Lifetimes of the Charmed Particles $D^{\pm}$, $F^{\pm}$, and Λ_c^+ Produced by Neutrinos

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We report final results for the $D^{\pm}$, $F^{\pm}$, and Λ_c^+ lifetimes measured with a hybrid emulsion spectrometer in the wide-band neutrino beam at Fermilab. In total, 3886 neutrino and antineutrino interactions were located in the fiducial volume of the emulsion. From these interactions we have unambiguously identified 6 $F^{\pm}$ and 13 Λ_c^+ decays, for which the fitted lifetimes are $\tau(F^{\pm})=(2.6^{+1.6}_{-0.9})\times10^{-13}$ s and $\tau(\Lambda_c^+)=(2.0^{+0.7}_{-0.5})\times10^{-13}$ s. 28 other decays are consistent with a D^+ or D^- hypothesis. From these events, we obtain a $D^{\pm}$ lifetime of $(11.1^{+4.4}_{-2.9})\times10^{-13}$ s.

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The first example of charmed-particle decay was published in 1971.[1] Subsequent experiments[2] provided qualitative confirmation of the theoretical prediction[3] that charmed-particle lifetimes are of the order of 10^{-13} s. The first quantitative measurement of lifetimes for several charmed-particle species (including the $F^{\pm}$ meson) were presented in 1979.[4] Only relatively recently have larger samples and better identification techniques allowed improved measurements of the lifetimes of different charmed-particle species.[5-8]

We report here final results from our collaboration on charged-charmed-particle lifetimes, based on 48 decays consistent with a charm-decay hypothesis. Lifetimes from 23 of these decays have been published previously[7]; the new events are from a second run of the experiment with an improved hybrid emulsion spectrometer.

The original configuration of the spectrometer has been described extensively elsewhere.[5,7,9,10] Several modifications to the neutrino beam and to the detector (Fig. 1) made significant improvements in the quantity and quality of the data from the second run. The incident-proton-beam energy was increased from 350 to 400 GeV, resulting in a more energetic neutrino spectrum. The muon background, which caused significant equipment deadtime in the first run, was reduced by replacement of the earth shield in the neutrino beam line with 6000 tons of steel. Four more drift chambers in the spectrometer permitted reliable reconstruction and fringe-field momentum measurement (to a precision of $\sigma_p=0.08P^2$), for tracks traversing only the upstream portion of the spectrometer. The momentum resolution for tracks passing through the complete spectrometer was improved to $\sigma_p=[(0.014\times P)^2+(0.004P^2)^2]^{1/2}$. A large cell drift chamber inside the magnet gap helped to connect charged tracks upstream and downstream of the magnet. The π^0 mass resolution was improved by insertion of a 2.9-radiation-length gamma-ray converter system, with a $\sigma=7.5$ mm position resolution, in front of the lead-glass–block electromagnetic calorimeter. The upstream half of the hadron calorimeter was instrumented with extruded proportional ionization chambers (EPIC's) which gave a position resolution of $\sigma=30$ mm.

Candidate neutrino interactions were recorded by use of a minimally biased trigger which required a signal of at least 2.5 times minimum ionizing in TOF I,

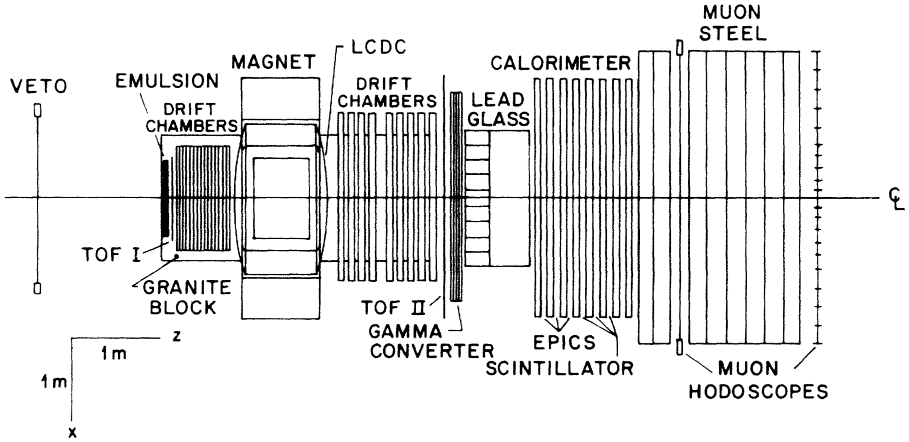

FIG. 1. Plan view of the experiment (LCDC: large cell drift chamber).

and a hit in at least two TOF II counters (Fig. 1).

