay times well consistent with the meanlife expected from current theoretical models ($\sim 5 \cdot 10^{-13}$ s). One of the events represents the production of a Λ_c^+ baryon which decays after $(7.3 \pm 0.1) \cdot 10^{-13}$ s to a $pK^-\pi^+$ final state. The identification of the final state is made possible by the combined information from the emulsion and the associated bubble chamber photo (BEBC).

In experiment E546 two neutral and one charged short decays have been detected in the FNAL 15' bubble chamber, in addition to one of undetermined charge. Two of them are interpretable as $D^0 \to e^+K^-\nu_e$ and $D^+ \to e^+K^-\pi^+\nu_e$ decays, yielding decay times consistent with those of the five events found in experiment WA17.

The status of another emulsion hybrid experiment at Fermilab (E553) is also briefly reported.

1. INTRODUCTION

Until recently rather conflicting results have been reported from experiments based on different techniques[1], concerning the lifetime τ_c of charmed particles. Thus, some three years after these new states of hadronic matter were found[2] as predicted by the "GIM mechanism"[3], no conclusive answer could be given to the fundamental question of whether or not the decay rate of charmed hadrons is governed basically by the Fermi weak coupling constant as expected.

The theoretical prediction is that charmed particles all have lifetimes of the same order of magnitude, essentially determined by the rate of the charmed quark β-decay ($c \to s + e^+ + \nu_e$) which is given by the same formula as for μ decay.*) Including first-order gluon effects and a correction for the finite mass of the s-quark the value $\tau_c = 5 \cdot 10^{-13}$ s has recently been reported[4] assuming a mass $m_c = 1.75$ GeV/c^2 for the c-quark as suggested from an analysis of D meson decays.

There is, of course, still a large uncertainty in the estimated value of τ_c, mostly due to the uncertainty in the value of m_c.

My task is to review briefly - in the 20 minutes allocated for my talk - the experimental situation concerning the decay of charmed hadrons produced in neutrino interactions. The review will be based on three contributed papers selected by the Conference Scientific Advisory Committee:

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*) Then $\tau_c = B_{sl}\,(m_\mu/m_c)^5\tau_\mu$, where B_{sl} = semileptonic inclusive branching ratio; m_μ = muon mass; m_c = mass of the c-quark; τ_μ = muon lifetime.

1) "Estimate of the lifetime of charmed hadrons produced in neutrino interactions" (Abs 26 rev.), by the Ankara-Brussels-CERN-Dublin UC-London UC-Open University-Pisa-Rome-Turin Collaboration - CERN exp. WA17.

2) "Bubble-chamber detection of short-lived particles produced by high energy neutrinos" (Abs 229), by the Berkeley-Fermilab-Hawaii-Seattle-Wisconsin Collaboration - FNAL exp. E-546.

3) "Study of neutrino interactions producing short-lived particles" (Abs 111), by the Cornell-Lund-Pittsburg-Sydney-York University Collaboration - FNAL exp. E-553.

Before presenting these new results I wish to recall that the first likely example of the decay of a charmed hadron produced in neutrino interactions was found in an experiment carried out at Fermilab in 1976[5] using a hybrid technique introduced in 1965.[6]

2. CERN EXPERIMENT WA17

2.1 Apparatus

This experiment uses a combination of emulsion, bubble chamber and counter techniques[7] in an experimental set-up schematically illustrated in Fig. 1.

Large stacks of 600 μm thick pellicles of nuclear emulsion are located in front of the beam entrance window of the Big European Bubble Chamber, BEBC, which is filled with liquid hydrogen and operates in a 35 KG magnetic field.

Tracks of secondary particles from ν-interactions occurring in the emulsion are observed and measured in BEBC to predict the position of the interaction vertices.

A large MWP chamber (D) covering BEBC window allows one to correlate the BEBC and emulsion reference frames. This correlation is achieved by locating in chamber D and in BEBC 2000 passing-through muons. The position of chamber D, and consequently of the emulsion stacks in BEBC frame, could thus be located with an accuracy of 3 mm in the beam direction (x) and 0.3 mm in the transverse directions (y and z).

A veto-coincidence counter system (VCS) coupled to chamber D, provides a time correlation with the "external muon identifier" (EMI) of BEBC. It also provides further information useful in the analysis of the recorded events.

2.2 Exposure

During two runs, 10 and 20 litres respectively of emulsion were exposed to the CERN SPS wide-band neutrino beam, with neutrino energy peaking at ∿ 25 GeV.

A total of 10^{18} protons of energy 350 GeV hit the neutrino target and 206.000 BEBC photos were recorded.

