INVESTIGATION OF THE DECAY OF CHARMED PARTICLES

PRODUCED IN NEUTRINO INTERACTIONS

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 - +) It is with deep regret that we record the death of Eric Burhop, and wish to recall his pioneering contribution to this field of Physics.
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- ABSTRACT -

The decay of charmed particles produced by high energy neutrinos has been studied by an experiment using simultaneously emulsion, bubble chamber and counter techniques. Eight charmed particles candidates, 5 of which positively charged and 3 neutral, have been found in the emulsion, where their production and decay have been directly observed. One of these events is identified as a Λ_C^+ baryon of mass $(2.26 \pm 0.02) \text{ GeV}/c^2$ which undergoes the decay $\Lambda_C^+ \rightarrow p \bar{K}^0 \pi^+$ after a proper time of $(7.3 \pm 0.1) 10^{-13} \text{ s}$.

A statistical analysis of the other observed decays leads to the mean-life values

$$\tau^+ = (2.5^{+2.2}_{-1.1}) 10^{-13} \text{ s} ; \quad \tau^0 = (0.53^{+0.57}_{-0.25}) 10^{-13} \text{ s}$$

for the sample of charged particles enriched of a similar event found in a previous experiment, and respectively, for the sample of 3 neutral particles. The former value is only slightly affected including in the sample the Λ_C^+ event or excluding that of the previous experiment.

1. - INTRODUCTION -

The existence of charmed particles, predicted some ten years ago in a classic theoretical work by Glashow, Iliopoulos and Maiani⁽¹⁾, has been now firmly established through extensive experimental investigations.

Soon after the discovery of the J/ψ particle it was found that the properties of this particle could be mostly easily accounted for on the assumption of "hidden charm"⁽²⁾, namely that the J/ψ particle consisted of a charmed quark and a charmed anti-quark. Later new particles were discovered⁽³⁾ compatible with having only one charmed quark or anti-quark amongst their constituents, the particles themselves, therefore, carrying charm. However, the definite conclusion that these newly observed particles were indeed the predicted charmed hadrons required a determination of their lifetimes.

On the assumption that the charm quantum number is conserved in electromagnetic and strong interactions, charmed hadrons are expected to decay weakly to final states containing ordinary (uncharmed) particles with mean lifetimes, τ_c , of the order of 10^{-13} s. Such lifetime values are predicted using current theoretical models⁽⁴⁾ which assume that the decay rates of the charmed hadrons are determined by the rate of the charmed quark beta decay: $c \rightarrow s + e^+ + \nu_e$, corrected for gluon effects⁽⁵⁾.

The production and subsequent decay of particles of lifetimes of the order of 10^{-13} s ($c \cdot \tau_c = \sim 30 \mu\text{m}$) can hardly be directly observed by conventional bubble chamber, spark chamber and counter techniques. The nuclear emulsion technique, on the other hand, with a spatial resolution of the order of $1 \mu\text{m}$, is ideally suited to make such observations, and it is this technique that has been adopted in the present experiment in order to "see" directly the decay of charmed particles produced in neutrino interactions. There are important advantages to be gained by producing these particles using neutrinos rather than other primary particles. These are:

- (a) a higher ratio between the produced charmed and uncharmed final states;
- (b) a smaller average multiplicity of other secondary particles, leading to there being less chance of the charmed particle decay being obscured.

However, because of the very small neutrino interaction cross-sections, large volumes of emulsion and long exposure times are required to collect a reasonable number of events. The emulsion scanning time, which otherwise would be prohibitive, can be drastically reduced by using auxiliary detectors placed mainly downstream of the emulsion target to help in locating the neutrino interaction vertices in the emulsion. The position of the interaction vertex can be deduced by tracing back the tracks of the charged secondary particles observed in the external detectors to their common vertex in the emulsion. For those interactions where the production of a short-lived particle is observed, the external detectors can provide part or all of the relevant information needed for the kinematical analysis of its decay, which is usually not derivable from the emulsion alone.

Such a hybrid technique, using a more primitive set-up, was tested for the first time in a neutrino beam at the CERN PS in 1964⁽⁶⁾; its great potential was demonstrated in an experiment performed at the Fermilab neutrino facility in which the first likely example of the decay of a charmed hadron was directly observed⁽⁷⁾.

In the present experiment, carried out at the CERN SPS neutrino facility, emulsion, bubble chamber, multiwire chamber and counter techniques have been combined for the first time in a large installation and matched to provide the maximum possible information on the single events. Six examples of the neutrino-induced production and decay of short-lived particles obtained in the exposure were preliminarily reported⁽⁸⁻¹¹⁾. This paper gives a full account of the experiment.

2. - EXPERIMENTAL SET-UP -

2.1 General description.

The essential features of the experimental set-up shown schematically in Fig. 1 are briefly presented.

The emulsion was assembled in large stacks, each of ~ 1.5 litres, of 600 μm thick pellicles. The stacks were located in front of the beam entrance window of the Big European Bubble Chamber (BEBC). The emulsion acts as a sensitive target recording both the primary neutrino interaction and the decay of short-lived particles emitted in the interaction with decay paths in the range from a few microns to several millimeters, an interval essentially inaccessible to other techniques.

BEBC, filled with liquid hydrogen and operated in a 35 kG magnetic field, fulfilled two functions. Firstly, the tracks of secondary particles from neutrino interactions occurring in the emulsion could be observed and measured in BEBC to predict the interaction vertices with the help of a vertex reconstruction program ⁽¹²⁾. Secondly, it was used as a magnetic analyser capable of measuring the momenta of the secondary particles. The magnetic field over the region of the emulsion was strong enough (~ 27 kG) to permit charge sign determination by curvature measurements ⁽¹³⁾.

