THE NEUTRINO PRODUCTION & WEAK DECAY OF CHARMED HADRONS

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Summary

Preliminary measurements of the lifetimes of weakly decaying charmed hadrons, obtained from Fermilab Experiment 531 are reported in this paper. The decay lengths of charmed particles produced by neutrinos were measured in the emulsion target. Measurements of the momenta of the charged and neutral decay products in a downstream spectrometer located the events in the emulsion and provided the mass and momentum of the decaying particle thus allowing the conversion of decay lengths to decay times in the unstable particle rest frame. Preliminary values for the Λc, D^0, $F^\pm$ and $D^\pm$ lifetimes are reported.

Introduction

Since before the discovery of the J/ψ theorists have used weak interaction models to estimate that charmed particle lifetimes will lie in the region of 10^{-14} to 10^{-11} seconds[2]. Photographic emulsions, with a spatial resolution of a few microns, provide the means to measure the track lengths of such short lived particles between their production and decay point. However the observation of a decay length $\ell = \beta\gamma\tau$ can only be converted to a decay time in the particle rest frame by a simultaneous measurement of $\beta\gamma$. We have therefore combined a large stack of emulsion (24 litres), which serves as production target and decay length detector with a charged and neutral spectrometer in which we can measure the momenta of the decay products and thus reconstruct the momentum, p and mass, m of the decaying particle. We have now analyzed about 1/3 of the data taken during our first run which took place between November 1978 and February 1979. We present here preliminary measurements of the lifetimes of the Λc and D^0 and a mean value of the lifetimes of 4 charged decays of an ambiguous sample of $F^\pm$ and $D^\pm$ decays.

There is considerable current interest in the lifetimes of charmed particles. A small number of short decay tracks, for a few of which constrained fits at the decay vertex have been obtained, were reported to this conference from bubble chamber, streamer chamber and other emulsion experiments. These results, some of which have already been published, are reviewed in the papers preceding and following this one. These indication of lifetimes in the 10^{-13} second range have laid to rest the doubts produced at the Tokyo conference by indications that charm lifetimes were either shorter than 10^{-14} or longer than 10^{-12} seconds or that production cross section were much smaller than predicted by theory or indicated by other preliminary experimental results.

Gratifying as the confirmation of simple weak interaction models may be, accurate measurements of the lifetimes of each of the weakly decaying charmed baryons and mesons nevertheless are still important. To understand the details of these decays requires the calculation not only of weak decay amplitudes but also of important strong interaction corrections. Charm decay lifetimes may provide one of the best arenas in which to observe the interplay of electroweak interactions and QCD.

Experimental data taking

The E531 apparatus is shown schematically in fig. 1. Twenty-four litres of Fuji emulsion were exposed to the horn focussed neutrino beam for a total flux of 7×10^{18}, 350 GeV/c protons on target.

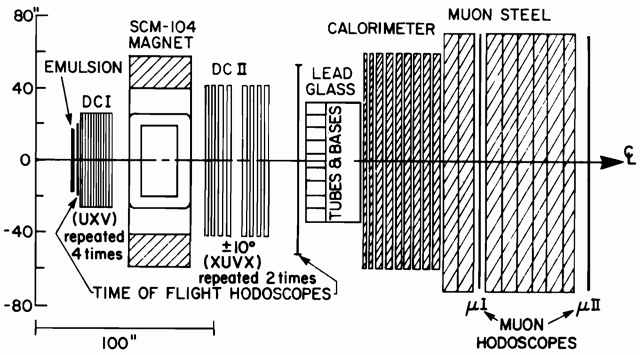

Fig. 1. E531 Spectrometer

The spectrometer, shown schematically in fig. 1 was used both to locate the neutrino events in the emulsion and also to measure momenta of the decay products from weak decays and of the other particles produced in the neutrino interactions. These measurements provide the momentum of the decaying particle and its mass thus allowing, in conjunction with the emulsion measurement of its decay length, a calculation of its proper decay time.