2.3 Event search procedure

BEBC photos are scanned to select event configurations with at least three tracks apparently converging to a point inside the emulsion, at least one of which has to have a momentum larger than 3.5 GeV/c. Selected events are then measured and processed, and their possible vertices in emulsion are predicted with errors by a "vertex program". The errors are typically 9 mm in the x direction and ∿ 1 mm in y and z. "Found ν-events" are those exhibiting a good matching between tracks seen in emulsion and BEBC*) and no incoming minimum ionization track. For the found ν-events all minimum ionization tracks are followed for 5 mm, to search for "charged decays". The search for "neutral decays" (V^0) is made by scanning in a forward cone of ± 30° aperture, 2 mm long.

2.4 Detection losses

The selection criteria just outlined reduce drastically (by a factor ∿ 30) the number of BEBC photos to retain for measurement but they introduce a large loss of "good" ν-events: 35-40% for ordinary charged current (c.c.) ν-events, as well as for c.c. events with production of charmed particles.**)

Even larger losses occur at the emulsion level, due to "white starts" (at least 10%), over-all scanning inefficiency including edge effects (∿ 20%), limited "search volume" (∿ 15%), nuclear interactions of hadrons from the ν-vertex (≃ 10%) and poor quality of emulsion in part of the stacks. Additional losses are expected for the "charmed ν-events" due to the difficulty of observing neutral decays and 1-prong charged decays.

As a consequence, the estimated ∿ 700 c.c. ν-interactions which occurred in the emulsion during the exposures should lead to 400-450 good vertex predictions, 160-170 "found c.c. ν-events" and, among the latter, 6 to 7 expected "charmed events".

2.5 Results

To date ∿ 90% of the BEBC photos have been fully analysed and about 3/4 of the corresponding vertex predictions have been searched for leading to 150 "found c.c. ν-events", in each of which the μ^- is unambiguously identified by the VCS-EMI system and its momentum determined by BEBC. Among these are the 5 charmed candidates listed in the table.

Event	Short-lived particle				
	Charge	Decay path	Final state	Nature	Decay time a)
1	+	96 μm	{ΔS = ΔC; ≥ 4 body	?	$0.5\text{-}1.2 \times 10^{-13}$s
2	+	354 μm	$pK^-\pi^+$	Λ_c^+ baryon	$7.3\pm0.1 \times 10^{-13}$s
3	+	906 μm	≥ 4 body	?	$1.6\text{-}5.3 \times 10^{-13}$s
4	0	54 μm	≥ 3 body	meson	$0.2\text{-}4.2 \times 10^{-13}$s
5	0	115 μm	≥ 3 body	?	$0.4\text{-}2.5 \times 10^{-13}$s

a) The two values reported for all events except No. 2 correspond to those obtained from the kinematical two-fold ambiguity mentioned in the text.

*) The requirement is that the differences between azimuth and dip angles of tracks measured in emulsion and those extrapolated from BEBC be smaller than 3°.

**) These losses are estimated on the basis of data kindly made available for WA17 by a parallel experiment with BEBC (WA21) and, for the "charmed events", by the FNAL 15' bubble chamber exposure of C. Baltay et al. in which 182 $e^+\mu^-$ charm decays were detected.

Three of them - already reported recently elsewhere[8)] - have the same general features of the first charm candidate produced in a ν-interaction[5)]: the track of a charged particle of minimum ionization, emitted from the ν-interaction occurring at a point A of the emulsion, splits at a point B into three tracks also of minimum ionization. There is no sign of either nuclear excitation or recoil at point B, so that the events are best interpreted in terms of the decay at B of unstable particles produced at A. Indeed the probability that the three new events[8)] and the old one[5)] are due to nuclear interactions of high energy hadrons presenting the observed decay topology is estimated[8a)] to be less than 10^{-7}. The decay paths AB are in the range from ~ 100 to ~ 900 μm, as reported in the table. The matching between tracks observed in emulsion and in BEBC fulfills the requirements mentioned above for virtually all associated tracks of the three new events. Furthermore the charges of the three secondary particles, and therefore that of the primary parents, are determined in the new events by the curvature of the corresponding tracks observed in BEBC. Parents of positive charge are thus found in all cases, as expected from the dominant quark transformation for charmed hadron production in ν_μ interactions ($\nu_\mu + d \to \mu^- + c$).

For two of these three positively charged charmed candidates the over-all information derivable from the apparatus is not sufficient to identify the final state, nor the mass of the decaying particle. There are several decay modes of known charmed hadrons which are kinematically compatible with them, and for each assumed decay mode there is a twofold ambiguity for the momentum, and therefore for the decay time of the parent charmed hadron, as briefly discussed in reference 8a. The third event is instead identified as the decay at B (Fig. 2) of a charmed baryon Λ_c^+ produced at A by a high energy neutrino. The arguments for such an identification can be briefly summarized as follows:

a) The transverse momentum imbalance, as derived from the momenta of the secondary particles measured in BEBC and the angles measured in emulsion, is compatible with zero (46 ± 28 MeV/c). Hence the event is interpretable as a 3-body decay;

b) One of the two positive secondary particles is identified as a proton by the kinematical analysis of the interaction it undergoes in BEBC (a p-p elastic scattering). Hence the primary particle is a baryon.

c) The negative particle is identified as a K^- meson by combining curvature measurements in BEBC with ionization measurements in emulsion, assuming that the third (positive) secondary particle, which crossed the same emulsion pellicles traversed by the negative particle, is a π^+ meson. Hence the event is most probably due to the production at A of a charmed baryon, Λ_c^+, which undergoes the decay process $\Lambda_c^+ \to pK^-\pi^+$ after travelling a path AB = 354 ± 3 μm.