A Veto-Coincidence Counter System (VCS), enclosing the emulsion stacks and coupled electronically to the BEBC External Muon Identifier (EMI) ⁽¹⁴⁾, gave the instant of occurrence of the event in the emulsion and was used to tag the corresponding BEBC frame. Charged current neutrino events (c.c. events) occurring in the emulsion were recognized by the presence, in the appropriate time slot of the EMI ⁽⁺⁾, of a spatially coincident hit for a negatively charged particle, a negative muon with more than 99% confidence level ⁽⁺⁺⁾.

(+) The BEBC EMI records the hits of the muons during the ~ 1.5 ms neutrino beam spill out in several hundred time slots of about 300 ns each.

(++) Because of the 35 kG magnetic field of BEBC and the EMI geometry only muons of momentum greater than ~ 3.5 GeV/c were recorded.

A multiwire chamber (D), representing an integral part of the VCS, was used to intercalibrate the coordinate systems of the emulsion and BEBC taking into account effects due to the expansion of BEBC and motion of the liquid. Chamber D also provided information on the particle trajectories in the dead region between the stacks and the BEBC sensitive volume. Pulse height measurements in the coincidence counter (C) enabled false triggers due to single particles missing the veto counter to be identified.

The VCS system was also used to monitor the integrated background which accumulated in the emulsion during the experiment.

2.2 The emulsion stacks.

Some 3150 pellicles of Ilford G5 and K5 emulsion, each 600 μm thick, 20 cm long and 8 cm wide (total volume ~ 31.5 litres), were assembled in 20 stacks. Each emulsion stack was pressed between two plexiglass bases and the whole block was carefully milled around four edges. Both bases were then connected along their long edge by two plexiglass sheets of thickness 8 mm fixed with screws and pins. In such an arrangement about 85% of the full target mass was made up of emulsion.

The stacks, with the emulsion pellicles horizontal and the short edge along the beam, were mounted on an aluminium frame fixed to a movable chariot placed in front of the BEBC window. The distance between the downstream edge of the emulsion and the bubble chamber liquid was ~ 40 cm, with interposed about 8 g/cm^2 of material (essentially iron).

The emulsion was irradiated in two lots of 10.5 and 21 litres respectively. In the last exposure the stacks were arranged on the frame in such a way as to leave a free space of $(5 \times 60) \text{ cm}^2$ area around the centre of the window for the passage of the RF separated kaon beam, S_3 , utilized for a parallel experiment when BEBC was operated in the double pulsing mode.

After the exposure, the stacks were dismantled and their residual heights were measured every time 10 to 20 emulsion pellicles were removed. Also the thickness and weight of each individual pellicle were measured.

The whole procedure allowed the position of a point within the pelli-
cle to be known with a precision better than 0.5 mm with respect to the
reference system of BEBC.

2.3 The Veto-Coincidence Counter System.

The Veto-Coincidence Counter System (VCS) is shown in Fig. 2. It con-
sisted of two scintillation counters (V and C) and a multiwire proportional
chamber (D); their characteristics are summarized in Tables 1 and 2.

Counter C consisted of four strips of plastic scintillator, each view-
ed from opposite sides by two photomultipliers connected through light
guides of length ~ 4.5 m. The photomultipliers were thus located in a re-
gion where the stray field of BEBC was at the level of about 1 kG, and could
be effectively screened.

The position of counter V was chosen, using a Monte Carlo calculation⁽¹⁵⁾,
as the best compromise between maximizing the angular veto capability and mi-
nimizing the vetoing of "good events" due to the curling effects of the lar-
ge stray magnetic field of BEBC on the secondary charged particles of low mo-
menta.

The passage of a charged particle through counter C gave the trigger si-
gnal for the data acquisition of the EMI-VCS system. For each trigger the fol-
lowing data were recorded on the standard EMI tape:

- a) Pulse height of each of the eight photomultipliers viewing counter C;
- b) The signal, if any, from the veto counter V;
- c) The signal from any of the 1024 wires of chamber D.

The logic signals CV and $\bar{CV}$ were obtained using fast "NIM electronics",
as shown schematically in Fig. 3.

2.4 Installation.

The installation of the emulsion as close as possible to the BEBC window required a large aperture of $(1.5 \times 1.0) \text{ m}^2$ to be made in the 20 cm thick iron screen surrounding the chamber. An accurate remapping of the magnetic field in the region of BEBC entrance window was therefore necessary for an accurate extrapolation of the tracks seen in BEBC back to the neutrino interaction vertex in the emulsion.

The emulsion stacks and all parts of the VCS, except counter C, were mounted on a movable chariot (see Fig. 2). Repositioning the chariot into its running position could be made to an accuracy of $\sim 0.2 \text{ mm}$.

The whole equipment was normally installed inside a pressurized aluminium box in which nitrogen was circulated as required by the safety rules in the BEBC hall. The circulating nitrogen was cooled to guarantee also a temperature between 10° and 15° C and a relative humidity of about 60% over the emulsion region.

3. - BEAM AND RUNNING CONDITIONS -

The emulsion was exposed during two separate runs to the CERN SPS neutrino wide-band beam. Respectively 10.5 l and 21 l of emulsion were irradiated by neutrino fluxes corresponding to 0.3×10^{18} and 0.7×10^{18} protons of 350 GeV/c momentum incident on the neutrino target. The neutrino energy spectrum peaks around 25 GeV and extends up to about 150 GeV.

Emulsions are continuously sensitive, so care had to be taken to keep the time integrated background of both neutral and charged particles present over the region of the stacks within tolerable limits.

