New Results for the Lifetimes of the $D^{\pm}$, $F^{\pm}$, and Λ_c^+ Particles

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In an experiment measuring charmed-particle lifetimes with use of a hybrid-emulsion spectrometer in the wide-band neutrino beam at the Fermi National Accelerator Laboratory, 1248 neutrino and antineutrino interactions have been located. Twenty-three charged charm decay candidates have been reconstructed, from which we determine the lifetime of the $D^{\pm}$ to be $11.5^{+7.5}_{-3.5} \times 10^{-13}$ s, that of the $F^{\pm}$ to be $1.9^{+1.3}_{-0.7} \times 10^{-13}$ s, and that of the $\Lambda_c{}^+$ to be $2.3^{+1.0}_{-0.6} \times 10^{-13}$ s.

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The lifetimes of charmed hadrons are of continuing interest.[1-4] Initially, it was believed that the spectator quark model,[5] in which the charm quark decays independently from the other quarks in the parent hadron, was the sole mechanism for charm decay. This model predicts equal lifetimes for all of the lowest-lying charmed hadrons: the D^0, $\bar{D}^0$, $D^{\pm}$, and $F^{\pm}$ mesons and the $\Lambda_c{}^+$ baryon. Other models[6,7] for charm decay have been proposed which involve the interplay of strong interactions with the weak interaction, and to which experimental data, such as the semileptonic branching ratios and the relative differences between the lifetimes of the $D^{\pm}$ and those of the other charmed hadrons, lend support.

This Letter discusses our final results for the lifetimes of the charged charmed hadrons from the first run data of a hybrid-emulsion spectrometer experiment at the Fermi National Accelerator Laboratory. These results are based on observations of the decays of the $D^{\pm}$ and $F^{\pm}$ mesons and the $\Lambda_c{}^+$ baryon. Results based on half the data sample, which included eleven of our charged charm candidates, were previously published.[3] We have reported the final result for the lifetime of the D^0 meson from our first run data.[4]

The experiment was carried out in the Fermilab wide-band neutrino beam. The apparatus consisted of a nuclear emulsion target in a large-acceptance spectrometer.[3,8,9] Reconstruction of charged tracks in the spectrometer predicted 1821 neutrino-interaction vertices in the fiducial volume, which were scanned for either by volume scanning near the predicted vertex position or by following spectrometer tracks back into the emulsion volume. The overall scanning efficiency was 69%, giving 1248 found vertices, which were then examined for short-lived decays.

Decays of charged particles were searched for in the following manner: All charged tracks leaving the neutrino interaction vertex, with both horizontal and vertical slopes relative to the beam direction less than 0.2, were followed for at least 6 mm or until they left the emulsion volume. Wider-angle tracks were followed for 3 mm. In addition, charged tracks reconstructed with the spectrometer, which could not be matched to emulsion tracks at the primary vertex, were followed back into the emulsion (scanback). The efficiency for finding decays has been measured[3] and is identical for $D^{\pm}$, $F^{\pm}$, and Λ_c^+ decays.

We have scanned 32.95 m of hadronic track, in which we have observed 89 multiprong nuclear interactions. Twenty-three multiprong charged decay candidates have been found. One of these is excluded because the analyzing magnet was off, and another event was not in our final fiducial volume. We estimate that the background due to nuclear interactions is 0.2 event for charm decays of momenta greater than 4 GeV/c, and one event for momenta less than 4 GeV/c. There are three unfitted, low-momentum events which have not been included in the lifetime calculations. In addition to the eighteen multiprong charm events, five single-prong events have been fitted as charm decays. None of these is consistent with strange-particle decay. The systematic errors have not been included in the quoted lifetimes because they are very much smaller than the statistical errors.