In order to obtain an unbiassed sample of neutrino interactions a very simple trigger was used which required a neutral incident particle and two or more outgoing charged particles. The veto counter, upstream time of flight (T of F) counter and downstream time of flight hodoscope identified these conditions.

The charged particle momenta were measured by 12 upstream and 8 downstream drift chambers and a large angular acceptance magnet with a central field of 0.6 Telsa.

Neutral pions and η^0 were reconstructed from the momenta of pairs of gamma rays measured in an array of 68 lead-glass blocks, 11 and 13 radiation lengths long and of 19 cm x 19 cm transverse dimensions.

A rudimentary hadron calorimeter with four columns of vertical counters each five layers deep and separated by 10 cm thick iron layers, provided a check on the total hadronic energy in the neutrino events and crude detection of missing neutral hadrons.

Two banks of muon counters, a horizontal hodoscope behind 1.2 m of steel and a vertical hodoscope behind a further 1.2 m of steel gave excellent muon identification above 4 GeV/c and reasonable muon-hadron separation down to 2 GeV/c.

The front T of F counter and the 30 rear T of F counters, with photomultipliers on both ends, gave 160 pico sec resolution and were useful for separating π and K up to about 2.2 GeV/c and identifying protons up to about 4.5 GeV/c.

Information on the resolution of the spectrometer is summarized in Table 1.

Table I

Quantity measured	Error (±σ)
charged particle momenta	upstream-downstream tracks $\frac{\Delta p}{p} = .013 + .005p$
	upstream only (fringe field) $\frac{\Delta p}{p} > .3p$
γ momenta	$\frac{\Delta E}{E} = \frac{.3}{\sqrt{E(\text{GeV})}}$
position	±5 cm
Time of flight	±160 pico sec

Location of neutrino interactions in the emulsion

Reconstruction of the drift chamber tracks from our neutrino triggers had yielded a sample of 1933 events with well defined vertices. 1670 of these lie in the region of the emulsion target and the remainder are associated with the support frame. Development of the spectrometer analysis is still in progress and from a comparison of our two independent reconstruction programs we estimate that the final sample of events in the emulsion region, from the first run, will contain 2200 events.

The results of the computer fits are used to search for the neutrino events in the emulsion by two techniques. In the first the emulsion is scanned in a small volume surrounding the predicted vertex location. The second technique depends on finding an individual track from the event where it leaves the downstream face of the emulsion stack and then following the track back to the vertex. Results of the search for 501 events are summarized in Table II.

Table II

Emulsion orientation	"Vertical"	"Horizontal"
Number of events searched for	296	205
Number found	230	82
Efficiency	78%	40%

Two sets of emulsion stacks composed the target. In the first the emulsion was divided into 27 modules in which emulsion layers of 330μ thickness were deposited on each side of a 70μ polystyrene sheet. 68 such composite sheets in each module gave a thickness of 5 cm along the beam direction. These stacks, in which the neutrinos were incident normal to the plane of the emulsion layers are referred to as "vertical". The other 12 modules containing slightly less than half of the total emulsion volume, were composed of 600μ thick, pure emulsion pellicles 5 x 14 cm^2 in area exposed with the beam parallel to the 5 cm dimension. For historical reasons these are referred to as "horizontal" emulsion.

The differences in the event finding efficiencies in the two samples (see Table II) is mainly due to the different search techniques. In the "horizontal" emulsion almost all the events were found by volume scanning whereas in the "vertical" emulsion almost all the scanning was done by track following. The latter method is somewhat more difficult to apply to the "horizontal" emulsions because of distortions of tracks near the edge of the pellicles but it has already been successfully used for a few events. By applying both scanning techniques we hope to obtain a final event finding efficiency close to 80%.