Careful measurements were made, before the start of the experiment, which showed that the major background source was due to muons originating from slow spill hadron beams in the West Hall experimental area and from the SPS beam splitter system. Both these contributions were subject to large variations depending on the specific operational modes of the different beams. Efficient shielding of the apparatus being difficult, appropriate

running conditions had to be imposed on the other users during the main exposure of the present experiment.

Hadrons from any sources and muons in equilibrium with the neutrino beam (~ 2 per SPS burst over BEBC beam entrance window) were found to contribute negligibly to the total background which was continuously monitored during the experiment by using counter C in coincidence with gate signals from the SPS ejection system⁽⁺⁾. This monitoring was made both on a burst-by-burst basis and on mechanical registers giving the integrated numbers of particles reaching the emulsion stacks. The exposure was stopped when the integrated muon background had reached the level of 250 particles per mm².

The wire chamber D was read on-line by the EMI read-out system as an additional chamber and the EMI programs were adapted to make specific on-line tests of the apparatus throughout the experiment. Standard tests of chamber D (gas pressure, detection efficiency, cluster size) were done periodically and the stability of the ADC connected to the photomultipliers of counter C was checked.

At the time of the experiment there was no experience of the effect of a magnetic field as intense as 30 kG on the operation of a multiwire chamber. In order to see whether any effect existed, a run was carried out with no field in BEBC, and the results were compared with those of the runs taken with the normal magnetic field in BEBC. The conclusion of this comparison was that, within the chamber resolution of about 1 mm, the field caused no appreciable displacement in the hits of the particles.

(+) In exceptional cases, caused by anomalous phase shifts of the RF signal of the separated kaon beam S₃, the instantaneous rate in coincidence with the gate signal from the fast SPS ejection used for this beam became inaccessible to digital counting methods. An "analogic monitor" was therefore also developed to evaluate this rate on the basis of the integrated current derived from the last dynodes of the photomultipliers viewing counter C.

4. - INTERCALIBRATION MEASUREMENTS -

In order to correlate the reference systems of BEBC and the emulsion stacks, about 2600 tracks due to high energy muons from the neutrino beam were measured in BEBC photos. These tracks were extrapolated back to the position of the multiwire chamber D, and their intersection points with the chamber plane were compared with the real hits, as given by the wires of the chamber. Let d_i be the distance between the extrapolated intersection point for the i^{th} track and the corresponding hit, and σ_i the associated error, which is mostly due to the 2 mm chamber wire spacing. Then the chamber position is obtained by minimizing the $\chi^2 = \sum_i (d_i^2 / \sigma_i^2)$, once d_i is expressed as a function of the geometric parameters of the chamber (coordinates of the centre and Euler angles between BEBC and the chamber reference systems).

By means of these "intercalibration measurements" the position of chamber D, with respect to BEBC reference system, could be located with an accuracy of about ± 1.5 mm in the beam direction (x), ± 0.2 mm in the transverse direction (horizontal, y, and vertical, z) and less than ± 1 mrad in the Euler angles.

In order to clarify these results Fig. 4 gives as an example the distribution of the differences between the extrapolated points and the real hits along the transverse horizontal coordinate y. A similar distribution holds for the vertical coordinate, z.

On the other hand, the position of the chamber along the beam direction, x, could be estimated exploiting the angular spread of the incoming muons, which had incident angles θ within about 50 mrad.

Clearly the differences Δy , Δz depend in general on θ , except when they are computed with the chamber located in the right position (see Fig. 5). Similarly, the Euler angles can be obtained exploiting the fact that the muons were incident over all the chamber plane, and that Δy , Δz did not depend on the hit points.

The reproducibility of the position of chamber D with respect to BEBC was checked several times during the exposures.

Finally the position of the emulsion stacks with respect to chamber D was obtained from accurate mechanical measurements before and after the runs.

5. - EVENT SEARCH PROCEDURE -

The search for neutrino interactions in the emulsion was carried out in three steps

- (i) analysis of the BEBC photos
- (ii) vertex prediction
- (iii) emulsion scanning.

These are now briefly described.

5.1 Analysis of the BEBC photos.

A total of 206.000 pictures was scanned for event configurations showing the tracks of at least three particles emerging from the BEBC window and apparently converging to a point inside the emulsion. At least one of these particles had to have a momentum larger than 3 GeV/c. In this way about 1 event candidate out of 40 frames was selected for measurement .

In part of the film, the selection of the photos to be scanned was made by using the pulse-height information on counter C.

Measured tracks were processed through the standard BEBC program chain (geometry + EMI) which provided track parameters at the BEBC entrance window and muon identification.

5.2 Vertex prediction.

Those tracks that appeared to be pointing to a common vertex were traced back using a "vertex program" which took into account the BEBC magnetic field and the energy loss of the particles in the traversed materials; BEBC measurement errors and the effects of multiple scattering were also propagated backward.

During the tracing back, the coordinates of the intersection points (y_i, z_i) with N planes, perpendicular to the beam direction, equispaced and spanning all the emulsion region, were computed together with the corresponding errors.

In each plane k ($k = 1, 2, \dots, N$) a weighted mean of the intersections can be defined, having the coordinates:

$$y_o(k) = \sum_i y_i(k) \cdot P_y^{(i)}(k) \quad ; \quad z_o(k) = \sum_i z_i(k) \cdot P_z^{(i)}(k)$$

where

$$P_{y,z}^{(i)}(k) = \frac{(1/\sigma_{y,z}^{(i)}(k))^2}{\sum_i (1/\sigma_{y,z}^{(i)}(k))^2}$$

and $\sigma_{y,z}^i$ is the error in y, z for particle i ($i = 1, 2, \dots, n$).

