Lifetime of D^0 Charmed Mesons Produced in Neutrino Interactions

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We report final results for the D^0 lifetime measured with a hybrid emulsion spectrometer in the wide-band neutrino beam at Fermilab. In a total of 3886 neutrino and antineutrino interactions located in the emulsion fiducial volume, we have found 58 D^0 decays, from which we determine the lifetime to be $(4.3^{+0.7}_{-0.5}{}^{+0.1}_{-0.2})\times 10^{-13}$ s.

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The simplest spectator-quark model predicts identical lifetimes for the ground-state particles D^0, $D^\pm$, $F^\pm$, and Λ_c^+ carrying a single charmed quark.[1] However, differences in measured lifetimes among these particles are becoming increasingly significant.[2–6] With better measurements of lifetimes and of semileptonic branching ratios, it is now meaningful to test the less restrictive hypothesis of equal semileptonic decay rates.

We report here the D^0 lifetime from the final sample of 58 decays obtained in our collaboration. This is the largest sample of visible D^0 decays to be used for a lifetime determination by any single experiment. Results based on sixteen of these decays have been published previously[2]; final results for the $D^\pm$, $F^\pm$, and Λ_c^+ lifetimes from this experiment appear in the preceding Letter.[6]

The data were obtained during two runs in the wide-band neutrino beam at Fermilab. The detector, which comprised an emulsion target followed by a wide-aperture electronic spectrometer, and the modifications made to it for the second run, are described elsewhere.[2,4,6,7] In total, 3886 neutrino and antineutrino interactions were located in the fiducial volume of the emulsion.[6] Most of these interactions were found by the followback technique.[7] Neutral secondary vertices in these interactions were found mainly by followback; drift-chamber tracks without matching tracks from the interaction vertex in the emulsion were followed back to their origin. In addition, volume scanning for decays was done for at least 300 μm downstream of the neutrino interaction. This method was primarily useful for finding very short decays.

Although charged secondary vertices can be found by the following of charged tracks downstream from the interaction, this technique is inappropriate for finding neutral vertices. It is therefore important that the one remaining efficient method, followback, be well understood. It is shown in Fig. 1(a) to have an efficiency nearly independent of the neutrino interaction position in the emulsion, along the beam direction. The ratio of interactions found to those searched for from the spectrometer predictions is on average 82%; most of the apparent 18% inefficiency is a result of interactions occurring outside, but near to, the fiducial volume of the emulsion. A second check is provided by e^+e^- pairs which were found by followback independently of the conversion distance [Fig. 1(b)].

Table I summarizes the categories of neutral secondary vertices found. The 75 decay-candidate events were reanalyzed according to the procedure described in Ref. 6 to find all possible matches between spectrometer and emulsion tracks, look for any other secondary vertices, identify particle type (30% were identified), and find all photon conversions and neutral hadron decays and interactions in the emulsion, spectrometer, and calorimeters.

A kinematic fit was attempted for all the expected decay modes of the D^0, K_S^0, and Λ^0 consistent with the observed neutrals and the allowed charged-particle identifications.

The 58 D^0 candidates included 36 two-prong, twenty four-prong, and two six-prong decays. 42 of these events were classified as constrained because they had