Kinematic fits were performed on the charm candidates after all the charged tracks had been reconstructed and their momenta analyzed. The existence of neutral particles, π^0 and K^0, was inferred from lead-glass and calorimeter data, and they were included when transverse momentum imbalance at the decay vertex required additional decay particles in the fit. For charged decay particles which were not uniquely identified by time of flight or by ionization measurements at the 90% confidence level, all possible hadron particle identifications were cycled through. Two-constraint (2C) fits, in which the mass and the momentum of the parent are fitted parameters, and three-constraint (3C) fits, where the parent momentum is the only fitted parameter, were possible for events for which the angles and momenta of all the secondaries were available. The parent masses used in the 3C fits were $m_{D^{\pm}} = 1868$ MeV/c^2, $m_{F^{\pm}} = 2030$ MeV/c^2, and $m_{\Lambda_c^+} = 2285$ MeV/c^2. For such events, only those fits which had a confidence level greater than 1% for the three-constraint fit were retained. Zero-constraint calculations were made for events which contained undetected neutral secondaries—neutrinos, and π^0 and K^0 which missed the lead-glass array or the calorimeter.

Eight events have been identified as Λ_c^+ candidates, four are identified as $F^{\pm}$ candidates, and eleven we classify as $D^{\pm}$. The $F^{\pm}$ and the Λ_c^+ candidates are in general cleanly extracted from our charged event sample because of minimum masses of the parent and/or the presence of a baryon in the decay particles. The D^+ sample contains events for which there were multiple allowed kinematic hypotheses.

The four $F^{\pm}$ candidates are listed in Table I. These particles are inconsistent with other charm-particle hypotheses. Final-state particles have been underlined if they have been identified at the 90% confidence level. The masses listed are those which have been obtained with use of two-constraint fits. The momenta are those found from the three-constraint fits to the decays with the mass of the $F^{\pm}$ constrained to be 2030 MeV/c^2.[10] None of the four $F^{\pm}$ candidates is kinematically consistent with a Cabibbo-favored decay of a $D^{\pm}$ or Λ_c^+. Using the method of maximum likelihood, we determine the lifetime of the $F^{\pm}$ to be $1.9^{+1.3}_{-0.7} \times 10^{-13}$ s. To ensure a clean $F^{\pm}$

TABLE I. The $F^{\pm}$ decay candidates. Particles which are underlined have been identified at the 90% confidence level. The masses are those fitted using 2C fits. $P_{\rm charm}$ are obtained using 3C fits.

Flight path (μm)	P_μ (GeV/c)	Hypothesis	$P_{\rm charm}$ (GeV/c)	Mass (MeV/c^2)	Decay time (10^{-13} s)
130	a	$F^+ \to \underline{K}^+\pi^-\underline{\pi}^+\overline{K}^0$	9.3	2057 ± 110	0.97 ± 0.09
153	−9	$F^+ \to \underline{K}^+\underline{K}^-\pi^+\pi^0$	6.0	2050 ± 45	1.72 ± 0.09
670	30	$F^- \to \underline{\pi}^+\pi^-\pi^-\pi^0$	12.2	2026 ± 56	3.70 ± 0.09
65	−7	$F^+ \to \underline{K}^+\overline{K}^0$	2.8	2055 ± 94	1.57 ± 0.12

[a]Muon not seen.

TABLE II. The Λ_c^+ decay candidates. Particles which appear in parentheses are not observed in the spectrometer.

DECAY LENGTH (μ)	Pμ (GeV/c)	HYPOTHESIS	Pcharm (GeV/c)	MASS (MeV/c^2)	DECAY TIME (x10^{-13}s)
40.6	-15	$\Lambda_c^+\to\underline{\Lambda}^0\underline{\pi}^+\pi^-\underline{\pi}^+$	5.7	2131±63	0.54±0.03
180	-15	$\Lambda_c^+\to\underline{\Lambda}^0\underline{\pi}^+\underline{\pi}^-\underline{\pi}^+$	8.4	2274±41	1.63±0.05
175	-6	$\Lambda_c^+\to\underline{p}\bar{K}^0$	5.8	2204±207	2.30±0.08
221	-8	$\Lambda_c^+\to\underline{\Lambda}^0\underline{\pi}^+\underline{\pi}^-\underline{\pi}^+$	4.7	2374±62	3.60±0.19
366	-189	$\Lambda_c^+\to\underline{\Sigma}^0\pi^+$	4.2	2269±17	6.60±0.19
27.7	-59	$\Lambda_c^+\to\underline{p\pi}^+\underline{\pi}^-(\bar{K}^0)$	2.7	0-C	0.79±0.08
			4.8		0.44±0.05
20.6	-11	$\Lambda_c^+\to\underline{p}K^-\underline{\pi}^+(\pi^0)$	1.9	0-C	0.77±0.07
			2.5		0.63±0.07
282.5	-20	$\Lambda_c^+\to\underline{p\pi}^+\underline{\pi}^-(\bar{K}^0)$	6.3	0-C	3.40±0.10

TABLE III. The $D^\pm$ decay candidates. This sample contains events which have several acceptable hypotheses.