The mass[*)] M_c, momentum p_c, and proper decay time t_c, of the primary baryon can be derived from the momenta measured in BEBC and the decay path AB measured in emulsion. The results are: $M_c = (2.29 \pm 0.015)$ GeV/c^2; $p_c = (3.74 \pm 0.02)$ GeV/c; $t_c = (7.3 \pm 0.1) \cdot 10^{-13}$ s. The invariant mass of the $K^-\pi^+$ system in this event is 0.866 GeV/c^2 suggesting a decay scheme $\Lambda_c^+ \to p\overline{K^*} \to p\pi^+K^-$.

*) The mass value given below does not take into account possible systematic errors. It is somewhat larger, but not inconsistent, with that reported for the few examples[2a)9)] of the Λ_c^+ baryon produced in bubble chamber.

In addition to the three charged charmed candidates mentioned above and reported in more detail elsewhere[8], two neutral candidates have been found. One of them, (event no. 5) found in the course of the search for c.c. ν-interactions, can be interpreted as the production at a point A of the emulsion of a neutral short-lived particle which, after travelling a path AB = 115 ± 3 μm, decays at B into two charged secondaries ("V^0"). The line AB makes an angle of 6^0 with the V^0 plane, indicating that if the event is indeed due to a neutral decay, at least one neutral particle has to be present among the decay products. Unfortunately, since no fully satisfactory correlation with a BEBC picture has been established as yet, the analysis of this event relies, for the moment, only on what is seen in emulsion. The opening angle of the V^0 is 20^0. The two charged secondaries, followed up to the edge of the stack, have pβ values of 1.15 ± 0.25 and 1.75 ± 0.45 GeV/c, as derived from multiple scattering measurements. The V^0 particle cannot be due to a $\Lambda^0 \to p\pi^-$ decay since the π^- momentum should then be smaller than 0.32 GeV/c. Even though it is consistent with a $K^0_s \to \pi^+\pi^-$ decay, the probability of a random coincidence of a K^0_s decay with a neutral induced interaction is negligible. In fact no other example of V^0 decay was found in the scan under high magnification of 500 mm^3 of emulsion.

The other neutral charmed candidate (Fig. 3) has similar features, with a decay path AB = 54 ± 3 μm and an opening angle of the V^0 of 23^0. Although there is good correlation with the BEBC photo used to predict its vertex, the analysis of this event has to be based again only on what is observed in the emulsion, since neither of the two tracks from the V^0 decay reaches BEBC sensitive volume.*) Multiple scattering measurements made on the ∿ 3 cm available track lengths yield pβ values of ∿ 0.9 ± 0.2 and ∿ 0.2 ± 0.02 for the two charged secondary particles, V_1 and V_2 respectively.

The magnetic field is strong enough over the stack region to allow significant curvature measurements, by which it is concluded that V_1 is a negative particle and V_2 a positive one. Furthermore, accurate ionization measurements on both tracks, and differential pβ measurements on the V_2 track which traverses ∿ 1 radiation length, lead to mass assignments which make V_1 compatible with being only an e^-, a μ^- or a K^- meson, and V_2 with either a μ^+ or a π^+ meson.

The line of flight of the V^0, derived from the vector momenta of particles V_1 and V_2, of which angles of emission and pβ values are known, is 12 ± 2 μm off the primary vertex A. Hence at least a neutral particle has to be present among the decay products of the V^0 in order to balance the momenta. A few Cabibbo-favoured decay modes of the D^0-meson are found to be compatible with the event ($D^0 \to \pi^+\pi^-K^0$, $\pi^+K^-\pi^0$, $\mu^+K^-\nu_\mu$...). For each decay mode there is, however, a kinematical ambiguity which leads to two values of the momentum, and therefore of the decay time of the parent particle. These decay times are within the interval 0.3-4 x 10^{-13} s.

*) This is because one of the two secondary tracks (V_2, see below) has a low momentum (∿ 200 MeV/c) and the other (V_1) is emitted with ∿ 900 MeV/c momentum at a large angle with respect to the direction of the ν-beam.

