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MEASUREMENT OF CHARMED PARTICLE LIFETIMES

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ABSTRACT

This talk briefly reviews recent measurements of charmed particle lifetimes, then presents in detail the lifetime measurements of Fermilab Experiment 531.

INTRODUCTION

I was really impressed by the preceding talk of Professor Carnegie, in which results of many experiments were synthesized to give a coherent picture of meson spectroscopy. The reason that this could be done is that all experiments relied on conventional techniques, and therefore could be trusted. Today, I want to talk to you about the charmed particle lifetime business. People in this business have been known to use emulsions and even cosmic rays, so all experiments have a unifying feature -- no one believes them. For example, when Professor Niu of Nagoya¹ discovered charmed particles in a cosmic ray emulsion exposure, very little excitement was created in the high energy physics community. In fact, the field lay dormant until the discovery of the J- Ψ .

Of course, there is some justification for this state of affairs. The GIM coupling of electroweak theory to hadrons made it possible to predict charmed particle lifetimes, and predictions ranged within less than an order of magnitude about 10^{-13} seconds. However, as recently as at the 1978 Tokyo High Energy Conference, experimental results were divided into two camps, one with lifetimes 10^{-13} seconds or longer and another with lifetimes 10^{-14} seconds or shorter. The latter was in flat contradiction to the above mentioned theory.

RECENT EXPERIMENTAL RESULTS

In the past year, results from several CERN and Fermilab experiments have supported longer lifetimes. CERN experiment WA 17 has published five decays, one of which has been mass fit.² CERN experiment WA 4 has found a decay generated in a photon interaction.³ Two bubble chamber experiments at Fermilab recently reported results at Bergen.^{4,5} Experiment 546 has four visible decays and experiment 53 has one visible charged decay. These experiments suffer from obvious deficiencies in seeing short lifetimes, but have the distinct advantage that they have a known number of decays. For example, experiment 53 has 250 μ -e di-lepton events, most of which presumably contain the decay of a charmed particle. If charmed lifetimes were long, they would have found 250 visible decays. Professor Baltay has furnished me the graph of expected visible decays versus lifetime shown in Figure 1; his result certainly is consistent with a charged lifetime of roughly 5×10^{-13} seconds.

Now that ballpark numbers exist for charmed particle lifetimes, we must determine lifetimes and branching ratios for each of the

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Figure 1: Expected number of visible decays given as a function of lifetime for Fermilab Exp.53.

different types of lightest charmed particles. It is even conceivable that the anomalously short measured lifetimes were the result of an unexpectedly broad spectrum of lifetime values. Three Fermilab experiments designed to answer more detailed questions completed data taking in February, 1979. Though they all exposed hybrid emulsion spectrometers to the same single horn wide band neutrino beam, each was quite different in character.

Experiment 553, shown in Figure 2, used thin emulsion modules, holey spark chambers for event location, a magnetic spectrometer for momentum analysis and a flash tube calorimeter for detection of electromagnetic and hadronic showers.

Figure 2: A layout for Fermilab Experiment 553.

The holey spark chamber is conceptually quite clever. The chambers consist of glass plates coated with a metallic layer so thin that sparks burn holes in the coating. Contact prints are then made of fired plates, enabling 50 micron accuracy in location of track coordinates. Professor Hand has informed me that on the basis of 1/3 to 1/2 of their total data sample they have located 25 neutrino interactions and have found one "kink" and one multiprong decay candidate. As neither has been mass fit, proper decay times are not yet available.

Fermilab experiment 564 placed Russian emulsions inside the 15-foot bubble chamber at cold temperature, so that the bubble chamber itself became the downstream detector. Professor Voyvodic has informed me that based on a small fraction of their expected data base, they have located about two dozen neutrino interactions and have discovered two three prong charged charmed particle decays.⁶ The proper time and particle identification are not yet available.

FERMILAB EXPERIMENT 531

A. Counter System

Now, I wish to exercise the time honored prerogative of rapporteurs everywhere by spending the remainder of the time discussing the experiment on which I work -- Fermilab experiment 531. The apparatus shown in Figure 3 was constructed and operated by a large collabora-

Figure 3: A layout for Fermilab Experiment 553.

tion of Canadian, Japanese, Korean and United States scientists.⁷ A simple neutrino trigger required only that no charged particle be incident and that two or more charged particles exit the emulsion and pass through the magnet. Charged and neutral current events were accepted equally. A magnet surrounded by drift chambers provided momentum analysis and aided in finding events within the emulsion. A time-of-flight system separated pions and kaons to $2\frac{1}{2}$ GeV, and protons to 5 GeV. A wall of lead glass detectors was used to identify electromagnetic showers and muons were identified by passage through 1.6 and/or 3 GeV equivalent of steel. Non-electromagnetic hadronic energy was recorded in a conventional iron plate calorimeter. Information on resolution of spectrometer elements is summarized in Table I.