The background of high momentum tracks with angles within 20^0 of the neutrino beam direction is so great (∿ 20,000/cm^2) that there are several emulsion tracks which match, within position and angle errors, the prediction for a particular track from the upstream chambers. Our ability to select the correct track to follow and find the neutrino event depends on changeable sheets of 800μ polystyrene coated front and back with 75μ layers of emulsion which covered the downstream face of all the emulsion stacks in the target. The troublesome background in the emulsion target is due mainly to beam associated muons and partly to nearby horizontal cosmic ray muons. The former background was worst at the beginning of the run and improved substantially later. The target, of course, integrated the background from both sources during the whole period between pouring and development. The changeable sheets however were poured, mounted for 2 days, and developed immediately and the background was thus reduced to ∿ 1000 tracks/cm^2. This allows unique identification of at least one spectrometer track in the changeable sheet for almost every event. The construction of a vertical module and the method of relating the changeable sheet position to that of the main emulsion stacks is illustrated in fig. 2. Four small, well collimated Fe^{55} sources permanently mounted in each emulsion stack produced small exposed spots on the changeable sheet allowing relative location of the two emulsions to better than 100μ accuracy. As will be explained below the ability to locate and follow individual tracks from the spectrometer to the emulsion target is important not only for increasing the event finding efficiency by about a factor of two but also for calibrating the efficiency of the search for neutral decays.

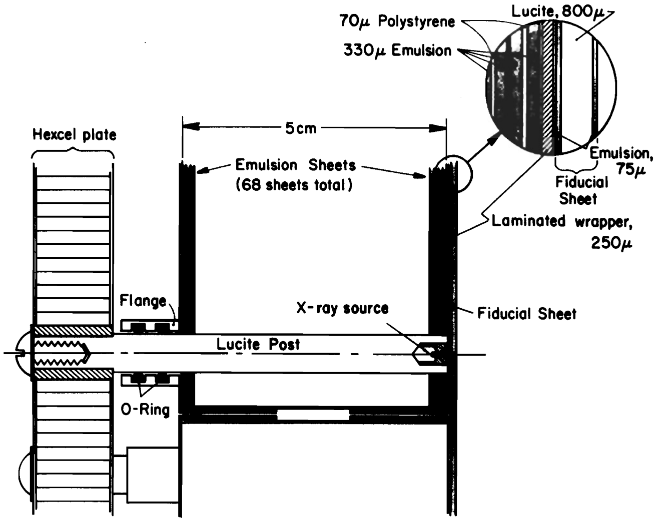

Fig. 2. Vertical emulsion and changeable sheet

Search for charm decays

The search for charm decays is made by following the charged tracks from the neutrino interaction and by volume scanning, at high magnification, a cylinder downstream of the neutrino interaction for neutral decays. Scanning criteria differed slightly in different groups but charged tracks were followed for a length of 3 - 5 mm and the neutral search was made in cylinders of 1.2 - 3 mm diameter 2 to 3 mm along the neutrino beam direction.

At the time of the conference we had found 16 multiprong (2, 3 or 4 prong) decay candidates and 13 single prong charged kinks with no visible recoil tracks. 15 of the multiprongs came from the 312 events in Table II allowing us to estimate

$$\frac{\text{charm decays}}{\text{neutrino interactions}} \geq \frac{15}{230 + 82} = 4.8 \pm 1.2\%.$$

If we use the data from our reconstruction program comparison and these figures we obtain a projection for our first run of 1120 neutrino interactions found in the emulsion target with $\sim$ 54 measurable multiprong charm decays.

Neutrino interactions in the Emulsion target

The emulsion target was exposed to the Fermilab horn focussed neutrino beam for a total of 7×10^{18} protons on target. Fig. 3 shows the distribution of all events reconstructed in the spectrometer as a function of E visible. E vis was calculated taking the muon and charged particle momenta from the spectrometer and using the lead glass and calorimeter to take account of neutral hadron energy. The distribution is typical of the horn beam and one can see that above 15 GeV the charm decay events are similarly distributed. As a result of our simple inclusive trigger this sample includes charged and neutral current events.

