Measurement of the D^0 Lifetime

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In an experiment measuring charmed-particle lifetimes with a hybrid emulsion spectrometer, 685 neutrino and antineutrino interactions produced by the wide-band beam at Fermi National Accelerator Laboratory have been located. These events have been carefully searched for visible decays. This Letter reports the seven neutral decays which are consistent with a D^0 hypothesis and determine a lifetime of $1.00^{+0.52}_{-0.31}\times 10^{-13}$ sec for this charmed state.

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In the simplest possible model for charm decay, the free-quark model predicts that the D^+, D^0, and F lifetimes are approximately equal, with an expected value for the total lifetime of $\sim 10^{-13}$ sec.[1] Decays of high-mass neutral particles have been reported from emulsion exposures to cosmic rays[2] and accelerator-produced protons,[3,4] from the 15-ft bubble chamber at Fermilab,[5] and most recently from two hybrid emulsion spectrometers at CERN.[6,7] With one exception[6] none of these decays is fully reconstructible and the reported decay times are in the range (0.2–52) $\times 10^{-13}$ sec.

In this and the following paper we report the first results on lifetimes of charmed hadrons obtained in the exposure of 23 liters of emulsion to the single-horn focused neutrino beam at Fermilab.[8]

The experimental apparatus is shown schematically in Fig. 1. The neutrino beam, produced upstream by 350-GeV/c protons, is incident from the left of the figure. Secondary particles from interactions in the target are tracked in a drift-chamber spectrometer with a wide angular acceptance. Time of flight (TOF) is measured with an accuracy of ± 120 psec by a thirty-element scintillator hodoscope, which in turn is followed by a wall of sixty-eight 19 cm× 19 cm× 30 cm lead-glass blocks. A simple hadron calorimeter contains five layers of iron each 10 cm thick interleaved with planes of four vertical scintillators each 2.4 m high by 0.75 m wide. This is followed by a hadron absorber in which muons are identified with scintillator hodoscopes behind 1.2 and 2.9 m of Fe. Events were recorded on magnetic tape if no signal was seen in the veto upstream of the emulsion target, and two or more charged particles left the emulsion and registered in the TOF hodoscope downstream of the magnet. This trigger does not distinguish between neutral- and charged-current interactions.

The 23-liter emulsion target was contained in a volume 86 cm wide by 71 cm high by 5 cm deep. The lower half consisted of 27 modules, each

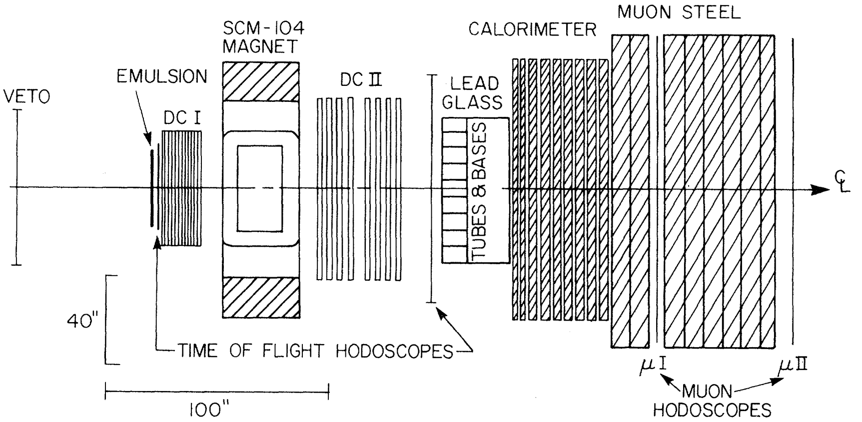

FIG. 1. Plan view of experiment.

composed of 68 films fabricated by coating each side of a 70-μm polystyrene sheet with 330 μm of emulsion. The films measured 12 cm × 9.5 cm × 0.073 cm. The upper half of the target was divided into twelve modules each containing 177 pure emulsion pellicles 14 cm high × 5 cm deep × 0.06 cm thick. The films and pellicles were then punched on a precision jig and stacked on four posts with the films mounted perpendicular to the beam and the pellicles parallel, as illustrated in Fig. 2.

A fiducial sheet of emulsion was placed immediately downstream of the emulsion stack, as shown in Fig. 2. The marks left on this sheet by the ^{55}Fe sources embedded in each mounting post and in a picture-frame support (not shown) recorded the relative positions of all modules. This sheet, changed every two days during data taking, serves as a low-background detector to couple the drift-chamber tracks to the corresponding tracks in the emulsion.

Events are found in the emulsion by two methods. For the pure pellicle stack events are searched for in a volume 4 mm on a side and 20 mm deep along the beam direction and centered on the predicted vertex coordinates. Interactions having only a small number of heavily ionizing nuclear fragment tracks are usually missed by this technique. Events not found are then searched for by following wide-angle tracks into the stack.