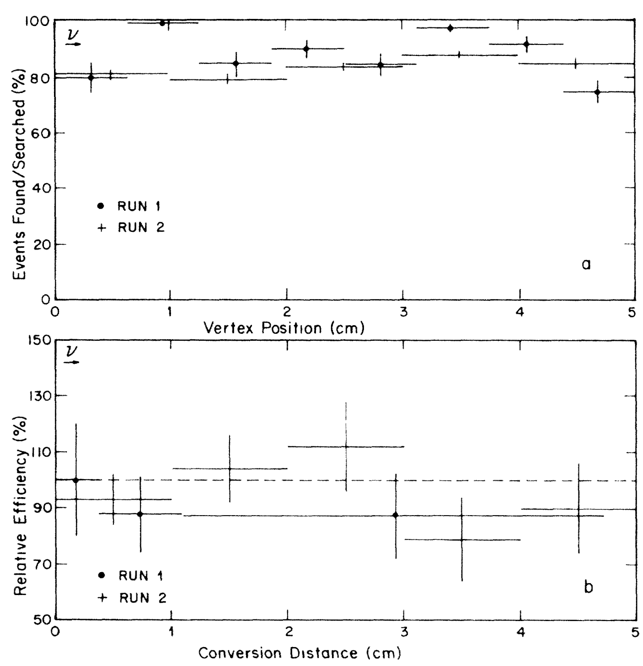

FIG. 1. Measurements of finding efficiency vs position in the emulsion. (a) Ratio of neutrino interactions found to those searched for from the spectrometer predictions. (b) e^+e^- pair (gamma conversion) relative finding efficiency. The data were compared with the expected distribution of gamma conversions and normalized to the observed number of events.

TABLE I. Summary of secondary neutral vertices in the fiducial volume.

Event type	Number	Comments
D^0	58	Consistent with D^0; K_S^0 and Λ^0 ruled out.
?	2	Impossible to fit by D^0 or strange particle. The effect of these two events on the D^0 lifetime was estimated to be smaller than the quoted systematic error.
Strange decays	15	6 K_S^0, 8 Λ^0, 1 K_S^0 or Λ^0. With our 30% efficiency, twenty strange-particle decays were expected to be found.
e^+e^-	523	Small opening angle in the emulsion and/or low invariant mass ($\lesssim 50$ MeV/c^2).
Nuclear interactions	12	Recognized by nuclear breakup or recoil tracks and/or apparent nonconservation of charge. An additional 0.5 interaction could have simulated a decay in the emulsion.

a fit confidence level greater than 1%. When there was more than one acceptable fit, a choice was made on the basis of the relative confidence level of the hypotheses and the number of neutrals used in the fits (the lowest possible number of neutral particles consistent with an acceptable fit was always used). If an event had both Cabibbo-favored and -unfavored hypotheses, the Cabibbo-favored hypotheses were retained.[8] If no clear choice could be made, all the hypotheses were kept and given equal weight in the lifetime calculation.

For the sixteen unconstrained events, all the Cabibbo-favored hypotheses with an unobservable neutral particle and a minimum invariant mass which allowed a D^0 solution were used with equal weight, except for two events which had two hypotheses which could be weighted according to their relative time-of-flight (TOF) confidence level. Usually, each hypothesis has two possible D^0-momentum solutions; if neither solution could be eliminated, both were weighted equally.

An additional fitting constraint is available for D^0's which can be shown to come from charged D^* decay. Figure 2 shows the difference between the measured invariant mass of all the $D^0\pi^+$ ($\bar{D}^0\pi^-$) combinations and the D^0 ($\bar{D}^0$). There is a peak containing ten events at the $D^{*+}-D^0$ ($D^{*-}-\bar{D}^0$) mass, with negligible background within 10 MeV/c^2. The average mass difference is 145 ± 1 MeV/c^2, very close to the currently accepted value.[9] This extra constraint (D^* mass) reduced the number of unconstrained events from twenty to sixteen.

The D^0 lifetime was calculated by use of the maximum-likelihood estimation method.[10] The D^0 mass used was 1864.7 MeV/c^2.[9] Each event was assigned a weight based on the finding efficiency, the minimum and maximum scanning-distance cutoffs for that event (typically 8 μm and 2.3 cm), and the hypothesis weight. As described above, the finding efficiency is nearly independent of decay distance; it includes the effects of losses due to track reconstruction efficiency, followback cuts ($P \geqslant 400$ MeV/c, $\theta \leqslant 300$ mrad) and efficiency, and confusion of tracks very near the primary vertex. The average finding efficiency for the neutral decay sample is 81%.