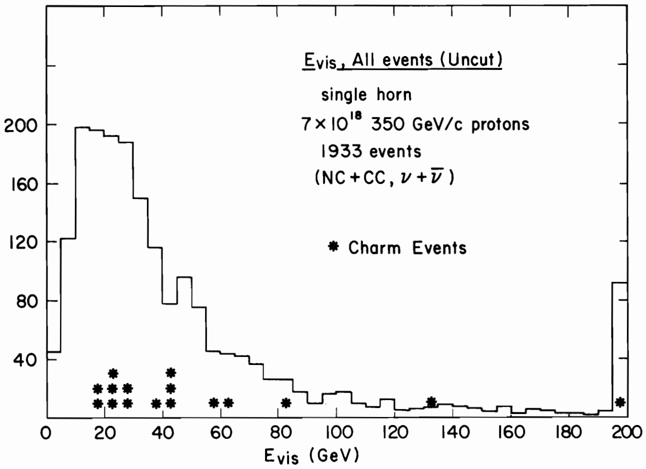

Fig. 3. Energy distributions of events.

A subset selected to have E vis > 10 GeV and a well tagged muon with $p_\mu > 4$ GeV contain only charged current events. They are assigned to neutrino and background anti-neutrino events by the charge of the fastest μ produced in the interaction. The x and y distribution, shown in figures 4 and 5, exhibit the expected features for charged interaction and again the charm decay events are similarly distributed. The curve in fig. 4(a) is $F_2(x)$ from the SLAC inelastic e d scattering data .

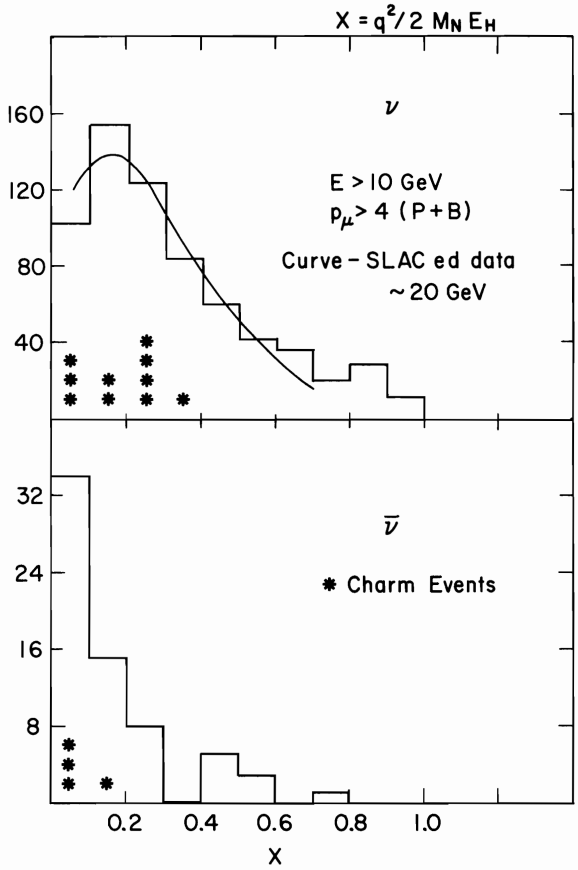

Fig. 4. X distribution of charged current events.