3. FNAL EXPERIMENT E-546

This is a pure bubble chamber experiment in which short-lived decays of dilepton events have been detected in neutrino interactions of the highest energies. The results are based on an exposure of the Fermilab 15' bubble chamber (3.4×10^{18} p on target, 326,000 photos) to the quadruple triplet neutrino beam for which the average ν-event energy is as large as ∿ 90 GeV.

Careful examination of a sample of 89 high-energy ν-induced dilepton events, out of ∿ 12,000 charged current events, has led to the observation of the production and semi-leptonic decay of 4 charmed candidates, of which one is positively charged, two are neutral and one is of undetermined electric charge. The decay paths are reported to be between about 6 and 9 mm, measured with a 15%-20% error.

The charged candidate is consistent with the hypothesis $D^+ \to e^+K^-\pi^+\nu_e$ (not with $\Lambda_c^+ \to pK^-e^+\nu_e$); the two neutral candidates are consistent with $D^0 \to e^+K^-\nu_e$. One of them, shown in Fig. 4, is not consistent with a K^0 decay. The charge of the remaining candidate is uncertain because the e^+ emerges from a tight jet. The event is reported to be again consistent with a D decay (not with a K^0 decay).

The estimated total background (largest contribution comes from asymmetric γ conversion with a low energy, undetectable e^-, and the random overlay of a negative hadron) is less than 0.14 neutral and less than 0.11 charged events.

Using the charged event and one of the two neutrals,*) an estimate of the decay times is obtained from a likelihood method based on the remaining 85 dilepton events for which no decay vertex is seen. The decay times for these two events are $(2.5 \, {}^{+\,3.5}_{-\,1.5}) \cdot 10^{-13}$ s for the D^+ and $(3.5 \, {}^{+\,3.5}_{-\,1.5}) \cdot 10^{-13}$ s for the D^0.

4. FNAL EXPERIMENT E553

This again uses a hybrid emulsion technique. The track sensitive target consists of 14 litres of Kodak NTB3 emulsion, exposed as horizontal pellicles, 600 μm thick, stacked in two separate slabs, each 2 cm along the beam direction. Spark chambers with aluminized glass electrodes, placed immediately downstream of each stack, allow one to find the vertices of the ν-events by extrapolation from measured positions of the spark-evaporated holes in the electrodes. Further downstream there is first a magnetic spectrometer and then a track-sensitive "plastic flash calorimeter"[10], which detects and separates in general electromagnetic and hadronic showers, and identifies passing-through muons. Two examples of dimuon events detected in this calorimeter are shown in Fig. 5.

The apparatus just outlined was exposed to the Fermilab broad band horn ν-beam early this year and more than 200 ν-events are expected to have occurred in the emulsion. To date several ν-events have been located in the emulsion, but no example of a charmed hadron candidate has been found. The analysis is in progress.

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*) The other neutral event occurred in a region of liquid turbulence.

5. CONCLUSIONS

With the inclusion of the first candidate observed in a previous experiment[5)] there is now a sample of 8 charmed hadron candidates produced in neutrino interactions which decay with lifetimes all well consistent with expectations based on current theoretical ideas. The sample includes a charmed baryon[8b)] (a Λ_c^+) for which decay mode, mass and lifetime have all been determined. Thus the last of the most important open questions about charm particle physics seems to be settled.