At this point, let me emphasize the philosophy of our counter system. A hybrid emulsion effort must be viewed as a complete counter effort in addition to the obvious emulsion technology. Many such experiments have suffered grievously because the counters were viewed as a necessary but minimal adjunct. Be assured that within statisti-

Table I

<u>Quantity Measured</u>	<u>Error (σ)</u>
Drift Chamber Position Resolution	120 microns
Charged Particle Momenta for Tracks passing through magnet	$\frac{\delta P}{P} = .013 + .005P$
Tracks analyzed only by fringe field	$\frac{\delta P}{P} \approx 0.3P$
Gamma Ray Energy	$\frac{\delta E}{E} = \frac{0.3}{\sqrt{E(\text{GeV})}}$
Gamma Ray Position	5 cm
Time-Of-Flight	120 picoseconds
Calorimeter	$\frac{\delta E}{E} = \frac{1.0}{\sqrt{E(\text{GeV})}}$

cal limitations, E-531 exhibits features typical of most bulk neutrino experiments. Using counter data only, the distribution in visible energy of events has been calculated and is displayed in Figure 4. The visible energy was calculated by summing muon energy with lead glass and calorimeter energies. The distribution is typical of the horn beam, and events with charm show no strong differentiation in shape.

Figure 4: Energy distribution of events for E-531. The asterisks indicate individual events which have charm decays.

A subset selected to have visible energy greater than 10 GeV have been assigned to neutrino or anti-neutrino distributions by the sign of the leading muon. The x and y distributions shown in Figures 5 and 6 exhibit the expected features for charged current interactions. The raw neutrino distributions are flat in y and agree in x with the exhibited $F_2(x)$ shape taken from SLAC inelastic e-D scattering data.

The distribution of events containing charm is similar to the overall event distributions. The anti-neutrino distributions as expected are peaked at small x and y, and there is a hint of the expected flat distribution in y of charmed events.

Figure 5: X distribution of charged current events for E-531.

Figure 6: Y distribution of charged current events for E-531.

B. Emulsion System

The emulsion target consisted of over three thousand sheets of emulsion, roughly half of which had 300 micron layers of emulsion coated on each side of a 70 micron plastic backing and which were mounted normally to the neutrino beam. One module of this type is exhibited in Figure 7. The remainder were 600 micron pure emulsion pellicles mounted edge-on to the beam. The latter were scanned for events by searching a small volume surrounding the vertex location inferred from intersection of drift chamber tracks. The normally mounted emulsion was scanned using the changeable sheet setup shown in Figure 7. An 800 micron sheet of lucite coated on both sides with a thin layer of emulsion was placed immediately downstream of the emulsion stack.

Figure 7: "Normally Mounted" emulsion module for E-531, see text for a description.

This sheet was located with respect to the emulsion modules by means of X-ray sources residing in the posts on which all emulsion modules were mounted. As there were almost 150 posts, changeable sheets were liberally speckled with precisely located blackened spots. By changing this sheet many times during the experiment, muon and other background were kept sufficiently low that individual tracks could be found from drift chamber information using computer-controlled semi-automatic scanning techniques. Once an individual track from an event was found, highly precise emulsion techniques could be employed to extrapolate tracks back to the interaction vertex. Such a technique is highly efficient because it does not rely on the existence of a large number of black tracks from nuclear breakup as does the volume scan method. Recent developments indicate that the scan-back technique will be applicable as well to emulsions mounted edge on.

Presently, we have 1700 events predicted via computer fits to drift chamber data. By comparing efficiencies of two separate fitting programs, we have determined that a final analysis should locate 2200 events; the final analysis should be available shortly. Scanning of the expected 2200 events is about 40% complete, resulting in the event finding efficiency exhibited in Table II.

C. Analysis

To date, we have located 20 multiprong charm decays, and have an additional dozen "kinks" in which a single track undergoes a large angle instantaneous change in direction without evidence of nuclear breakup. Eleven of the multiprong decays have unique identification, and three more are ambiguous between assignment as D or F mesons.