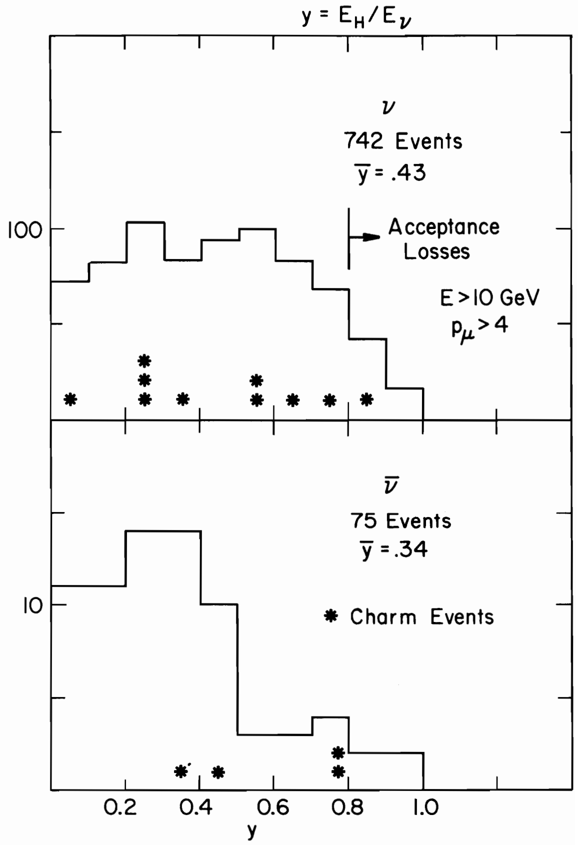

Fig. 5. Y distribution of charged current neutrino events.

Charm decay candidates and charmed hadron lifetimes

The track following search for charged decays and the volume scan for neutral decay vertices yielded 16 multiprong decays. In these events constrained or unconstrained kinematic fits have been made for 10 of the decays and a proper lifetime has been calculated for the decay track.

Two of the ten appear to be decays of Λc^+. In the first of these one positive decay track is identified as a proton by time of flight. In the decay hypotheses the underlined particles are identified by time of flight or emulsion ionization measurements. Particles in brackets are missing neutral particles from the decay the existence of which has been assumed in order to account for observed missing momentum transverse to the decaying track. Table III shows the decay track length, decay hypothesis, momentum of the decaying track and proper decay time.

Table III

Decay length (μm)	Decay hypothesis	P_{ch} (GeV/c	Decay time (10^{-13}sec)
27	$\Lambda c \to \underline{p}\pi^+\pi^-(K^0)$	3.2	0.63
1802	$\Lambda c \to K^- p\underline{\pi}^+\underline{\pi}^0$ $(D^+ \to K^+K^-\pi^+\pi^0)$	17.7	7.67

The second fit to the second decay is a Cabibbo unfavoured D^+ decay with no accompanying γ or π^0 to form a D^{*+} mass combination.

The PRELIMINARY mean life for the Λc obtained by averaging the decay times of those 2 events is $\langle\tau\rangle = 4.2 \times 10^{-13}$sec.

The four neutral decays include 2 with 2 charged particles and 2 with 4 charged particles in the decay products. Two are identified as D^0 decays and two as $\overline{D^0}$ decays by the sign of the associated muons. Table IV gives a summary of these four neutral decays.

Table IV

Decay length (μm)	Decay hypothesis	P_{ch} (GeV/c)	Decay time (10^{-13}sec)
40	$D^0 \to K^-\pi^-\underline{\pi}^+\underline{\pi}^+\pi^0$	15.5	0.16
74	$D^0 \to \pi^+\pi^-(\overline{K^0})$	12.4	0.37
210	$\overline{D^0} \to K^+\pi^-$	6.8	1.9
33.8	$\overline{D^0} \to \pi^+\pi^+\underline{\pi}^-\pi^-(\pi^0)$	10	.21

The minimum mass for the 0 constraint calculation for the last event in the table is 1886 ± 47 MeV. This is well within 1 standard deviation of the accepted D^0 mass of 1863 MeV. This constraint gives a unique value for the momentum of the missing π^0 thus avoiding the usual quadratic ambiguity in the momentum of the decaying particle. The direction of the π^0 from this calculation is such that there is a high probability of both its decay γ rays missing the lead glass array which is consistent with the lack of signals in the lead glass for this event.

For the event with the missing $\overline{K^0}$ the lower momentum solution was chosen because the combined mass of the D^0 and another π^+ from the event is closer to the D^* mass for the selected momentum solution than for the other and because the momentum sharing between the D^0 and the π^+ is also more probable. The choice of the other solution would only reduce the decay time for this event by about 30% and would have a negligible effect on the mean for the four events. This latter is

$$\langle\tau\rangle_{D^0} = 0.66 \times 10^{-13}\text{seconds.}$$

This result is PRELIMINARY. It should particularly be noted that we are currently checking the efficiency of our downstream scan for neutral decays by tracing back tracks which are seen in the spectrometer but are not found in the emulsion. When this has been done for all found neutrino events we will have a careful experimental calibration of our efficiency for finding neutral decays. Any dependence of efficiency on distance from the primary vertex could, of course, seriously affect our measurement of the D^0 lifetime.