DECAY LENGTH (μ)	Pμ (GeV/c)	HYPOTHESIS	Pcharm (GeV/c)	MASS (MeV/c^2)	DECAY TIME (x10^{-13}s)
570	-150	$D^+\to\pi^+K^-\pi^+\pi^0$	32.6	1933±73	1.09±0.05
		$F^+\to K^+K^-\pi^+\pi^0$	32.4	2099±73	1.19±0.05
		$\Lambda_c\to pK^-\pi+$	31.7	2317±76	1.36±0.06
185	-16	$D^+\to\pi^+K^-\pi^+$	9.4	1717±260	1.23±0.08
		$D^+\to\pi^+K^-\pi^+\pi^0$	9.7	2036±291	1.19±0.07
		$F^+\to\pi^+\pi^-\pi^+\pi^0$	10.8	2209±323	1.15±0.07
		$\Lambda_c^+\to\pi^+\pi^+K^-(n)$	11.0	0-C	1.27±0.07
457	>150	$D^+\to K^-\pi^+\pi^+\pi^-\pi^0$	10.4	1829±35	2.77±0.05
		$F^+\to K^-K^+\underline{\pi}^+\pi^0$	10.3	2011±33	3.00±0.05
1802	-11	$D^+\to K^-K^+\underline{\pi}^+\pi^0$	17.4	1862±25	6.45±0.13
		$\Lambda_c^+\to K^-p\underline{\pi}^+\pi^0$	17.9	2179±38	7.63±0.14
		$D^+\to\pi^-\underline{\pi}^+\pi^+(\bar{K}^0)$	22.3	0-C	5.04±0.04
		$F^+\to K^-\underline{\pi}^+\pi^+(\bar{K}^0)$	21.8	0-C	5.60±0.05
		$F^+\to K^-K^+\underline{\pi}^+\pi^0(\pi^0)$	18.4	0-C	6.59±0.05
2203	-7	$D^+\to\pi^+\pi^+\pi^-\bar{K}^0$	11.9	2061±156	11.5±1.2
		$F^+\to\pi^+\pi^+K^-\bar{K}^0$	11.7	2246±166	12.7±0.8
		$\Lambda_c^+\to\pi^+\pi^+K^-n$	13.3	2330±123	12.6±1.9
2547	-57	$D^+\to\pi^+\pi^0(\bar{K}^0)$	55.4	0-C	2.9±0.1
		$F^+\to K^+(\bar{K}^0)$	43.1	0-C	4.0±0.1
		$F^+\to K^+\pi^0(\bar{K}^0)$	38.4	0-C	4.5±0.1
13000	>150	$D^+\to K^-\pi^+\underline{e}^+(\nu_e)$	114.3	0-C	7.08±0.44
		$F^+\to\pi^+\pi^-\underline{e}^+(\nu_e)$	96.8	0-C	8.36±0.47
2150	-7	$D^+\to K^-\pi^+\underline{\mu}^+(\nu_\mu)$	16.6	0-C	8.06±0.22
		$F^+\to\pi^+\pi^-\underline{\mu}^+(\nu_\mu)$	13.3	0-C	10.94±0.16
			36.8		2.95±0.02
5246	-9	$D^+\to\pi^+\pi^0(\bar{K}^0)$	40.1	0-C	8.1±0.1
		$F^+\to K^+(\bar{K}^0)$	34.8		10.2±0.1
2307	+7	$D^-\to\pi^-\underline{K}^+\underline{e}^-(\bar{\nu}_e)$	9.5	0-C	15.20±0.40
			10.0	0-C	14.37±0.36
13600	-51	$D^+\to\pi^+\underline{\pi}^+K^-(\pi^0)$	23.5	0-C	36.0±1.8
			31.7		26.7±1.3
		$F^+\to K^+\underline{\pi}^+K^-(\pi^0)$	22.5	0-C	40.9±1.9
			32.7		28.1±1.1
		$\Lambda_c^+\to p\underline{\pi}^+K^-(\pi^0)$	22.5	0-C	46.0±2.5
			31.5		32.9±1.3

sample for lifetime determination we effectively required each $F^\pm$ candidate to have a mass greater than 2000 MeV/c^2. The weighted average mass of this sample is 2044± 30 MeV/c^2. We note that the F^- has an all-pion decay mode and that there is no evidence of a resonance containing substantial $s\bar{s}$ component in the decay pions from this event.[3] This may indicate the importance of alternative decays processes, such as annihilation, for which several theoretical predictions have been made.[6]