To find events in the lower half of the stack, predicted tracks are first searched for in the fiducial sheet shown in Fig. 2 and then followed into the emulsion films. The event-finding efficiency of this method is quite high and is independent of the number of heavily ionizing tracks produced in the interaction.

We have reconstructed 2355 event candidates with a vertex in the target and at least two tracks downstream of the magnet. The fraction of the events with a tagged muon with $p > 4$ GeV/c is 0.52 ± 0.03,[9] and the ratio of events with a single positive muon to those with a single negative muon is 0.10 ± 0.01. After fiducial cuts around post holes and the edges of pellicles, 1821 events remain as candidates for scanning. Thus far 1077 of these events have been searched for and 685 found, yielding a net finding efficiency of 64%. All found events have been searched for visible decays. Neutral decays are looked for downstream of the primary vertex in a cylinder 1000 μm long with a radius of 300 μm and also by following back tracks into the emulsion films. In the course of this search ten neutral multiprong candidates have been found.[10] These are defined as secondary vertices with no evidence of nuclear breakup or recoil ("white stars") and an even number of prongs. The estimated back-

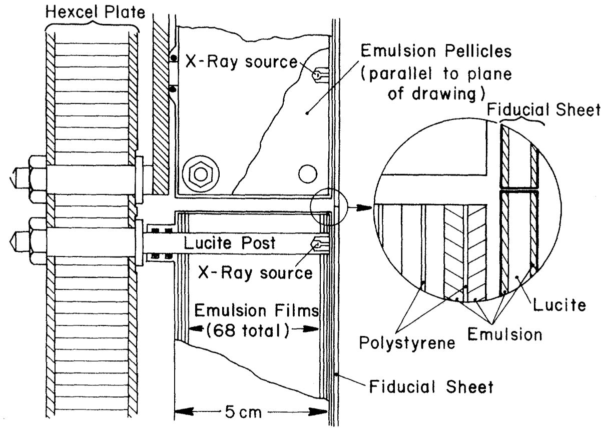

FIG. 2. Cutaway view of the target.

ground from nuclear interactions is less than 0.3 events. None of the events has a mass consistent with K^0 or Λ^0.

Tracks found in the emulsion are matched to those in the spectrometer by comparing the slopes, which can be determined with a resolution of ± 1.9 mrad in the emulsion and ± 0.6 mrad in the drift chambers.

The momentum is measured for all charmed decay tracks. For the 80% of the charged secondaries which traverse the spectrometer the momentum resolution is given by $\Delta p = \pm[(0.005p^2)^2 + (0.013p)^2]^{1/2}$. The momentum calibration has been checked with a sample of protons identified by TOF and is accurate to ± 1.5%. The momenta of the remaining tracks are measured using the fringing field of the magnet with $\Delta p = \pm 0.34 p^2$, or by determining multiple scattering in the emulsion.

Particle identification is obtained from ionization in the emulsion, time of flight, the lead-glass counters, and by range in steel. The counter systems were calibrated with 2×10^5 muon triggers taken throughout the data run. The ionization measurements successfully separate π and K to 800 MeV/c and K-p up to 1.5 GeV/c. Pions and kaons are distinguished by TOF at 1 standard deviation to 3 GeV/c, kaons and protons to 6 GeV/c. The lead-glass energy resolution is $\Delta E = 0.14E^{1/2}$; the absolute energy calibration was determined in a test beam, and checked for electron tracks from observed gamma conversions in the emulsion. The efficiency for tagging muons with $p > 2$ GeV/c is (92 ± 5)%. We note that we cannot reliably identify muons below 1.6 GeV/c nor electrons below 300 MeV/c, nor can we identify wide-angle ($\theta \gtrsim 20°$) fast particles.

To identify π^0's we make use of pair production observed in the emulsion with electron momentum measured in the spectrometer, and γ's which shower in the lead-glass counters.

The seven neutral decays consistent with D^0 or $\overline{D}^0$ hypotheses are listed in Table I. Final-state particles are underlined, (e.g., $\underline{p}$,) if identified by ionization and/or TOF with a confidence level of 90% or better. Decay times are calculated with 1863 MeV/c^2 for the D^0 mass. The decay time error includes uncertainties in the determination of flight path and in the momentum of the D^0.

For events 4, 6 (a semileptonic decay), and 7, a kinematic analysis predicts unseen neutral particles with a confidence level of 99% or higher. These assumed neutrals are enclosed in parentheses, e.g., (π^0). An additional missing neutral is not indicated for event 4 and is not kinematically allowed for event 7. For event 6 an additional π^0 in the final state would yield momentum solutions of 24.2 and 30.2 GeV/c. Event 5 is so short (6.5 ± 1.0 μm) that the direction of the decaying neutral cannot be measured and a 1-constraint fit (assuming the mass of the D^0) is made for this event. For all others the masses listed are for 2-constraint fits to the assumed hypotheses. For the events with an unseen neutral, only kinematically possible charmed hypotheses are listed for which $\Delta C = \Delta S$. A neutral-charmed-baryon hypothesis with a mass less than 2425 MeV/c^2 cannot be excluded for events 4, 5, or 6. We have calculated the $D^0\pi^+$, and $D^0\pi^-$ mass combinations for all events. Events 3, 4, and the low-momentum solution of event 7 are consistent with D^* production with $m(D^0\pi^+) = 2007 \pm 3$ and 2010 ± 3, and $m(\overline{D}^0\pi^-) = 2008 \pm 1$ MeV, respectively. There

TABLE I. Neutral decay candidates. (The event numbers and the corresponding record numbers are as follows: 1, 513-8010; 2, 518-4935; 3, 556-152; 4, 577-5409; 5, 654-3711; 6, 661-6517; 7, 670-7870.)