In the following, decay hypotheses have been shown and particles

Table II

Event Finding Summary

Scanning Method	Computer Predictions	Predicted Events After Fiducial Cuts	Events Searched For	Found
Volume Scan	900	700	460	184
Track Following	850	620	343	300
Total	1750	1320	803	484

Table III

 Λ_c^+ Baryon Fits

Decay Length (Microns)	Hypothesis	P (GeV/c)	Mass (MeV)	Decay Time $\times 10^{-13}$ Seconds
27	$\Lambda_c^+ \underline{p} \underline{\pi}^+ \pi^- (K^0)$	2.4 4.8	>2070	0.8 0.4
15	$\Lambda_c^+ K^- \underline{p} \underline{\pi}^+ (\pi^0)$	1.9 2.7	>2170	0.6 0.4
40	$\Lambda_c^+ \underline{\Lambda}^0 \underline{\pi}^+ \underline{\pi}^- \pi^+$	5.3	2220 ± 90	0.6

which have been identified as well as momentum analyzed are underlined. Unseen particles added to balance momentum transverse to the direction of the parent particle are indicated in brackets. When all particles are momentum-analyzed a two constraint fit is possible; when a particle is missing the resulting zero constraint fit in general has two solutions. Frequently, one of these solutions may be eliminated, as in cases where the mass solution is at a minimum or when in conjunction with another particle a better higher mass meson (such as D^* or F^*) may be formed. Decay lengths are given in microns, P is the momentum determined for the parent charmed particle and proper decay times are given in units of 10^{-13} seconds. Table III

contains the three Λ_c^+ events, Table IV the four D^0 events and Table V the charged D and F events, including the three events which cannot be uniquely assigned.

The preliminary mean life for the Λ_c^+ baryon obtained by averaging the individual proper decay times is

$$\langle \tau \rangle = 0.6 \times 10^{-13} \text{ seconds} \quad (1)$$

Table IV

 D^0 Meson Fits

Decay Length (Microns)	Hypothesis	P (GeV/c)	Mass (MeV)	Decay Time $\times 10^{-13}$ Seconds
34	$\overline{D}^0 \rightarrow \pi^+ \pi^+ \pi^- \pi^- (\pi^0)$	10	>1880	0.21
40	$D^0 \rightarrow K^- \pi^- \pi^+ \pi^+ \pi^0$	15	1830 ± 40	0.16
74	$D^0 \rightarrow \pi^+ \pi^- (K_L^0)$	12.4	1870 ± 180	1.9
210	$D^0 \rightarrow K^+ \pi^- (\pi^0)$	6.7 8.3		1.9 1.6

For the event with the missing 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. The preliminary mean life for the D^0 obtained by averaging the proper decay times of these events is

$$\langle \tau \rangle = 0.7 \times 10^{-13} \text{ seconds} \quad (?)$$

In addition to volume scanning downstream of each neutrino interaction for neutral decays, a variation of the track scanback technique was applied to search for decays undiscovered by the first technique. In this variation, tracks found by the drift chambers which had slopes different from those measured in the emulsion at the primary vertex were identified in the changeable sheet and traced back into the emulsion. In 150 events treated in this manner, many nuclear interactions and electron-positron pairs were discovered, but no new charm decays were identified. This fact coupled with the short decay lengths of found events supports a high efficiency for finding D^0 decays.

Table V

F and Charged D Meson Fits

Decay Length (Microns)	Hypotheses	P (GeV/c)	Mass (MeV)	Decay Time x 10 ⁻¹³ seconds
<u>F Mesons</u>				
670	$F^- \rightarrow \underline{\pi}^+ \underline{\pi}^- \pi^- \pi^0$	12.8	2068 ± 60	3.6
130	$F^+ \rightarrow \underline{K}^+ \underline{\pi}^+ \underline{\pi}^- (K^0)$	10.4	~2130	0.8
<u>Charged D Mesons</u>				
1802	$D^+ \rightarrow K^+ K^- \underline{\pi}^+ \underline{\pi}^0$	17.8	1851 ± 30	6.4
2145	$D^+ \rightarrow K^- \pi^+ \underline{\mu}^+ (\nu)$	12.8		10.4
		24.8		5.4
<u>Ambiguous Events</u>				
530	$F^+ \rightarrow K^- K^+ \pi^+ \underline{\pi}^0$ (Favored)	34	2057 ± 60	1.1
	$D^+ \rightarrow K^- \pi^+ \pi^+ \underline{\pi}^0$	34	1964 ± 60	1.0
2307	$D^- \rightarrow \underline{K}^+ \pi^- \underline{e}^- (\nu)$ (Favored)	6.7 10.5		21.4 13.7
	$F^- \rightarrow \underline{K}^+ K^- \underline{e}^- (\nu)$	6.9 7.5		22.7 20.9
457	$D^+ \rightarrow K^- \pi^+ \underline{\pi}^+ \underline{\pi}^0$	10	1835 ± 50	2.8
	$F^+ \rightarrow K^- K^+ \pi^+ \underline{\pi}^0$	10	2012 ± 49	3.1