The remaining four fitted multiprong decays are identified as either $D^\pm$ or $F^\pm$ mesons. One of these events has no fits for a D^- and gives a good 2 constraint fit to an $F^- \to \underline{\pi}^+\underline{\pi}^-\pi^-\underline{\pi}^0$ decays with a resultant mass of 2068 ± 55 MeV. The primary vertex contains a well identified μ^+ track and we therefore conclude that the decaying particle is indeed an F^-.

As shown in Table V the remaining 3 events are ambiguous between D and F hypotheses. Two of them are semi leptonic decays with identified μ^+ and e^- decay tracks respectively and the resulting missing neutrino leads to a quadratic ambiguity in the decay track momentum and therefore a corresponding ambiguity in the decay time.

Table V

Decay length (μm)	Decay hypothesis	P_{ch} (GeV/c)	Decay time (10^{-13}sec)
670	$F^- \to \underline{\pi}^+\underline{\pi}^-\pi^-\underline{\pi}^0$	12.8	3.6
2145	$D^+ \to K^-\pi^+\mu^+(\nu_\mu)$	{12.8 24.8	{10.4 5.4
	$F^+ \to K^-K^+\underline{\mu}^+\nu_\mu$	{13.0 19.5	{11.2 7.5
457	$D^+ \to K^-\pi^+\pi^+\underline{\pi}^0$	10	2.8
	$F^+ \to K^-K^+\pi^+\underline{\pi}^0$	10	3.1
2307	$D^- \to \underline{K}^+\pi^-\underline{e}^-(\bar{\nu}_e)$	{6.7 10.7	{18.3 15.4
	$F^- \to \underline{K}^+K^-\underline{e}^-(\bar{\nu}_e)$	{6.7 7.7	{23.4 20.4

Assigning weights of 1, .5 and .25 to the unique doubly ambiguous and four fold ambiguous lifetimes we can estimate

$$\text{"}D^\pm\text{"} \quad \langle\tau\rangle = 8 \times 10^{-13}\text{sec}$$

$$\text{"}F^\pm\text{"} \quad \langle\tau\rangle = 9 \times 10^{-13}\text{sec}$$

Charge 2e decay track

One event has been found in which 3 tracks emerge from a neutrino interaction. Two of these are approximately minimum ionizing while the 3rd has been measured by two methods to have an ionization of 4 ± .5 times as dense as nearby minimum ionizing tracks. We take this to indicate a charge of 2e for this track. Furthermore after 66 microns this track decays to 2 charged tracks of approximately minimum ionization and one or more neutral particles. Multiple scattering measurements in the emulsion have yielded momentum values of $p_{2-1} > 3.0$ GeV/c and $p_{2-2} = 0.6 \pm .15$ GeV/c respectively. The former track travels about 1 cm in the emulsion before interacting or decaying to give 2 minimum ionizing tracks and an electron of momentum 60 ± 10 KeV/c.

Unfortunately this event occurred when the spectrometer magnetic field was off due to a power supply failure. As a result we have no momentum measurements for the tracks found in the spectrometer.

A schematic sketch of this event is given in fig. 6. Two of the spectrometer tracks appear to originate from a neutral decay in the upstream chambers that is consistent with either a K^0 or Λ decay. An e^+e^- pair is also observed in the emulsion and connected to spectrometer tracks which show that it is in time with and therefore associated with this event. Further attempts to fit this event will be made when more extensive emulsion measurements have been completed and when all the drift chamber tracks have been reconstructed. In the meantime we can only speculate that the 66 μm track may have been produced by a doubly charged charmed baryon.

