Measurement of D^+, F^+, and $\Lambda_c{}^+$ Charmed-Particle Lifetimes

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From the analysis of 685 neutrino and antineutrino interactions in an emulsion target, fifteen candidates for the multiprong decay of charged charmed particles are found. This Letter presents lifetimes for the $D^\pm$, $F^\pm$, and $\Lambda_c{}^+$ states based on the fitted events of the sample.

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Several experiments have reported measurements of charged-, charmed-particle decay times. The first example of a possible charged decay in emulsion was published in 1971 by Niu, Mikumo, and Maeda.[1] By 1975 ten possible decays had been reported from cosmic-ray exposures.[2] Accelerator experiments have seen decays in the 15-ft bubble chamber at Fermilab,[3] the streamer chamber,[4] and in hybrid emulsion spectrometers at Fermilab and CERN.[5,6] Only one of the above events was fully reconstructible and was reported to be a $\Lambda_c{}^+$ decay.[6] The measured decay times ranged from 0.2×10^{-13} sec to greater than 2.0×10^{-12} sec.

We have found 25 multiprong–charm-decay candidates in the hybrid–emulsion-spectrometer experiment at Fermi National Accelerator Laboratory described in the preceding Letter.[7] Lifetimes of the charged charmed particles, based on the 15 charged multiprong decays, are reported here. Approximately 60% of the expected data from the first exposure for the experiment has been scanned.

The charged-particle decays were located by following all charged tracks leaving the neutrino interaction vertex (with $\theta<0.2$ rad) for a distance of 6 mm, and by following back spectrometer tracks into the emulsion. We have scanned 13.9 m of hadronic track length and have observed 53 nuclear interactions (57 are expected), 24 single-prong or kink events, and 15 charged multiprong decay candidates (all three prong).[8] The background from nuclear interactions in the three-prong–decay sample is less than 0.8 events.[9] None of the multiprong decays are consistent with the decay of a charged strange particle.

For determining lifetimes it is important to have clean samples of events. Of the 15 multiprong-decay candidates of charged particles, 11 are unambiguous, or at most twofold ambiguous in assignment of parent particle type and are listed in Table I. All decay hypotheses with a 3-constraint confidence level (C.L.) greater than 1% are shown. Decay tracks which have been identified at the 90% confidence level as to particle type are underlined. Particles in parenthe-

TABLE I. Charged decay candidates. (The event numbers and the corresponding record numbers are as follows: 1, 527-3682; 2, 597-1851; 3, 598-1759; 4, 512-5761; 5, 580-4508; 6, 546-1339; 7, 663-7758; 8, 610-4088; 9, 650-6003; 10, 549-4068; and 11, 476-4449.)