Most neutrino interactions were found by use of the followback technique,[10] in which typically one or two tracks were followed back from the spectrometer into the emulsion. Charged-particle decays produced in these interactions were searched for mainly by our following all the charged tracks from the neutrino interaction vertex (6 mm if $\theta < 200$ mrad, up to 3 mm at larger angles), also by followback for the tracks with $P \geqslant 400$ MeV/c and θ (emission angle) $\leqslant 300$ mrad, and by volume scan. The followback efficiency (typically 80%–85%) was determined from the probability that a decay product was reconstructed in the spectrometer combined with the probability that a track can be followed back to a vertex in the emulsion. This last point was also useful to calibrate the track-following efficiency (typically 95%). The final data sample consists of 1248 (2638) neutrino interactions in the fiducial volume (5 cm along the beam direction) in the first (second) run. A total of 62 charged charm-decay candidates was found, in addition to 276 secondary interactions.

Each of the decay-candidate events was reanalyzed to match the emulsion and drift chamber tracks, and to look exhaustively for spectrometer tracks which might have been missed in the first reconstruction. To account for all the particles, emulsion tracks which had no match in the spectrometer were followed to the downstream end of the emulsion. Similarly, good drift-chamber tracks without an emulsion match were searched for in the emulsion by use of the followback technique. This search had high efficiency for finding a second charm decay in the same event if any were present. One such event ($D^0 + \bar{D}^0$) was found.[7] Usually the extra drift-chamber tracks originated at a gamma conversion, a strange-particle decay, or a secondary nuclear interaction.

An attempt was made to identify the particle type of each track in the decay-candidate events (38% were identified). Our typical time-of-flight (TOF) resolution was $\sigma = 80$ ps. Figure 2 shows the mass obtained from the TOF system for a sample of particles with $P < 2$ GeV/c. Particles could also be identified by measurement of their ionization in the emulsion, a method whose typical precision is 5%. Electrons with energies above 1 GeV could be identified in the electromagnetic calorimeter; muons with $P > 1.5$ GeV/c were identified by their range in steel.

The electromagnetic and hadron calorimeters and the emulsion were searched for evidence of neutral particles in the decay-candidate events. All gamma combinations with an invariant mass less than 3 standard deviations from the π^0 mass were tried as π^0 candidates in the kinematic fits. Energetic π^0's (above 1.5 GeV) aiming at our detector were detected with an efficiency above 90%.

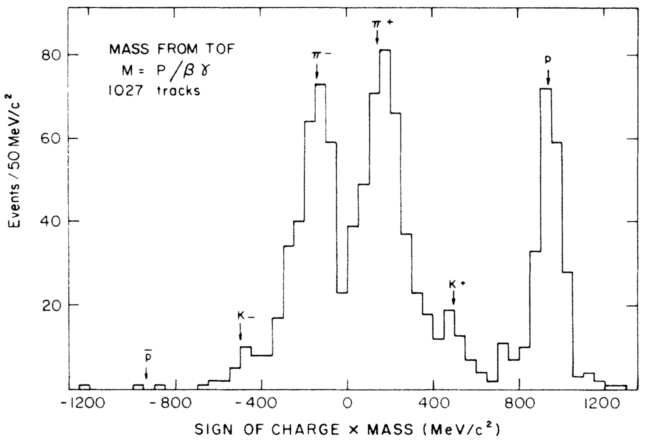

FIG. 2. Typical distribution of sign of charge times mass for particles for which time of flight is measured. A momentum cut of 2 GeV/c has been applied.

Since the direction of the charmed particles was measured in the emulsion, the transverse momentum of the decay products could be measured relative to this direction with a typical precision of 40 MeV/c. This constraint was valuable in selecting which, if any, of the observed neutral particles came from the decay vertex.