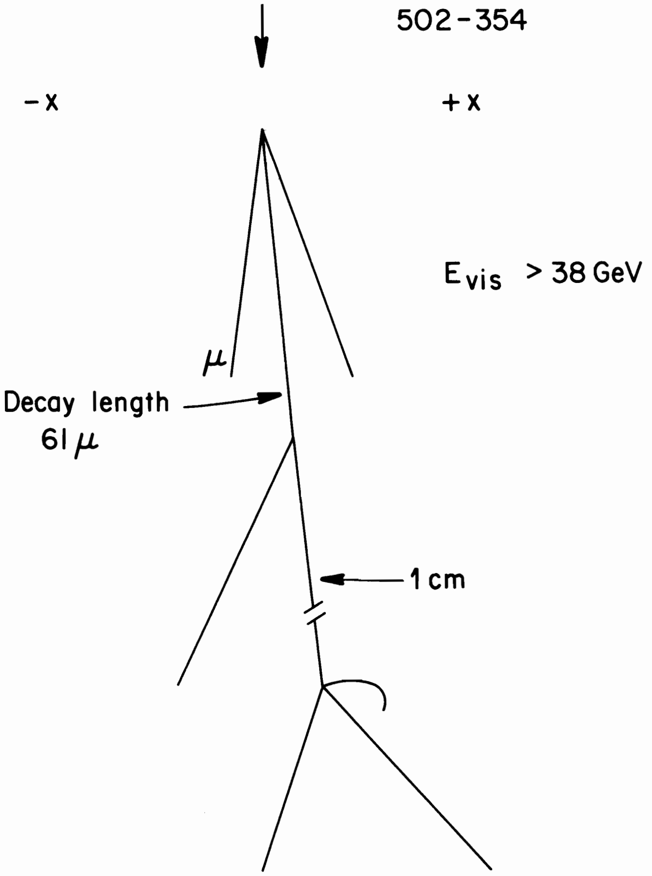

Fig. 6. Decay of doubly charged particle

Summary

Preliminary analysis of the first run of Fermilab experiment 531 has yielded 1670 computer reconstructed neutrino events of which 380 have been found in the emulsion target with an efficiency of about 60%. A search for charm decays has yielded 16 multiprong candidates of which 10 have been kinematically fitted. The preliminary lifetime estimates together with the number of events on which they are based are shown in Table VII.

Table VII

Preliminary lifetime estimates from 10 fitted charm decay events

Number of events	Particle	$<\tau>$
2	Λ_c^+	4×10^{-13}sec
4	D^0	0.7×10^{-13}sec
3 ambiguous	$F^\pm D^\pm$	10×10^{-13}sec
1	F^-	$\tau = 3.6 \times 10^{-13}$sec

We expect to complete the analysis of the first run in about 8 months and to obtain about 50 multiprong decays of charmed particles.

The experiment has been approved for a second run in late summer of 1980. At that time we intend to expose 35 litres of emulsion in an improved spectrometer. Modifications include the addition of 4 drift chambers to aid the reconstruction of high multiplicity events, improved particle identification and improved position resolution for gamma rays in the lead glass array. All these improvements should contribute to an increased yield of fitted charm decay events per incident neutrino.

Acknowledgements

We gratefully acknowledge the financial support of the U.S. D.O.E., the Canadian N.S.E.R.C., the Japanese Ministry of Education, and the Korean Science Foundation. We thank the many members of the Fermilab staff who assisted us in this experiment especially members of the accelerator division and neutrino department. We should like to thank the many technical personnel in our universities for their valuable contributions which were vital to the success of the experiment.