Event number	Flight path (μm)	p_μ (GeV/c)	Hypothesis	3-C C.L.	p (GeV/c)	Mass (2-C fit)	Decay time (10^{-13} sec)	Hypothesis used in lifetime
1	670	+30	$F^- \to \pi^- \underline{\pi^-}\, \underline{\pi^+} \pi^0$	0.51	12.25	2026 ± 56	3.70 ± 0.12	F^-
2	130	not seen	$F^+ \to \underline{K^+}\, \underline{\pi^-}\, \underline{\pi^+} \bar{K}^0$	0.68	9.70	2089 ± 121	0.91 ± 0.12	F^+
3	1802	−11	$D^+ \to \underline{K^-}\, \underline{K^+} \pi^+ \pi^0$	0.52	17.0	1862 ± 25	6.60 ± 0.17	D^+
			$F^+ \to K^- K^+ \pi^+ \pi^0 (\pi^0)$	⋯	18.7	⋯	6.53 ± 0.33	⋯
4	457	$\|p\| > 150$	$D^+ \to K^- \pi^+ \underline{\pi^+} \pi^0$	0.07	10.1	1829 ± 35	2.82 ± 0.09	D^+
			$F^+ \to K^- K^+ \underline{\pi^+} \pi^0$	0.10	⋯	2011 ± 33	⋯	⋯
5	2307	+7	$D^- \to \pi^- \underline{K^+}\, \underline{e^-} (\bar{\nu})$	⋯	9.4	⋯	15.3 ± 1.68	D^-
6	2145	−7	$D^+ \to K^- \underline{\pi^+}\, \underline{\mu^+} (\nu)$	⋯	16.1	⋯	8.33 ± 1.03	D^+
			$F^+ \to \pi^- \underline{\pi^+}\, \underline{\mu^+} (\nu)$	⋯	13.0	⋯	11.19 ± 0.16	⋯
				⋯	36.8	⋯	3.95 ± 0.14	⋯
7	13 000	$\|p\| > 150$	$D^+ \to K^- \pi^+ \underline{e^+} (\nu)$	⋯	118	⋯	6.86 ± 0.69	D^+
			$F^+ \to \pi^- \pi^+ \underline{e^+} (\nu)$	⋯	101.5	⋯	8.66 ± 0.76	⋯
8	221	−8	$\Lambda_c{}^+ \to \underline{\pi^+} \pi^- \pi^+ \underline{\Lambda^0}$	0.01	4.70	2382 ± 90	3.58 ± 0.29	$\Lambda_c{}^+$
9	40.6	−15	$\Lambda_c{}^+ \to \underline{\pi^+} \pi^- \pi^+ \underline{\Lambda^0}$	0.25	5.73	2164 ± 88	0.54 ± 0.14	$\Lambda_c{}^+$
10	20.6	−11	$\Lambda_c{}^+ \to K^- \underline{p \pi^+} (\pi^0)$	⋯	2.23	⋯	0.70 ± 0.07	$\Lambda_c{}^+$
11	27.7	−59	$\Lambda_c{}^+ \to \underline{p \pi^+} \pi^- (\bar{K}^0)$	⋯	2.9	⋯	0.73 ± 0.08	$\Lambda_c{}^+$
	⋯	⋯		⋯	5.0	⋯	0.42 ± 0.05	

ses are assumed in order to balance transverse momentum. The two momentum solutions for kinematically ambiguous events are shown if they differ in decay time by more than 10%. For these unconstrained events only decay hypotheses with $\Delta C = \Delta S$ are considered.

A photomicrograph of the first event is shown in Fig. 1. This figure has been slightly retouched to improve contrast.

$F^\pm$ decays.—In the first event in Table I time-of-flight (TOF) identifies two of the decay particles as charged pions, and a π^0 (seen as two γ's in the lead-glass counters) is necessary to balance transverse momentum. If we assume the unidentified negative track is a pion, the constrained mass of the decaying particle is 2026 $\pm$ 56 MeV/c^2 consistent with the F mass.[10] The confidence level for a Cabibbo-unfavored D decay is 0.0001 and even smaller for the Cabibbo-favored mode (not allowed by TOF in any case). We note that the neutral mass combinations of the decay particles are $M\pi^+\pi^- = 611 \pm 27$ and 780 ± 17 MeV/c^2 and $M\pi^+\pi^-\pi^0 = 1296 \pm 59$ and 1338 ± 41 MeV/c^2, not consistent with any known particles with appreciable $s\bar{s}$ quark components.[11]

In the second event all the charged decay tracks are identified by TOF. In addition a neutral hadron which balances transverse momentum is seen in the calorimeter. If this neutral particle is assumed to be a $K_L{}^0$ the event fits the hypothesis of an F^+ decay. A neutron hypothesis would require a doubly Cabibbo-forbidden $\Lambda_c{}^+$ decay and has a confidence level of less than 10^{-4}.