Event number	Flight path (μm)	p_μ (GeV/c)	Hypothesis	3-C C. L.	p (GeV/c)	Mass (MeV/c^2)	Decay time (10^{-13} sec)
1	27.2	+ 11	$\overline{D}^0 \to K^+\pi^+\underline{\pi}^-\underline{\pi}^-\pi^0$	0.05	9.2	1766 ± 48	0.18 ± 0.020
2	116	− 4	$D^0 \to \pi^+K^-\pi^0\pi^0$	0.88	30.1	1935 ± 132	0.24 ± 0.019
3	41	− 10	$D^0 \to \pi^-K^-\underline{\pi}^+\underline{\pi}^+\pi^0$	0.97	15.4	1855 ± 43	0.17 ± 0.013
4	67	− 30	$D^0 \to \pi^+\pi^-(\overline{K}^0)$		11.3		0.37 ± 0.035
5[a]	6.5	− 4	$D^0 \to \pi^+\underline{\pi}^+K^-\underline{\pi}^-\underline{\pi}^-\underline{\pi}^+$		19.2	1923 ± 46	0.021 ± 0.003
6	2647	− 26	$D^0 \to K^-\underline{\mu}^+(\nu)$		22.8		7.20 ± 0.367
					38.7		4.24 ± 0.216
7	187	+ 34	$\overline{D}^0 \to K^+\underline{\pi}^-(\pi^0)$		6.8		1.71 ± 0.115
					9.5		1.22 ± 0.082

[a] Zero constraint.

are no other mass combinations within 4 standard deviations of the charged-D^* mass.

The scanning efficiency for neutral decays is measured to be (14 ± 7)% for decay distances from 2–5 μm, (32 ± 6)% from 5–10 μm, (68 ± 5)% from 10–30 μm, (81 ± 15)% from 30–400 μm, (71 ± 11)% from 400–1000 μm, and (60 ± 4)% beyond 1000 μm. The drop in efficiency below 30 μm is due to the obscuring of decays by tracks from the primary vertex. The resulting loss of events at short distances has been determined by estimating the length within which a secondary vertex could not be seen for 200 events.

To check for events missed in the neutral-decay volume scan we have examined a subset of 420 interactions carefully to see if there are tracks present in the drift-chamber spectrometer which do not match in angle with those coming from the primary vertex. All tracks with $p > 700$ MeV/c which extrapolate to within 2 mm of the primary vertex are searched for in the fiducial sheet and once found are followed back through the emulsion to their origin (most often a γ conversion). The measured efficiency for finding and tracing back the tracks is (96 ± 2)%. Events 2 and 6 were located by this follow-back technique. The charm decays have one to four tracks meeting the criteria above and for these events the finding efficiency is 98_{-6}^{+2}%. Weighted for the portion of the data sample where this follow-back is not possible because of high muon background, the net efficiency of the technique for events which decay at distances greater than 30 μm from the primary vertex is (60 ± 4)%.

The lifetime determined by maximum liklihood with use of all seven events is $1.00_{-0.31}^{+0.52} \times 10^{-13}$ seconds for the D^0, where we have used the preferred low-momentum solution for event 7 and the high-momentum solution for event 6.[11] The error quoted is statistical only. The effect of choosing the low-momentum solution for event 6 is to shift the lifetime higher by 40%. The effect of uncertainties in the efficiency calibration is much smaller, ± 8% in the worst case. Finally, the effect of errors in the decay times is completely negligible and is less than 5%.

We anticipate that an additional 500 neutrino interactions will be found before the present data sample is exhausted, and that the number of D^0 decays will be correspondingly increased.

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[9] After correcting for the measured muon-detection efficiency above 4 GeV (0.89 ± 0.05) and for the estimated loss of charged-current (CC) events with $P_\mu < 4$ GeV/c [(18 ± 4)%], the (total interaction)/(CC interaction) ratio is 1.40 ± 0.10.

[10] Two of these decays have identified protons and therefore cannot be D^0 decays.

[11] We have tested whether the data are consistent with the hypothesis of one lifetime and find the confidence levels are 1.3% and 0.15% for the high- and low-momentum solutions of event 6. Additional events found since this article was first written indicate no change in the fitted lifetime and a confidence level of 44% for the one-lifetime hypothesis. These new data are not yet fully analyzed.