The corresponding errors are:

$$\sigma_{y_o} = \{ \sum_i (1/\sigma_y^{(i)})^2 \}^{-1/2} \quad , \quad \sigma_{x_o} = \{ \sum_i (1/\sigma_z^{(i)})^2 \}^{-1/2}$$

A $\chi^2(k) = \sum_i (d_i^2/\Delta_i^2)$ can be defined, where d_i is the distance of each intersection from (y_o, z_o) and Δ_i is the corresponding error. The coordinate parallel to the beam direction (x_o) for the plane for which the χ^2 is minimum, defines, together with the corresponding y_o and z_o , the first approximation to the vertex.

The procedure was then repeated, with a smaller x interval centred around the previous minimum until a satisfactory minimum was found. At each iteration a test was done, on the plane of minimum χ^2 , to check whether the distance in the y, z plane of each track from the "centre of gravity" was compatible with the propagated errors. If it was not, the worst track was considered as being spurious and rejected. When the final minimum was reached, a parabolic fit to the $\chi^2(k)$ was made to get the error in the x direction.

Typical errors on the predicted vertices were about 7 mm along and about 0.7 mm transverse to the beam direction.

In order to check that the vertex prediction was insensitive to the mathematical method, a second program was developed in which the measured track parameters were varied to force all tracks to converge to a com-

mon point. This fitting procedure also took into account the measurement and multiple scattering errors and allowed the definition of a χ^2 with $2T-3$ degrees of freedom, T being the number of converging tracks. The program was applied to most of the recorded events, and gave results entirely consistent with those obtained by the first method.

5.3 Emulsion scanning.

Since charmed hadron production by muon-neutrinos is expected to occur dominantly through the elementary process $\nu_\mu d \rightarrow \mu^- c$, the systematic search in emulsion was restricted to (i) all the events identified as charged-current candidates by the EMI-VCS system (483 events) and (ii) the events for which no EMI information was available but in which the particle of both higher longitudinal (p_L) and transverse ($p_\perp$) momenta measured in BEBC was of negative charge and left the chamber without interaction (40 events).

The poor quality of the emulsion (low minimum of ionization, and some fogging) as well as the high level of muon track background precluded any systematic "along-the-track" scanning being performed which would have allowed the detection with high efficiency of the neutrino interaction vertices even in the absence of nuclear evaporation fragments.

An area scan was therefore carried out for the bulk of the events under 200 x to 300 x magnification, over an emulsion volume centred on the predicted vertex position and of minimum dimensions: 7 plates, 5 mm in y and 31 mm in x . The scanning was stopped when a neutrino event (see definition below) was found. When no event had been detected the search was extended to a minimum volume corresponding to three standard deviations on the three predicted coordinates.

During the scanning all interactions occurring in the emulsion were noted and carefully examined under high magnification (~ 800 x) for the presence of minimum ionization tracks in the forward hemisphere. For the events found in the emulsion, and not clearly incompatible with the patterns expected on the basis of BEBC predictions, the emission angles of the minimum ionization tracks were measured with an accuracy of about 0.5° in azimuth and 1° in dip.

5.3.1 Selection of neutrino interactions.

Stars were accepted as "found neutrino events" if they (i) contained no minimum ionization track coming from the beam direction⁽⁺⁾; (ii) consisted of tracks which could be followed from pellicle to pellicle⁽⁺⁺⁾; (iii) contained at least two tracks of minimum ionization with azimuth and dip angles, measured in emulsion, agreeing within 3° with the corresponding predicted angles of two tracks measured on the BEBC photograph. For each star to be accepted as a c.c. neutrino event one of these matched tracks had to be due to the negative muon as identified by the EMI-VCS system or selected by the higher p_L , $p_{\perp}$ criterion.

5.3.2 Search for charmed events.

To search for decays of charged charmed particles the minimum ionization tracks from the found neutrino events were followed through the stack for at least 5 mm from the interaction vertex, unless the corresponding particles interacted or left the stacks earlier.

To search for decays of neutral charmed particles an area scan at high magnification (800 x) was carried out within a cone of 30° opening angle to a distance of 2 mm from the neutrino interaction vertex.

Particular care was paid to c.c. events with bubble chamber tracks unassociated with tracks from the neutrino interaction in emulsion, as this might indicate the decay of a charmed particle a little further downstream of the neutrino interaction vertex.

(+) About 8% of the stars had such a primary track showing that they were of hadronic origin.

(++) Events due to cosmic ray interactions occurring in the emulsion before the stack assembly were eliminated by this requirement.

6. - EVENT SEARCH RESULTS -

6.1 Predicted and found neutrino events.

The 206.000 BEBC photos selected, scanned and processed as outlined in Section 5 led to prediction of 935 neutrino interaction vertices inside the emulsion, 523 of which were c.c. events.

The 523 predictions of c.c. neutrino events and a fraction ($\sim 60\%$) of the remaining 412 predictions, were scanned leading to 214 "found events". Among these 169 were c.c. events, all the criteria listed in Section 5.3.1 being fulfilled.

The distributions of the differences Δx , Δy , Δz between predicted and found coordinates are given in Figs 6 a), b), c). The r.m.s. of these distributions are ~ 1 mm in the y and z coordinate and ~ 8 mm in x, somewhat larger than the values predicted from the vertex program.

Relevant data on the predicted and found c.c. neutrino events are reported in Table 3.

Table 4 gives the breakdown of the 169 found c.c. neutrino interactions in terms of numbers of minimum ionization (n_s) and heavily ionizing particles (n_H).