References

1. The names and institutions of the physicists who are currently working on this experiment are: N. Ushida, Aichi University of Education, Japan. T. Kondo, Fermi National Accelerator Lab. G. Fujioka, H. Fukushima, Y. Homma, O. Minakawa, J. Orimoto, Y. Takayama, S. Tatsumi, Y. Tsuzuki, Kobe University, Japan. S.Y. Bahk, T.G. Choi, C.O. Kim, S.N. Kim, J.N. Park, Korea University. D.C. Bailey, S. Conetti, J.-R. Fischer, J.M. Trischuk, McGill University, Canada. H. Fuchi, K. Hoshino, K. Niu, K. Niwa, H. Shibuya, Y. Yanagisawa, Nagoya University, Japan. S.M. Errede, M.J. Gutzwiller, S. Kuramata, N.W. Reay, K. Reibel, T.A. Romanowski, R.A. Sidwell, N.R. Stanton, Ohio State University. K. Moriyama, H. Shibata, Okayama University, Japan. T. Hara, O. Kusumoto, Y. Noguchi, Y. Takahashi, M. Teranaka, Osaka City University, Japan. J.-Y. Harnois, C.D.J. Hébert, J. Hébert, B. McLeod, University of Ottawa, Canada. K. Okabe, J. Yokota, Science Education Institute of Osaka Prefecture, Japan. S. Tasaka, University of Tokyo, Japan. P.J. Davis, J.F. Martin, D. Pitman, J.D. Prentice, P. Sinervo, T.-S. Yoon, University of Toronto, Canada. J. Kimura, Y. Maeda, Yokohama National University, Japan.

2. M.K. Gaillard, B.W. Lee and J.L. Rosner, Rev. Mod. Phys. 47 (1975) 277.

Discussion

Sacton, Brussels: Could you show again your charge 2 event? It's tempting from that drawing to extrapolate track 21 straight back to the vertex. Is it possible that track 2 is the superposition of 2 tracks.

Prentice: We worried a lot about that and I would be less than candid if I didn't say that the angle measurements on these two tracks have oscillated around a little. The careful measurements that have now been made and checked suggest that the angle between track 2 and track 2 - 1 is more than 5 standard deviations from zero. So I think that that's a good confirmation of the ionization measurements which are the chief reason for our claim of charge 2.

Diambrini, Genoa: If you take 300 neutrino events with multiplicity 5 and follow the tracks you should expect around 25 secondary EMULSION INTERACTIONS. This is just a remark. Now the question: did you detect these 20 or so secondary interactions? Then the second remark is 10% of this, let's say 2 to 3, should be "white" interactions, something which simulate charm decay, so could we possibly in principle in your sample have a contamination of 2 or 3?

Prentice: Yes, I think it's certainly true that we could have of the order of 1 three-pronged background event and we haven't done a careful calculation of our backgrounds yet. However the numbers that are applicable in our experiment are as follows: 1780 mm of charged track have been scanned in the vertical emulsion. 190 mm of this is in the polystyrene backings that the emulsions are stuck to. We predict 7.7 interactions in the emulsion and .34 in the polystyrene. We only have the detailed information for the found interactions on 98 out of 233 events. I'm sorry that we haven't finished this but we have found 3 nuclear interactions in this sample and if you scale the expected number down by 98/233 you expect 3.4. So we find 3 for 3.4. There include 2 interactions and one kink. In the horizontal emulsions we found 6 kinks and 7 clear nuclear interactions with 11.5 interactions predicted. So that's how it stands. Of course we don't have all charged 3 particle decays in our sample of charmed candidates. The most likely type of background would be 3 prong diffraction dissociation with no heavy tracks and no neutrals. Diffraction dissociation to 4 bodies is very rare.

Garfinkel, Purdue: I wonder if you can give us the invariant mass of the visible tracks of your identified F^-.

Prentice: We haven't quoted the masses that we've been calculating because we're still working on the errors. With the bad position resolution in the lead glass it's a little difficult. In that particular event the F^- has a fitted mass of 2068 ± 55 MeV if we allow the mass to vary and therefore have a 2 constraint fit.

J. Sandweiss: Did you find your charge 2 event in the horizontal or vertical emulsions and secondly isn't it possible to interpret it perhaps as an alpha particle which is kicked out of the nucleus by the original interaction and then interacts.

Prentice: It's from the vertical emulsion, that's the easy question. You capture the alpha particle in the nucleus and emit two minimizing tracks.

Q: If you had an energetic alpha it could presumably fragment into 2 protons and the neutrons escape. You don't see them.

Prentice: Yes, okay, that's a possible suggestion.

Bill Reay, Ohio State: If you had that happen, you would expect to see dark nuclear fragments from a nuclear breakup which were not seen at the second vertex.