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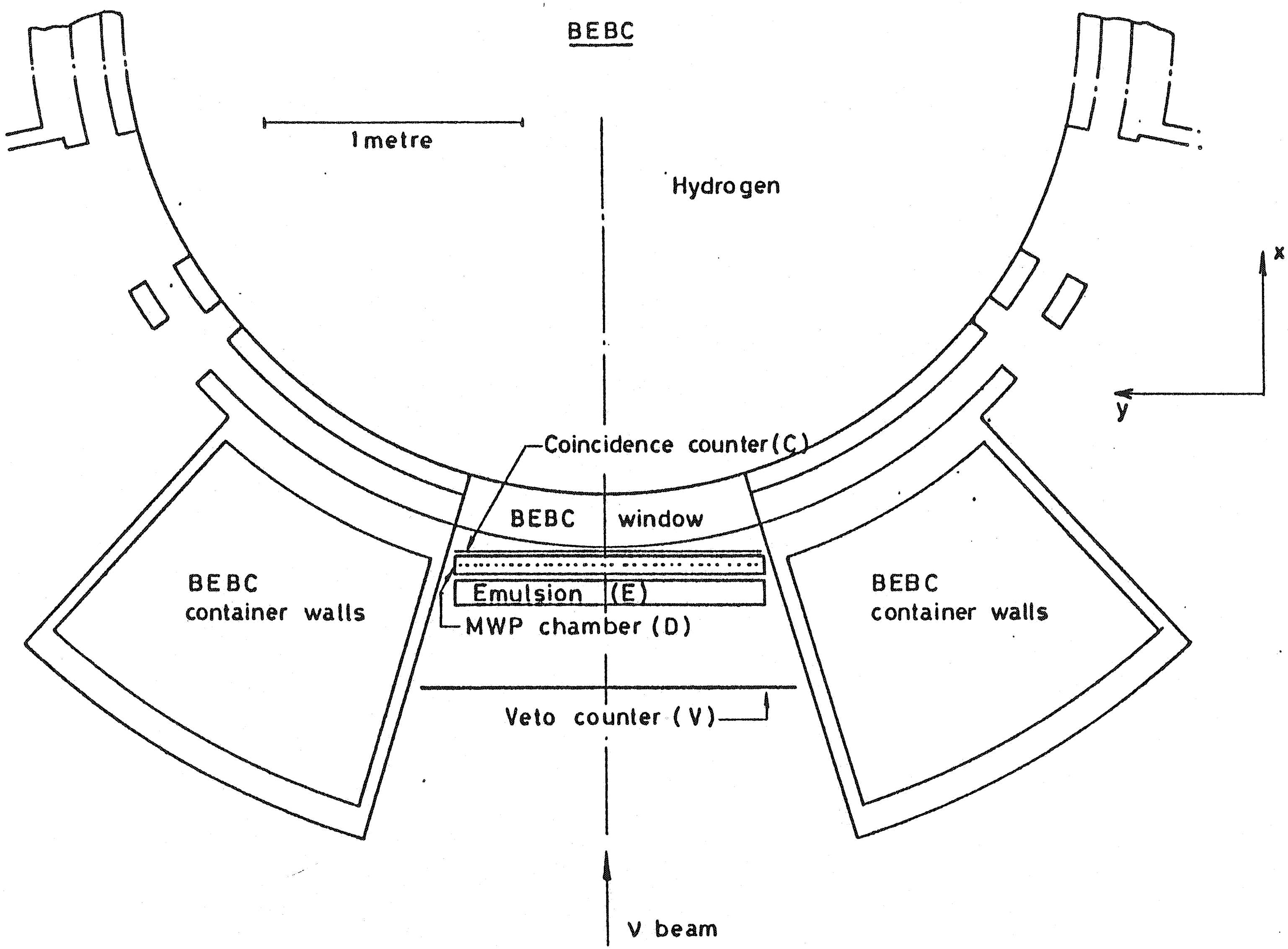
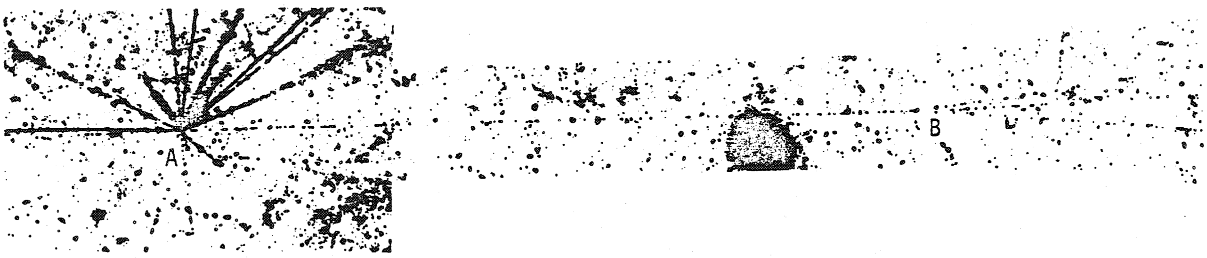
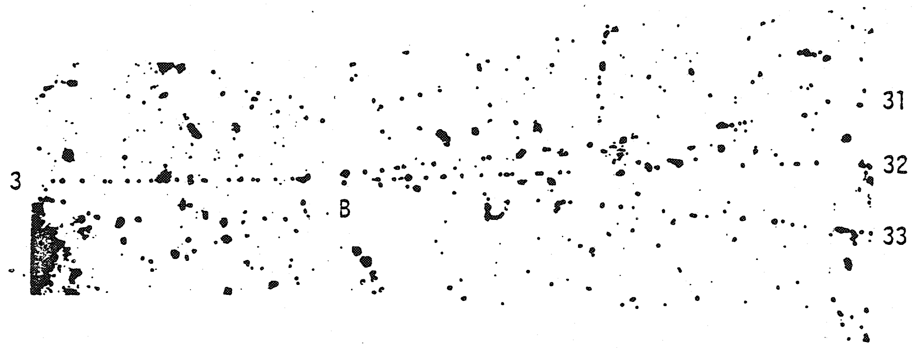