Out of the 169 found c.c. events, the following 8 candidates of charmed particle decays were found:

- 3 charged particles decaying with a three prong configuration
- 3 neutral particles decaying with a two prong configuration
- 2 charged particles decaying with a one prong configuration.

It is worth while mentioning also the observation of the following events found in the sample of 169 c.c. interactions:

- 1) two events showing secondary interactions occurring at $2 \mu\text{m}$ and $3 \mu\text{m}$ respectively from the primary neutrino interaction vertices, both compatible with the non-mesonic decay of ordinary heavy spallation Λ^0 -hypernuclei;
- 2) one event exhibiting the production of a Λ^0 -hyperon with a momentum of $(550 \pm 50) \text{ MeV/c}$, which was associated to the neutrino interaction and underwent the decay process $\Lambda^0 \rightarrow p + \pi^-$ after a path of $395 \mu\text{m}$.

6.2 Detection efficiencies.

The scanning requirements outlined in Section 5.1, the limited angular acceptance, the curling effects of the strong magnetic field on charged particles, the EMI inefficiency for low energy muons ($E_\mu < \sim 3.5$ GeV)⁽⁺⁾, and any possible inefficiency in the vertex reconstruction procedure, all led to losses of c.c. neutrino events which have been estimated by a Monte Carlo simulation.

Events generated in the emulsion were selected if their topological appearance in the bubble chamber satisfied the scanning criteria, and analyzed using the vertex reconstruction program. The over-all efficiency of the method was found to be $\sim 65\%$. This figure should then be multiplied by a $\sim 95\%$ scan efficiency, estimated from a double scan of about one-third of the film.

This detection efficiency was checked empirically using the information from a parallel BEBC experiment (WA 21)⁽⁺⁺⁾. From the number of charged current events observed inside the bubble chamber, in a fiducial volume just behind the stacks, the number of events in the emulsion was inferred to be between 850 and 900 once allowance was made for the isoscalar nature of the emulsion target. Comparing this number with the actual number of predicted vertices (523, see Table 3) leads to an efficiency value ($\sim 60\%$) consistent with that derived from the Monte Carlo simulation.

The loss occurs mainly for low multiplicity events, as can be seen in Fig. 7 a) where the multiplicity distribution of fast particles for the found events is compared with that observed in a "Gargamelle" exposure to the wide band neutrino beam⁽⁺⁺⁺⁾. Fig. 7 b) shows the distributions of BEBC multiplicity for predicted and found events. The lower average track multiplicity in BEBC with respect to that seen in emulsion for the same events is a consequence of the limited acceptance, and other effects mentioned previously. These latter effects are also seen in the distributions of visible energy in BEBC reported in Fig. 8 for the predicted and found neutrino events.

(+) The EMI-VCS system had also an estimated over-all inefficiency of $\sim 10\%$ for muons of energy greater than 3.5 GeV.

(++) We wish to thank the members of the Collaboration of experiment WA 21 for all information received throughout the parallel runs.

(+++)

Unpublished data kindly supplied by the WA14 Collaboration.

It was also checked that the detection efficiency for charmed events was almost the same as for ordinary c.c. events. This was done by a Monte Carlo simulation which used, as input data, the vector momenta of the particles emitted in a sample of $182 e^+ \mu^-$ attributed to charmed particle decays⁽⁺⁾, observed in the Fermilab 15' bubble chamber exposure of C.Baltay et al.⁽¹⁶⁾.

As a result of bad measurements in BEBC, wrong tracks association, and/or secondary interactions occurring in the emulsion or in the BEBC window, the predicted vertex could be located far from its real position. Although these effects are difficult to estimate, they are expected to influence more those predictions based on a small number of converging tracks. This is clearly illustrated in Table 3 where the fraction of found events is reported as a function of the number of converging tracks used in predicting the vertex position. The fraction is constant and about 45% for multiplicities greater than three but drops significantly for multiplicities of three and two.

Other losses occurred at the emulsion level, mainly due to the over-all poor and in some instance abysmal sensitivity of the emulsion used. The situation is illustrated in Fig. 9 where the percent efficiency, ε_f , of finding the predicted vertices is plotted against the blob (grain) density, b_0 , for fast (minimum ionization) particles as measured from the observed events. It is seen from this figure that ε_f drops from $\sim 50\%$ for $b_0 = 21$ blobs/100 μm to $\sim 11\%$ for $b_0 = 8$ blobs/100 μm .

Neutrino interactions with no appreciable sign of nuclear evaporation were mostly lost in the present experiment, where the event search by "area scan" was imposed by the unfavourable experimental conditions (Section 5.3). This was an important loss if it is true that some 30% of the neutrino interactions are of such a type, as claimed for a recent neutrino emulsion experiment⁽¹⁷⁾ to which a "track following" technique could be applied.

Apart from an over-all scanning inefficiency, other losses at a maximum level of some 10% are expected to arise from edge effects (see Fig. 10 a) and 10 b)) and limitations in the search volume.

(+) We are greatly indebted to Dr. C.Baltay for providing us the relevant data on these $182 e^+ \mu^-$ events.

7. - CHARMED CANDIDATES -

The main characteristics of the 8 found candidates for the neutrino production and subsequent decay of charmed particles are reported in Table 5. The 3 charged particles decaying with a three-prong configuration and the 3 neutral particles decaying with a two-prong configuration have been discussed elsewhere⁽⁸⁻¹¹⁾.