$D^\pm$ decays.—Events 3 through 7 are consistent with the decays of $D^\pm$ mesons. For all these events, the Λ_c hypothesis, obtained by postulating a missing neutron or by assuming an untagged positive hadron is a proton, is ruled out because

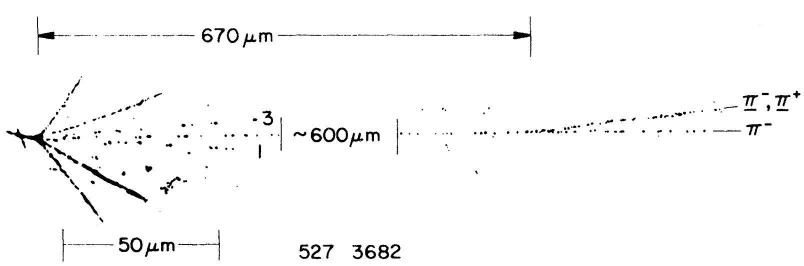

FIG. 1. Event 1.

the minimum mass possible is more than 3 standard deviations above the mass of the Λ_c or $\overline{\Lambda}_c$. However, a small F background may exist and is estimated below on an event-by-event basis under the conservative assumption of equal F and $D^{\pm}$ production.

For event 3 the only constrained hypothesis with confidence level greater than 0.002 is the Cabibbo-unfavored decay of a D^+. A zero-constraint hypothesis, such as $D^+ \to K^-\pi^+\pi^+\pi^0(\pi^0)$ or $F^+ \to K^-K^+ + \pi^+\pi^0(\pi^0)$ is kinematically possible, but no evidence for an additional π^0 is seen in the apparatus. We estimate the probability of such a π^0 avoiding detection is $\lesssim 20\%$, giving a maximum F background for this event of 10%. Event 4, a constrained fit, is ambiguous with F but the D hypothesis is favored by TOF at 80% confidence level. The only kinematically allowed hypothesis for event 5 is $D^- \to \pi^-\underline{K^+e^-}(\bar{\nu})$. Events 6 and 7 may be either $D^+ \to K^-\pi^+l(\overline{\nu_l})$ or $F \to \pi^-\pi^+l(\nu_l)(m\pi^0)$.

The total F contamination in the sample is thus

$$0.1 + 0.2 + 0 + 0.5 + 0.5 = 1.3 \text{ events}$$

under the above assumptions. The most conservative method of estimating the effect of background of order one short-lived F in these data is to cast out the ambiguous event with the shortest decay time (event 4). Doing so raises the average decay time of the remaining events by 16%, a small effect compared to the statistical error on the lifetime computed below.

$\Lambda_c{}^+$ *decays.*—The last four events are consistent with the decays of $\Lambda_c{}^+$ baryons. The first two $\Lambda_c{}^+$ decays have a Λ^0 decay seen in the spectrometer which balances transverse momentum with the charged decay tracks. In events 10 and 11 one of the decay tracks is identified as a proton by time of flight. In both cases the three charged decay tracks do not balance transverse momentum, however, and a neutral decay particle must be assumed. The minimum mass for these two decays is such that additional missing neutrals are excluded. A higher-mass charmed-strange state cannot be excluded for event 10.

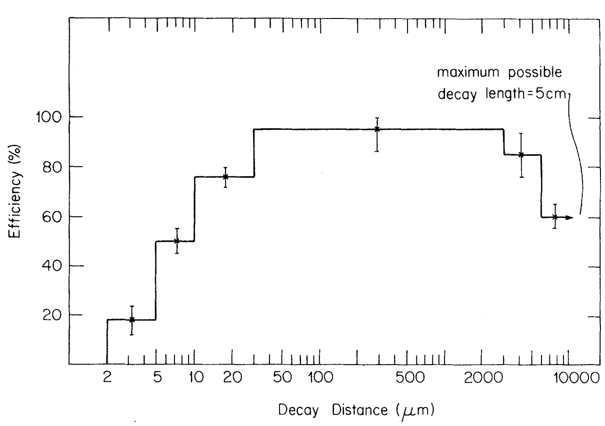

FIG. 2. Scanning efficiency for charged-particle decays.