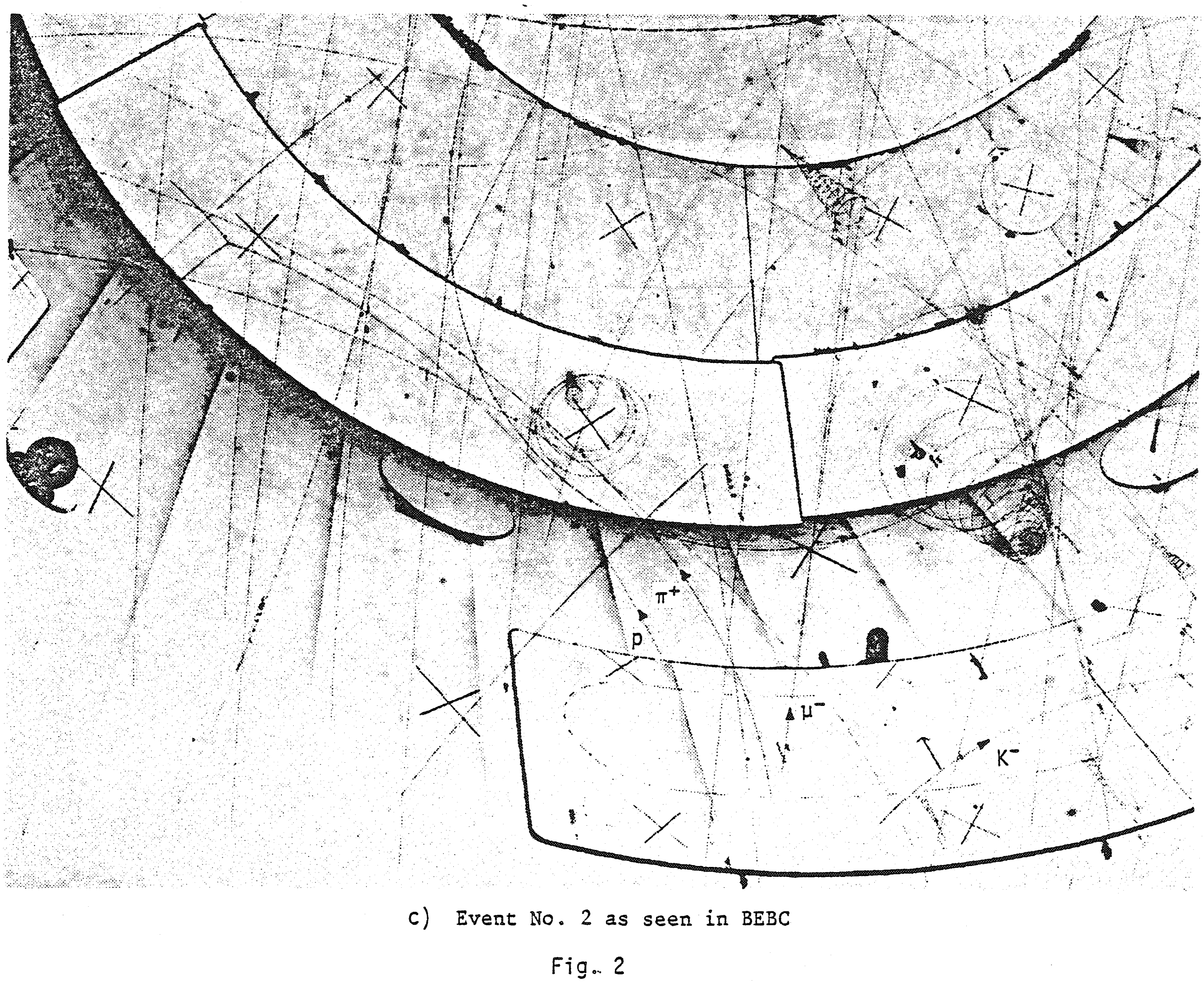
Fig. 1 The experimental set-up of CERN SPS experiment WA17



a) Event No. 2 as seen in the emulsion



b) The decay of the identified Λ_c^+ baryon at point B, as seen under high magnification