One of the three charged particles (event n.2) has been identified as a Λ_C^+ baryon of mass⁽⁺⁾ $M(\Lambda_C^+) = (2.26 \pm 0.02) \text{ GeV}/c^2$, which after a time $t = (7.3 \pm 0.1) \cdot 10^{-13} \text{ s}$ undergoes the decay process $\Lambda_C^+ \rightarrow p k^- \pi^+$. The proton was unambiguously identified by its elastic pp scattering in BEBC, and the k^- meson by combined measurements of its momentum in BEBC and its relative ionization in emulsion. The kinematical analysis indicates that the final state is reached through an intermediate $k^{*0}(892)$ -proton state ($\Lambda_C^+ \rightarrow p k^{*0}$, $k^{*0} \rightarrow k^- \pi^+$).

For the remaining 2 three-prong decays, various assignments as Λ_C^+ , D^+ or F^+ were obtained, in all cases with at least one missing neutral decay particle.

The three neutral particles have been shown to be compatible with D^0 meson decays involving neutral secondaries. The kinematical analysis of event n.4 shows that it is compatible with the production of a $D^{*+}(2010)$ which decays strongly to a $D^0 \pi^+$ state ($D^{*+} \rightarrow D^0 \pi^+$).

Details on the 2 one-prong decay candidates are given in Table 6. The changes in direction observed for these events were 7.6° and 10.8° and occurred, respectively, at 317 and 1595 μm from the primary c.c. neutrino interaction vertices. Both decay particles, seen in BEBC, are positively charged and have momenta of 2.4 and 2.9 GeV/c , respectively. In each case the kinematics are inconsistent with the decay of a k^+ meson or Σ^+ hyperon.

(+) This mass value, slightly smaller than that ($2.295 \text{ GeV}/c^2$) previously reported⁽⁹⁾, takes into account a small correction for the thickness of the emulsion pellicle at the position where the event occurred, which turns out to be $\sim 5\%$ smaller than the average pellicle thickness used previously. The uncertainty in the local thickness is included in the new quoted error.

Hence, the only alternative possibility to charmed particle decay is that the two events be ascribed to nuclear scatterings of ordinary hadrons. However, the corresponding probability, computed taking into account of the results quoted above and using previously published data on pion scattering in emulsion⁽¹⁸⁾, is found to be less than 10^{-3} .

8. - EVALUATION OF CHARMED PARTICLE MEAN LIFETIMES -

Only one of the found charmed particle candidates (ev. nr.2) was uniquely identified. The proper decay time, $t = L/\beta c\gamma$, was derived in this case with no ambiguity from the measured decay path, L , and the known value of the velocity of the decaying particle. In all other cases this derivation is not possible since there are undetected neutrals among the decay products and ambiguities are present in the kinematic analysis. It can be shown⁽¹⁹⁾, however, that under certain assumptions which are essentially verified for the events listed in Table 5, an estimate of the mean lifetime τ_c is possible even if the velocity of the decaying particle is unknown. The method derives the value of τ_c from the distribution of the measured distances, Δ , between the lines of flight of the decay particles and the production vertex⁽⁺⁾, using the fact that Δ is nearly independent of β when the decaying particles are energetic ($\beta \approx 1$) and massive enough ($\beta^* \approx 1$, where β^* are the C.M.-velocities of the decay products) as in the present experiment.

On the assumption that the angular distribution of the decay particles is isotropic in the C.M.-system and that Δ is determined with no bias and with a negligible error, the distribution function, $f(y)$ of the dimensionless quantity $y = \Delta/c\tau_c$ is given by⁽¹⁹⁾ $f(y) = 2 \int_0^\infty [yz^2/(z^2 + y^2)^2] \exp(-z) \cdot dz$ ($z = t/\tau_c$) for a sample of one prong decay events. This distribution function

(+) Note that by definition $\Delta = L \sin \theta = \beta c \gamma t \sin \theta$, where L is the decay path and θ is the angle between the decay and the parent particle trajectories in the laboratory system. In the limit $\beta \rightarrow 1, \beta^* \rightarrow 1$ one finds $\Delta = v c t \cdot \tan(\theta^*/2)$, where θ^* is the angle in the C.M.-system corresponding to θ .

can be modified, as shown in reference 19, to take into account that n values of Δ are obtained for a single event with n decay prongs. The Maximum Likelihood method can then be applied to the distribution function to derive the meanlife τ_c and the statistical error from the measured values of Δ .

The measured values of Θ and Δ are reported in Table 7 for the 8 events found in the present experiment and for the first event (exhibiting a three prong decay configuration and labelled "O" in the table) found in a previous neutrino experiment⁽⁷⁾.

On the assumption that (i) the charged events other than event n.2 are all due to D^+ mesons, (ii) the neutral events are all due to D^0 mesons and, (iii) there is no preferential loss of D^0 mesons with increasing decay length, the mean lives derived by the method outlined above are found to be:

$$\tau^+ = (2.5 \begin{smallmatrix} + 2.2 \\ - 1.1 \end{smallmatrix}) \cdot 10^{-13} \text{ s}$$

$$\tau^0 = (0.53 \begin{smallmatrix} + 0.57 \\ - 0.25 \end{smallmatrix}) \cdot 10^{-13} \text{ s}$$

These results are best expressed by the probability distribution functions shown in Fig. 11.

The addition of the Λ_c^+ event to the sample of charged charmed candidates results in a $\sim 10\%$ increase in the value of τ^+ ($\tau^+ = 2.8^{+2.0}_{-1.1}$); the subtraction of event "O" has no appreciable effect on the central value of τ^+ .