In summary, from 15 charged multiprong decays we have a clean F sample of two events, a clean $\Lambda_c{}^+$ sample of four events, and a $D^{\pm}$ sample of five events which has a possible F background of ≤ 1.3 events.

In fitting the lifetimes of the charmed particles the method of maximum likelihood is used as in the previous Letter. The scanning efficiency for charged-particle decays is shown in Fig. 2.

The effect of systematic 1-standard-deviation changes in the scanning efficiency is to shift the fitted lifetime of the D^+ by ±8%. For the $\Lambda_c{}^+$ the average of the two-decay-time solutions for event 11 is used in the fit. Choosing the high or low solution displaces the lifetime by ±3%.

We have tested the data sample for each particle type to check consistency with the hypothesis of a single lifetime. A test variable $T = \int_0^\infty [D(t) - \tilde{D}(t)]^2\, dt$ is computed where $D(t)$ is the set of decays seen and $\tilde{D}(t)$ is the spectrum expected for lifetime τ. A confidence level is generated by substituting random decay spectra for the experimental data set and comparing the T values generated with that of the experimental data. For the $D^{\pm}$, $F^{\pm}$, and $\Lambda_c{}^+$ particles the confidence levels obtained are 33%, 85%, and 20%, respectively.

The lifetimes measured by this experiment for the $\Lambda_c{}^+$, $D^{\pm}$, $F^{\pm}$, and D^0 (from Ref. 7) are summarized in Table II. The uncertainties indicated are ±1 standard deviation and include only the statistical errors. We note that the D^0, F, and $\Lambda_c{}^+$ are significantly shorter lived than the D^+

TABLE II. Charmed-particle lifetimes from this experiment. The value for the D^0 is from Ref. 7.

Charmed particle	Assumed mass (MeV/c^2)	Fitted lifetime (10^{-13} sec)	Number of Events
$\Lambda_c{}^+$	2285	$1.14^{+0.90}_{-0.44}$	4
$D^{\pm}$	1868	$10.3^{+10.5}_{-4.1}$	5
$F^{\pm}$	2030	$2.24^{+2.78}_{-1.05}$	2
D^0	1863	$1.00^{+0.52}_{-0.31}$	7

and processes other than the simple radiative decay of the free charmed quark may be important in the calculation of decay rates for these particles. The existence of differing lifetimes for the D^+ and D^0 has been suggested by several authors.[2,12-16]

Averaging semielectronic branching ratios measured by experiments at SLAC,[17] we obtain the branching ratio $R(D^+ \to X^0 e^+ \nu_e) = 0.20$. Combining this number with our measurement of the $D^\pm$ lifetime, we obtain for the partial width $\Gamma(D^+ \to X^0 e^+ \nu_e) = 1.9_{-1.0}^{+1.4} \times 10^{11}\ \text{sec}^{-1}$. This is in good agreement with several theoretical calculations.[18] Assuming the D^+ and the D^0 have the same semielectronic partial widths, and using the D^0 lifetime, we obtain the branching ratio $R(D^0 \to X^- e^+ \nu_e) = 0.019_{-0.009}^{+0.021}$.

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[8]The 24 single-prong events will be described in a later paper.

[9]For 5–30-GeV/c points the probability for the topology $0+3p$ is (2–4)% [Jain *et al.*, Nucl. Phys. 67, 641 (1965)]. We take 3% as an upper limit. The softer-momentum spectrum of the charged hadrons from the neutrino interaction relative to the decays reduces the background to 1.5%.

[10]For the 3-constraint fit the mass of the F meson was assumed to be 2030 MeV/c^2.

[11]This result may suggest a contribution from the $c\bar{s}$ annihilation diagram which has received considerable theoretical attention. See, for example, H. Fritzsch and P. Minkowski, Phys. Lett. 90B, 455 (1980); N. Deshpande, M. Gronau, and D. Sutherland, Phys. Lett. 90B, 431 (1980).

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