If only uniquely determined decays are used, two charged D and two F meson events give

$$\langle \tau \rangle = 7 \times 10^{-13} \text{ seconds} \quad (3)$$

$$\langle \tau \rangle = 2 \times 10^{-13} \text{ seconds} \quad (4)$$

After assigning two additional decays to their one sigma favored particle types and weighting the ambiguous event by 0.5 for each of its twofold ambiguous solutions, the following lifetimes may be obtained.

$$\langle \tau \rangle = 9 \times 10^{-13} \text{ seconds} \quad (5)$$

$$\langle \tau \rangle = 1.8 \times 10^{-13} \text{ seconds} \quad (6)$$

The ratio of D^0 to charged D lifetimes is then

$$\frac{\langle \tau_{D^0} \rangle}{\langle \tau_{D^\pm} \rangle} = 0.08 \pm 0.06 \quad (7)$$

(though with the small statistics involved, a $\pm$ error is inferior to values determined by maximum likelihood). Evidence that all four D^0 decays are non-leptonic, whereas the three decays favoring the charged D identification were semi-leptonic or Cabibbo-unfavored non-leptonic also is supportive of the large difference in lifetimes.

We also studying an increasingly interesting amount of dynamical information concerning these decays. All Λ_c^+ baryons were produced slowly in the laboratory, as might be expected if their production is assumed to be target-like. Many, if not most of the D and F mesons appear to come from strong decays of D^* and F^* higher mass states, and about half of the charmed particles appear to contain most of the visible hadronic energy. We should have more to say about these points in the near future.

Scanning should be complete by next summer, obtaining roughly 50 multiprong and an uncertain number of analyzed single track decays. At that time we are approved to run again with improvements both to backgrounds and equipment, and expect to find even more decays. I could bore you with lists of improvements and dreams for the future, but the proper time to discuss this sort of thing is after running and not before. Let me close instead by discussing two "zoo" events which are as yet incompletely understood.

Figure 8: Decay of doubly charged particle, see text for a description.

D. Two Unusual Events

We have found the charged two decay track illustrated in Figure 8. Three tracks emerge from a neutrino interaction, two of these are minimum ionizing while the third has been measured by two methods to have an ionization 4.0 ± 0.5 times more dense than nearby minimum ionizing charged tracks plus at least one neutral particle. Multiple scattering measurements in the emulsion have yielded momentum values of $P_{2-1} > 3.0$ GeV/c and $P_{2-2} = 0.6 \pm 0.15$ GeV/c. The former track travels about 1 cm in the emulsion before interacting without evidence of nuclear breakup (or decaying) to give two minimum ionizing tracks and an electron of momentum 60 ± 10 KeV/c.

Unfortunately, this event occurred when the spectrometer magnet was off due to a power supply failure and no momentum measurements could be performed by the magnetic spectrometer. A "vee" materialized downstream of the emulsion and was identified by time-of-flight measurements to be a

lambda hyperon. An electron-positron pair also is observed in the emulsion and has been connected to spectrometer tracks which show that it is in time with and therefore associated with this event. We are still working and though we are strongly tempted to speculate on the existence of a weakly decaying charge two baryon, we will make no claims at this time.

The second unusual event, shown in Figure 9 is one which contains three electrons. The table given as an insert in Figure 9 tells the story. Tracks 1 and 2-2 were clearly identified as electrons, as the momentum measured by the magnetic spectrometer equalled the energy measured by the lead glass blocks struck by these tracks. The identification of track 3 is not so clear, as the energy measured by the lead glass is only 70% of that measured by the magnetic spectrometer. This event could be quite exciting, but we are waiting for emulsion measurement on the two tracks found in the emulsion but not picked up by our drift chambers. Visions of many exciting possibilities dance in our heads, but if these two tracks turn out to be electrons the event could be as ordinary as a gamma-induced shower. It is safe to say that we do not yet understand this event, and I am hopeful that after the end of the talk one of you will leap up with an explanation. So without further ado let me close by thanking you for this invitation to talk in the beautiful city of Montreal.

Figure 9: Multi-electron event, see text for a description.

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DISCUSSION

A.Abashian, National Science Foundation:

Of the neutrino events in which a charmed particle is produced, how many are charged current(outgoing μ) and how many are neutral current(outgoing neutrino)?

N.W.Reay:

Based on our Monte Carlo, we have a 35-40% ratio of neutral to charged currents, which is a little high. On an event by event basis it is difficult to say whether an event is truly a neutral current event or appears to be so because the muon missed the detector. At least one of our charmed decay events has no tagged muon.

Isgen, University of Toronto:

I was concerned by your F with a mass of around 2130 MeV. You mentioned that the event was difficult; are the problems sufficient to make the mass consistent with the DESY value of about 230 MeV?

Reay:

This event was tough to measure in the emulsion; re-measurements gave considerably different values. I would say that for this event the minimum mass in this OC fit has a large error and could be consistent with 2030 MeV.

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