The ratio between the mean lifetimes of the D^+ and D^0 mesons is found to be

$$\tau^+/\tau^0 = 5 \begin{smallmatrix} + 6 \\ - 3 \end{smallmatrix}$$

This result provides a direct confirmation of that indirectly inferred from the leptonic branching ratios (B^+ and B^0) of the D^+ and D^0 mesons measured by electron-positron colliding beams⁽²⁰⁾ ($B^+/B^0 = \tau^+/\tau^0 > 4$, with 95% c.l.).

The results given above for the lifetimes of charmed particles are consistent with those preliminarily reported¹⁷⁾ for a sample of 10 events with kinematic fits found in a recent neutrino emulsion exposure at Fermilab.

9. - CONCLUSIONS -

In the present experiment, 8 examples of the neutrino induced production and subsequent decay of charmed particles have been observed. Five of these particles were found to be positively charged and three were neutral. One particle has been identified as a Λ_c^+ baryon with a mass of (2.26 ± 0.02) GeV/c² and underwent the decay process $\Lambda_c^+ \rightarrow p k^- \pi^+$ after a proper time $t = (7.3 \pm 0.1) \cdot 10^{-13}$ s.

With the assumptions mentioned in the previous Section the mean lifetimes of D^+ and D^0 mesons are found to be respectively $\tau^+ = (2.5^{+2.2}_{-1.1}) \cdot 10^{-13}$ s and $\tau^0 = (0.53^{+0.57}_{-0.25}) \cdot 10^{-13}$ s.

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TABLE 1 - Relevant data on the "coincidence" (C) and "veto" (V) scintillation counters, both made of plastic material 2 cm thick and viewed by photomultipliers (Philips 56 AVP) through plexiglass light pipes ~ 4.5 m long.

	Counter C	Counter V
Structure and shape	Four rectangular strips 128 cm long	Single rectangle
Horizontal width	128 cm	140 cm
Vertical height	28 cm	40 cm
Distance from BEBC window	0.5 cm	42 cm
Total nr. of photomultipliers	8	4

TABLE 2 - Relevant data on multiwire chamber D.

Useful area	$128 \times 28 \text{ cm}^2$
Total nr. of wires	1024
Nr. of wire planes	3 (horizontal and $\pm 45^\circ$ inclin.)
Gap	6 mm
Wire diameter	20 μm
Wire spacing	2 mm
Operating voltage	~ 3.8 k Volt
Gas mixture	70% A and 30% CO_2

TABLE 3 - Numbers of c.c. neutrino events predicted by the "vertex program" (column 2) as a function of the numbers of BEBC tracks (column 1) accepted by the program as converging to an interaction vertex. The corresponding numbers of found c.c. events are also given (column 3) together with their breakdown (column 4) in terms of the numbers of emulsion tracks which match the predictions within $\pm 3^\circ$. The "finding efficiency" is also reported in the last column.

Nr. of converging tracks (1)	Nr. of predicted vertices (2)	Nr. of found events (3)	Breakdown of found events for Nr. of matching emulsion tracks								Finding efficiency (5) = (3)/(2)
			2	3	4	5	6	7	8	(4)	
2	118	17	17								.14
3	167	50	16	34							.30
4	110	45	5	15	25						.41
5	70	32	1	6	9	16					.46
6	38	14	1	1	1	6	5				.37
7	10	5	0	1	0	1	0	3			.50
8	10	6	0	0	1	2	1	0	2		.60
	523	169	40	57	36	25	6	3	2		.32

TABLE 4 - Numbers of c.c. neutrino interactions as a function of n_s and n_H
(the numbers of minimum and heavily ionizing particles, respectively).

n_s $\downarrow$	$n_H \rightarrow$																				
	0	2	4	6	8	10	12	14	16	18	20	22	24	25							
2	-	1	-	1	-	-	1	-	-	-	-	-	-	-	5						
3	-	-	2	1	-	-	1	-	-	-	-	-	-	-	9						
4	-	1	2	3	1	1	-	-	-	-	-	-	1	-	18						
5	2	1	3	4	5	3	2	3	4	1	1	1	-	-	33						
6	-	2	4	5	3	1	3	-	3	-	1	1	-	1	27						
7	-	1	2	2	-	3	2	2	1	2	4	-	2	-	25						
8	1	2	1	2	1	4	-	2	2	-	1	1	1	-	20						
9	-	1	1	-	-	2	-	1	-	1	-	-	-	1	7						
10	1	1	-	1	-	-	-	1	2	-	1	2	1	-	12						
11	-	-	-	1	-	1	1	-	-	-	-	-	-	1	4						
12	-	-	-	-	-	-	-	-	-	-	1	-	-	1	3						
13	-	-	-	-	-	-	-	-	-	-	-	-	1	-	2						
14	-	-	1	-	-	-	-	-	-	-	-	-	-	1	2						
15	-	1	-	-	1	-	-	-	-	-	-	-	-	-	2						
	4	11	16	20	14	15	11	9	16	4	6	10	5	5	3	-	1	1	4	1	169

TABLE 5 - Charmed event candidates.

Event nr.	Charge of prim. part.	nr. of prongs	Final state	Nature of prim. part.	Decay path AB
1	+	3	$\left\{ \begin{array}{l} \geq 4 \text{ body} \\ \text{for } \Delta S = \Delta C \end{array} \right.$	?	96 μm
2	+	3	$p k^- \pi^+$	Λ_c^+ baryon (identified)	354 μm
3	+	3	$\geq 4 \text{ body}$	?	906 μm
4	0	2	$\geq 3 \text{ body}$	D^0 meson	54 μm
5	0	2	$\geq 3 \text{ body}$	D^0 meson	115 μm
6	0	2	$\geq 3 \text{ body}$	D^0 meson	182 μm
7	+	1	$\geq 2 \text{ body}$	?	317 μm
8	+	1	$\geq 2 \text{ body}$	?	1595 μm

TABLE 6 - Results of measurements on the two candidates of charmed particles produced at point A and decaying at point B with a one prong configuration.