Kinematic fits were tried for all expected decay modes of the $D^\pm$, $F^\pm$, and Λ_c^+ consistent with the observed neutrals and the charged-particle identifications. A decay hypothesis with a fit confidence level greater than 1% was considered constrained. Filtering of the constrained fits was done with use of the charmed-particle mass, the confidence level, and the quality and number of neutrals. For each decay mode, the best possible constrained fits were kept; if both Cabibbo-favored and -unfavored fits were possible, we kept only the Cabibbo-favored fits. For the unconstrained events, only the Cabibbo-favored hypotheses consistent with an unobservable neutral were used.

Of the 62 decay candidates, fourteen (five kinks, nine tridents) could not be fitted to a charmed-particle decay because they were poorly constrained or underconstrained. The expected background to charmed-particle decays due to the interaction of particles with $P > 4$ GeV/c is one event. The 48 fitted decays (seven kinks, 41 tridents) consisted of 6 $F^\pm$, 13 Λ_c^+, 28 decays with hypotheses ambiguous among $D^\pm$, $F^\pm$, or Λ_c^+, and one between F^+ and Λ_c^+. In order to obtain the purest $F^\pm$ (Λ_c^+) samples possible, only the events with no other allowed hypotheses were considered as $F^\pm$ (Λ_c^+). A mass of 1971 MeV/c^2 was used for fitting the $F^\pm$, and 2282 MeV/c^2 for the Λ_c^+.[11] All the Λ_c^+ events had a final-state proton tagged by TOF; this includes protons from Λ^0.

The $F^\pm$ lifetime was obtained from the decay times by the maximum-likelihood estimation method[12]; it is

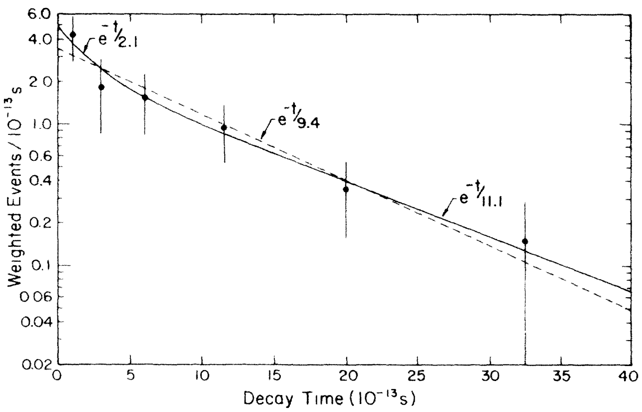

FIG. 3. Differential lifetime plot for ambiguous events. The dashed (solid) curve is from the one- (two-) parameter lifetime calculation.

$(2.6^{+1.6}_{-0.9}) \times 10^{-13}$ s. The weighted average of the six fitted $F^{\pm}$ masses is 1980 ± 15 MeV/c^2. Similarly, the Λ_c^+ lifetime was found to be $(2.0^{+0.7}_{-0.5}) \times 10^{-13}$ s. The eight fully constrained decays have an average mass of 2266 ± 13 MeV/c^2.

28 decays were consistent with a $D^{\pm}$ hypothesis. However, $F^{\pm}$ or Λ_c^+ hypotheses, or in some cases both $F^{\pm}$ and Λ_c^+ hypotheses, could not be ruled out for most of these events. If we assume that all of these decays are $D^{\pm}$, we obtain a lifetime of $(9.4^{+2.4}_{-1.8}) \times 10^{-13}$ s, and an average mass of 1891 ± 14 MeV/c^2. However, since some of these decaying particles were probably $F^{\pm}$ or Λ_c^+, we used a two-parameter likelihood function to estimate this contamination in the $D^{\pm}$ sample. The two parameters fitted were the $D^{\pm}$ lifetime and the fraction of $D^{\pm}$ in the sample. Using a lifetime of 2.1×10^{-13} s for the short-lived component, we found a $D^{\pm}$ lifetime of $(11.1^{+4.4}_{-2.9}) \times 10^{-13}$ s, and a short-lived contamination of $4.8^{+5.0}_{-5.6}$ events. Although both curves in the differential lifetime plot (Fig. 3) are consistent with the data, the two-parameter result with its larger error reflects more accurately the uncertainties in the contamination.

We have also investigated the effects on the lifetimes of possible biases in the scanning, tracking, and π^0 reconstruction efficiencies and in the charmed-particle momentum. The corresponding overall bias on the lifetime from each of these effects was at most a small fraction of the quoted errors.

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