The eight events in Table II are identified as Λ_c^+ by their kinematic fits and the presence of an identified baryon in the decay products. Neutrals which have been assumed in order to balance transverse momentum are enclosed in parentheses. The mass used in the 3C fits is 2285 MeV/c^2. Five events have 3C fits with confidence levels greater than 1%. Three of the events have neutrals which are not reconstructed by the spectrometer, thus limiting the analysis for these events to zero-constraint calculations. The lifetime is $2.3_{-0.6}^{+1.0}\times10^{-13}$ s for the eight Λ_c^+ candidates. The weighted average mass of the Λ_c^+ candidates is 2265± 30 MeV/c^2.

The remaining charged events which are used to determine the $D^\pm$ lifetime are shown in Table III. For each event, all hypotheses with acceptable 3C confidence levels have been listed. We have performed a two-dimensional maximum-likelihood calculation on this sample in order to extract the lifetime of the $D^\pm$, and to determine the fraction of the sample likely to be $D^\pm$. The method of maximum likelihood for two independent variables[9,11] was used, where the two variables were the lifetime of the $D^\pm$ and the fraction of the sample which were $D^\pm$. In performing this analysis, an average of the measured $F^\pm$ and Λ_c^+ lifetimes, i.e., 2.1×10^{-13} s, was used as the lifetime of the contaminants, and an integration was performed to take into account the uncertainty in the measured $F^\pm/\Lambda_c^+$ lifetime. A contour plot of the likelihood function is shown in Fig. 1. This gives a lifetime of $11.5_{-3.5}^{+7.5}\times10^{-13}$ s for the $D^\pm$. The fraction of $D^\pm$ which are contained in this sample is $0.97_{-0.29}^{+0.03}$.

The lifetimes we have measured for the $D^\pm$, $F^\pm$, and Λ_c^+ are summarized in Table IV. The lifetime of the $D^\pm$ appears to be somewhat longer than the lifetimes of the $F^\pm$ and Λ_c^+.

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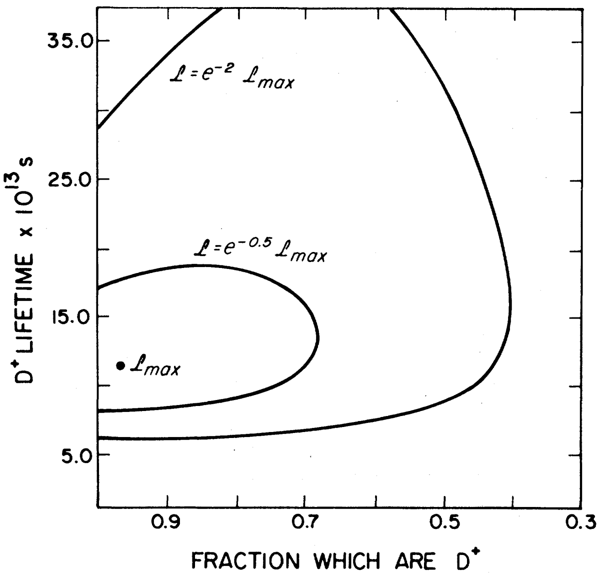

FIG. 1. Contour plots for the likelihood function $\mathcal{L}(\tau,f)$. The contours shown correspond to the one- and two-standard-deviation limits.

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TABLE IV. The lifetimes of the charged charm particles.

Particle	Fitted lifetime (10^{-13} s)	Number of events
$D^{\pm}$	$11.5^{+7.5}_{-3.5}$	11
$F^{\pm}$	$1.9^{+1.3}_{-0.7}$	4
Λ_c^{+}	$2.3^{+1.0}_{-0.6}$	8