c) Event No. 2 as seen in BEBC

Fig. 2

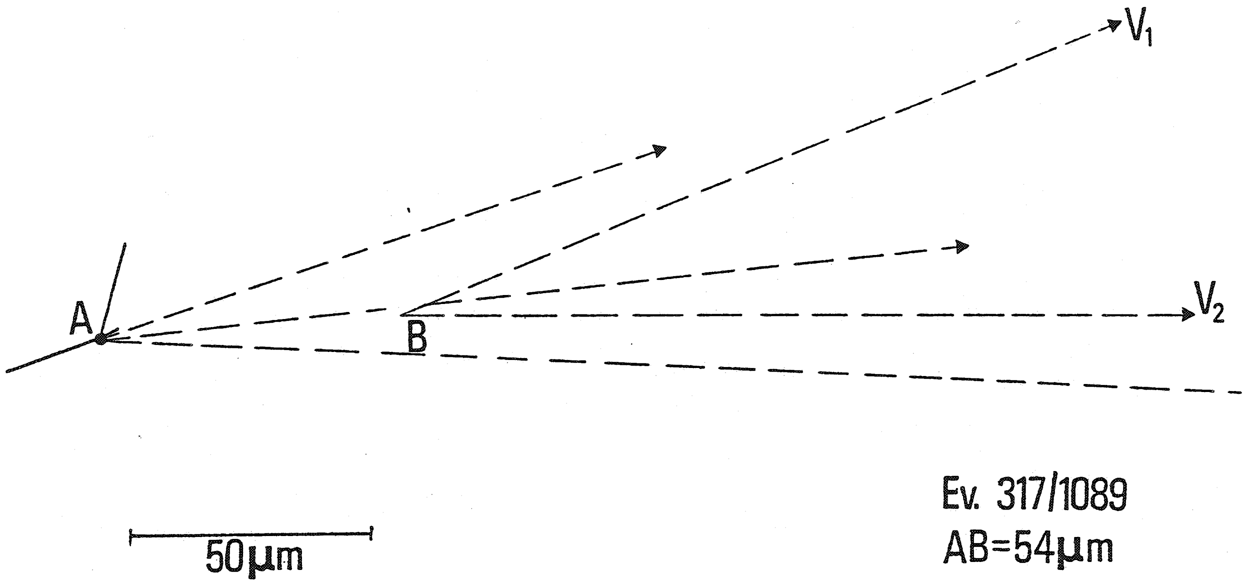


Fig. 3 Sketch of a probable example of ν-induced production and decay of a neutral charmed particle in emulsion (event No. 4). One of the tracks emerging from point A is well correlated with that of a negative muon seen in BEBC and identified by the EMI of BEBC.

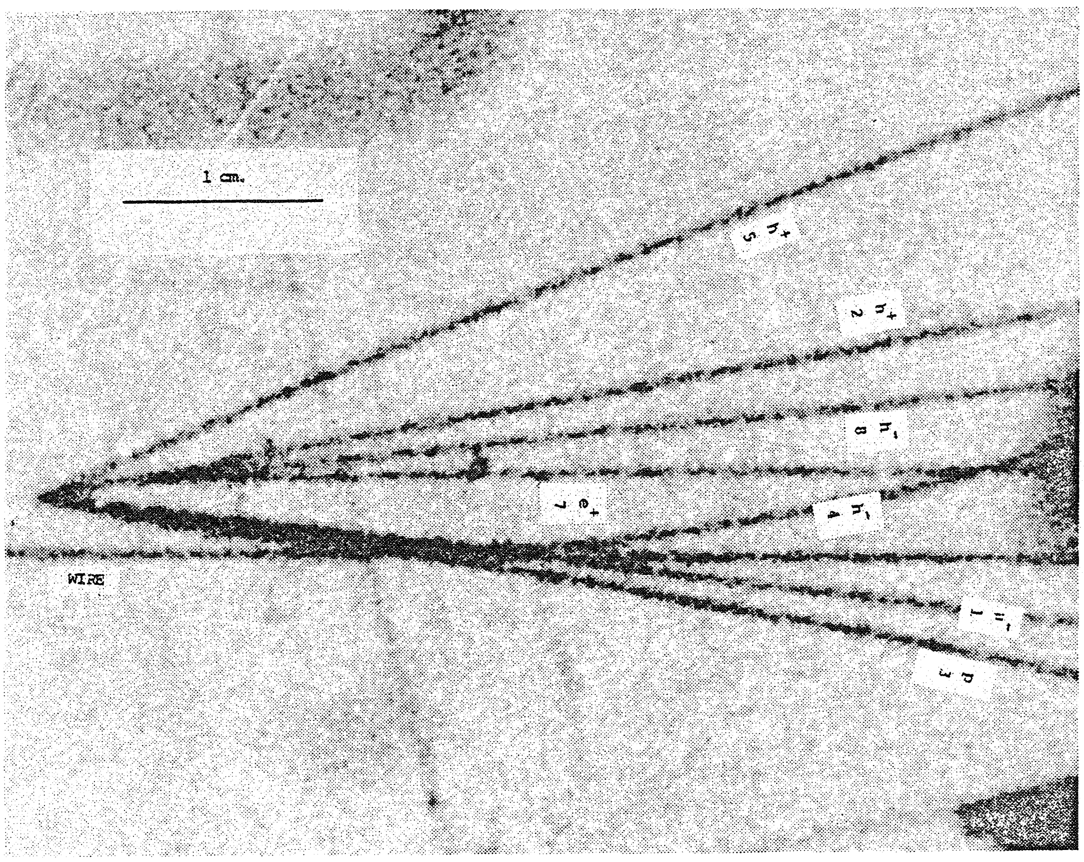
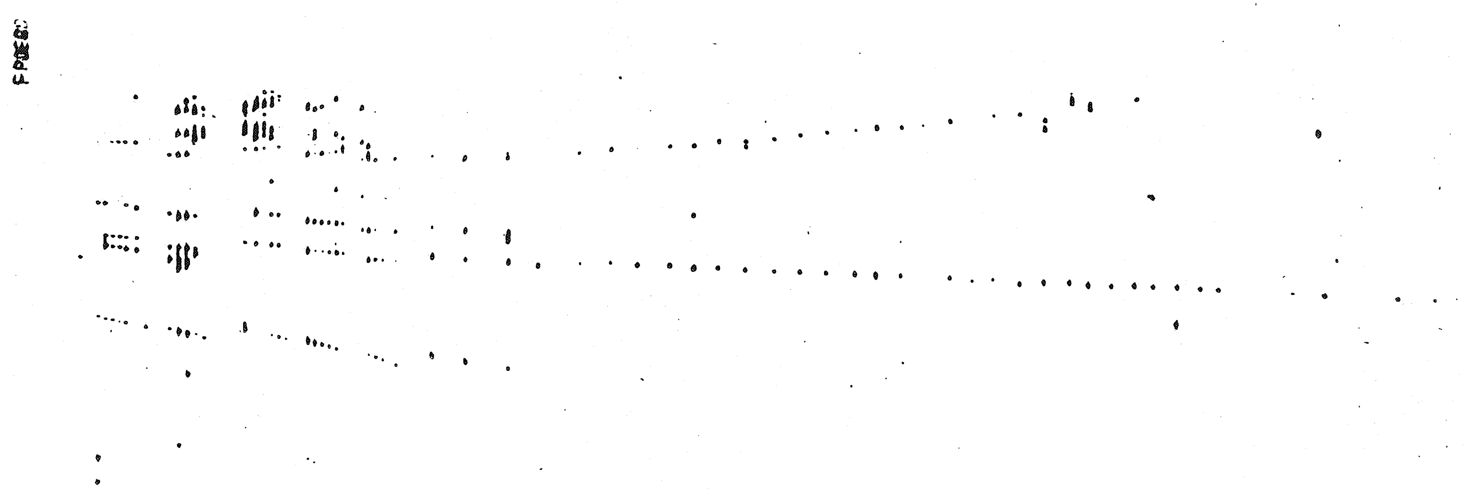