Event nr.7; AB = 317 μ m			x(mm)	y(mm)	plate	
Predicted vertex			68.7 $\pm$ 4.3	62.6 $\pm$ 0.4	63.7 $\pm$ 1.5	
Found vertex			76.4	61.5	63	

Track Parameters in Emulsion			Predicted parameters at vertex from BEBC measurements			
<u>Track</u>	<u>Dip</u>	<u>Azimuth</u>	<u>Dip</u>	<u>Azimuth</u>	<u>Momentum</u> (GeV/c)	<u>Charge</u>
(1)	-26.5°	-16.0°	-30.4°	-20.6°	0.7	+
(2)	35.0°	-16.0°		not seen		
(3)	-9.5°	-5.5°	-10.1°	-5.4°	1.6	+
x (4)	2.0°	-5.0°				
xx (4)	9.5°	-3.5°	10.8°	-4.1°	2.4	+
(5)	-8.0°	-4.0°	-8.2°	-4.0°	3.7	+
(6)	3.0°	-2.0°	3.0°	-1.6°	34.3	- (μ^-)
(7)	-14.5°	6.0°		not seen		
	not seen		2.7°	-2.6°	4.9	+

Event nr.8; AB = 1595 μ m			x(mm)	y(mm)	plate	
Predicted vertex			130.4 $\pm$ 7.1	112.4 $\pm$ 0.6	56.1 $\pm$ 1.4	
Found vertex			119.9	109.9	54.0	

Emulsion			BEBC			
<u>Track</u>	<u>Dip</u>	<u>Azimuth</u>	<u>Dip</u>	<u>Azimuth</u>	<u>Momentum</u> (GeV/c)	<u>Charge</u>
(1)	22.4°	9.1°				
(2)	21.9°	-8.9°		not seen		
(3)	1.5°	-8.5°	0.5°	-9.4°	17.1	- (μ^-)
(4)	3.6°	8.7°	2.7°	7.8°	2.1	+
x (5)	1.6°	9.9°				
xx (5)	-0.9°	-0.6°	-2.8°	-1.3°	2.9	+

x Before point B

xx After point B

TABLE 7 - Decay angle θ , and distance Δ , between line of flight of decay prong and primary interaction vertex (A) for the 8 charmed event candidates found in the present experiment and the event, labelled "0", reported in Ref. 7). Also the decay paths (AB) are given.

Event	nr. of prongs	AB (μm)	θ (degrees)	Δ (μm)
0	3	182	19.9	61.9
			14.0	44.0
			18.5	57.7
1	3	96	15.2	25.2
			4.1	6.9
			15.2	25.2
2	3	354	14.5	88.6
			19.6	118.7
			24.7	147.9
3	3	906	12.0	188.4
			5.5	86.8
			0.5	7.9
4	2	54	17.2	16.0
			7.0	6.5
5	2	115	18.1	35.8
			7.0	14.0
6	2	182	3.6	11.5
			3.5	11.0
7	1	317	7.6	41.9
8	1	1595	10.8	298.9

- FIGURE CAPTIONS -

- Fig. 1 - Lay-out of the experimental set-up. The External Muon Identifier (EMI), not shown in the figure, was about 9 m downstream from the center of the BEBC.
- Fig. 2 - Schematic prospective view of the Veto-coincidence Counter System, VCS, mounted on the movable "chariot" in front of BEBC beam entrance window.
- Fig. 3 - Formation of the logic signals CV, $\bar{CV}$. The symbol D indicates discriminator circuit; the symbols $C_{i,i+1}$ indicate coincidence signals (used to get rid of photomultiplier noise) from pairs of photomultipliers placed on the opposite sides of each counter strip.
- Fig. 4 - Distribution of the differences Δy between the extrapolated points and the real hits along the transverse horizontal coordinate, y , as derived from the "intercalibration measurements".
- Fig. 5 - Dependence of Δy on the incident angle θ for three positions of the multiwire chamber along the beam coordinate x .
- Fig. 6 - Distribution of the differences Δx (a), Δy (b), Δz (c) between predicted and observed values of the vertex coordinates, x , y , z , of charged current neutrino interactions in the emulsion.
- Fig. 7 - Multiplicity distributions of c.c. neutrino events as seen (a) in emulsion (full lines histogram) and for comparison in the heavy liquid of "Gargamelle" (dotted lines), and, (b) in BEBC. The cross hatched histogram refers to the multiplicity distribution in BEBC for the found events.
- Fig. 8 - Distribution of visible energy in BEBC for c.c. neutrino events. The cross-hatched histogram refers to the found events.
- Fig. 9 - Percent efficiency in finding the predicted vertices as a function of the grain density (blobs per 100 μm) for particles of minimum ionization.
- Fig. 10 - a) Distribution along the beam coordinate x , of predicted and found (cross -hatched histogram) c.c. neutrino events. The arrows indicate the limits of the emulsion stack.
b) Distribution along the plate thickness of the found c.c. neutrino events normalized to unity.
- Fig. 11 - Maximum likelihood logarithm as a function of meanlife τ for positively charged (D^+) and neutral (D^0) charmed particle candidates. The intervals in τ corresponding to one standard deviation are shown.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6a

Fig. 6b

Fig. 6c

Fig. 7

Fig. 8

Fig. 9

Fig. 10a

b)

Fig. 10b

Fig. 11