A lifetime of $(4.3^{+0.7}_{-0.5}{}^{+0.1}_{-0.2})\times10^{-13}$ s was determined from the 58 events. The systematic error was estimated by our varying the finding efficiency and by our

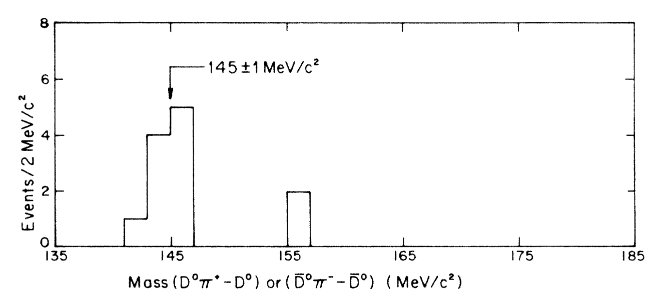

FIG. 2. Difference between the invariant mass of all the $D^0\pi^+$ ($\bar{D}^0\pi^-$) and the D^0 ($\bar{D}^0$) mass; most combinations are off scale. For each event, the D^0 mass used was the observed invariant mass of the D^0 decay products.

studying the effect (using a Monte Carlo program) of adding a second missing neutral to the unconstrained events. We have also studied possible shifts which would be caused by association of a wrong secondary neutral with the decay, obtaining an incorrect D^0-momentum solution. We estimate that the probability of simulating a constrained fit is 4% in this case, and that possible systematic shifts in the measured lifetime from this source are less than 1%. The weighted average mass of 38 constrained D^0's is 1865 ± 6 MeV/c^2.

Figure 3 is a plot of the differential decay-time distribution dN/dt. The data are well described by a single exponential curve computed by use of the measured lifetime.

In our earlier published results,[2] three semileptonic decays (which are unconstrained because of undetected neutrinos) had an average lifetime 3 times longer than the sixteen hadronic decays. Since the momentum of each of these three events is uncertain up to a factor of 2, and because of the possibility that the sample might contain other long-lived heavy particles in addition to the D^0, the published lifetime was obtained from the sixteen hadronic decays. With more decays this effect has disappeared. The six semileptonic decays in the present sample have an average lifetime equal within statistics to that of the hadronic decays, and all are used in the final lifetime determination.

Using the $D^{\pm}$ lifetime from this experiment $[(11.1^{+4.4}_{-2.9})\times 10^{-13}$ s],[6] and the D^0 lifetime reported above $[(4.3^{+0.7}_{-0.5})\times 10^{-13}$ s], we find the ratio of the $D^{\pm}$ to D^0 lifetimes to be $2.6^{+1.1}_{-0.8}$. The ratio was calculated with a two-parameter likelihood function, where the two parameters are the $D^{\pm}$ and D^0 lifetimes.

One can compare the three semileptonic decay rates using the most recent electron semileptonic branching ratios for the D^+ and D^0 [11] and the Λ_c^+,[12] and the lifetimes measured in the experiment. We calculated rates (in units of 10^{11} s^{-1}) of 1.7 ± 0.5, $1.5^{+0.4}_{-0.6}$, and $2.3^{+1.0}_{-1.2}$ for the D^0, D^+, and Λ_c^+, respectively. This result indicates that the W-boson radiation, which is believed to be the only source of semileptonic decays, contributes equally to the D^0, D^+, and Λ_c^+ decay rates. The recently observed branching ratio of $(0.99 \pm 0.32 \pm 0.17)$% for $D^0 \rightarrow \bar{K}^0\phi$ is attributed to W-boson exchange.[13] This may indicate that the D^0 lifetime is shorter because its hadronic decay rate is enhanced by W-exchange processes.

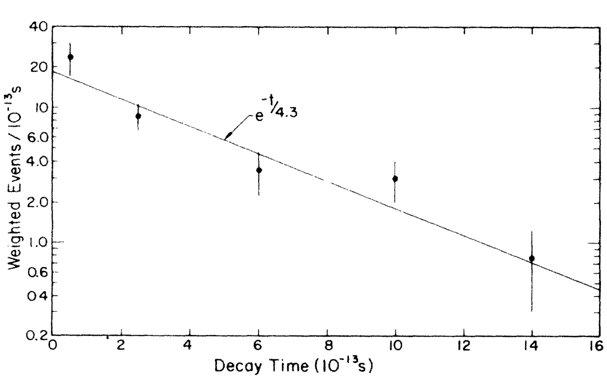

FIG. 3. dN/dt plot. Each entry has a weight based on the scanning efficiency, the short- and long-distance cutoffs, and the hypothesis weight. The curve is computed from the measured lifetime.

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