Fig. 4 Probable example of ν-induced production and decay of a neutral charmed particle in the 15' Fermilab bubble chamber (FNAL experiment E246)



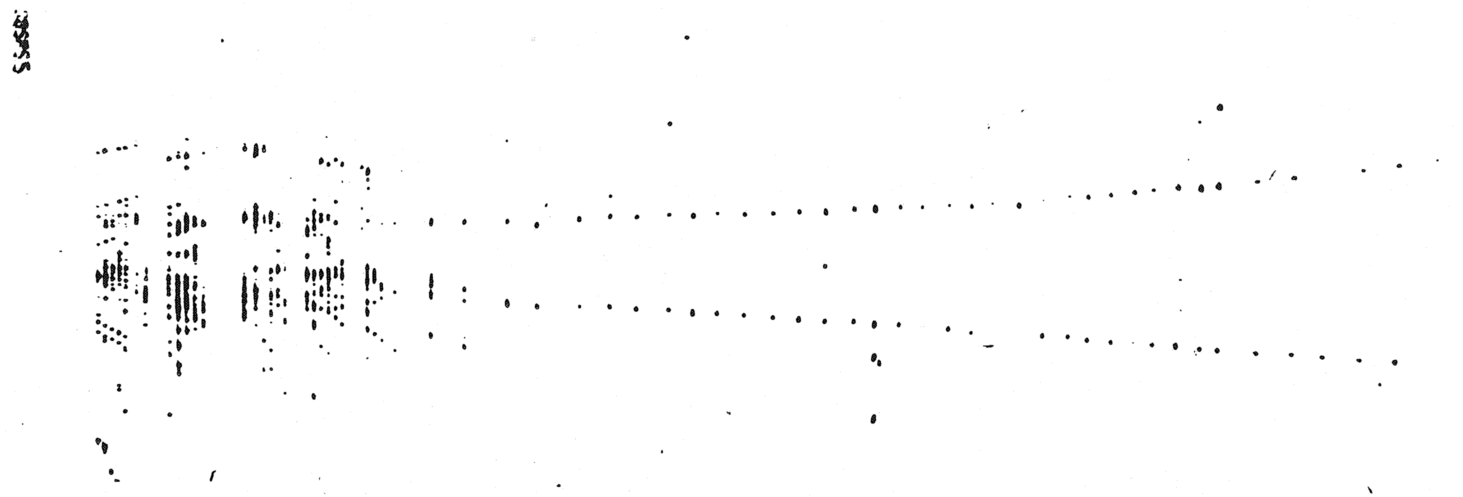


Fig. 5 Two examples of dimuon events recorded in the large plastic flash chamber calorimeter of FNAL experiment 553. The two electromagnetic showers which can be seen on the left of the top photo possibly originate from a π^0 meson decay.