bility can be ruled out altogether.[5]

In the event that the B coefficients for neutrino-electron and neutrino-quark scattering all turn out to be zero or negative, then one must make use of the much more detailed tests of Kayser and Shrock[3] to decide the Majorana versus Dirac issue for neutrinos. Or, alternatively, one must search for the occurrence of no-neutrino double-β decay.[6]

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[1]L. Michel, Proc. Roy. Soc. London, Ser. A 63, 514 (1950); T. Kinoshita and A. Sirlin, Phys. Rev. 107, 844 (1957).

[2]S. E. Willis *et al.*, Phys. Rev. Lett. 44, 552 (1980).

[3]Neutrino-electron scattering as a test for Majorana neutrinos was first discussed by B. Kayser and R. Shrock, SLAC Report No. SLAC-PUB-2815(T) (unpublished).

[4]B. Kayser, E. Fischbach, S. P. Rosen, and H. Spivack, Phys. Rev. D 20, 87 (1979); R. L. Kingsley, F. Wilczek, and A. Zee, Phys. Rev. D 10, 2216 (1974); S. Pakvasa and G. Rajasekaran, Phys. Rev. D 12, 113 (1975).

[5]J. E. Kim, P. Langacker, M. Levine, and H. H. Williams, Rev. Mod. Phys. 53, 211 (1981); H. H. Williams, private communication.

[6]H. Primakoff and S. P. Rosen, Rep. Prog. Phys. 22, 121 (1959).

New Result for the Lifetime of the D^0 Meson

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In an experiment measuring charmed-particle lifetimes with a hybrid emulsion spectrometer, 1248 neutrino and antineutrino interactions produced by the wide-band beam at Fermi National Accelerator Laboratory have been located. Twenty-one candidates for the decay of neutral charmed particles are found. The lifetime for the D^0 based on the sixteen constrained events of this sample is measured to be $2.3^{+0.8}_{-0.5}\times 10^{-13}$ sec.

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In the spectator quark model all charmed particles are predicted to have the same lifetime. Experimentally the neutral D mesons are shorter lived than the charged D's and in fact have lifetimes similar to those of the weakly decaying charmed particles F and Λ_c.[1-5] Previous analy-

TABLE I. Total secondary neutral vertices.

Type	Number	Comments
γ conversions	113	Opening angle < 8 mrad and/or $m_{e^+e^-} \ll 50$ MeV.
Nuclear interactions	3	From this we can deduce a background of less than 0.1 event for our D^0 sample (Ref. 9).
Decay candidates		
(a) $K_S{}^0$	2	Fit $K_S{}^0 \to \pi^+\pi^-$.
(b) Λ^0	2	Identified proton; consistent with Λ^0.
(c) ?	1	Identified proton; long-lived baryon candidate; to be reported elsewhere.
(d) ?	1	Spectrometer magnet was off. Event excluded.
(e) D^0	19	No identified proton; not consistent with strange particle decay or γ conversion. Consistent with D^0 decay.

ses using visual techniques have sometimes assumed that all weakly decaying neutral charmed particles are D^0 mesons. Since it is possible that other long-lived heavy particles may exist, we examine an enlarged sample with the particular view of identifying a pure subset of D^0 events.

In this Letter we report final results for the lifetime of the D^0 meson from the exposure of a hybrid-emulsion spectrometer[2,6,7] to the Fermilab wide-band neutrino beam. Events are found either by searching directly for the predicted vertex (volume scan) or by following tracks back into the emulsion films. 1821 events are predicted to lie within the fiducial region of the emulsion. All have been searched for and 1248 found for a net finding efficiency of 69%. Neutral

TABLE II. D^0 decay candidates.

Event No.	Flight Path (μm)	P_μ (GeV/c)	Hypothesis	P (GeV/c)	Mass (MeV/c²)	Decay Time ($\times 10^{-13}$ sec)	Comments
1[a]	126	-4.8	$D^0 \to \underline{\pi}^-\pi^-\underline{\pi}^+\underline{\pi}^+K^-\pi^+\pi^0$	7.5	1897±26	1.03±.08	
2	324	-20	$D^0 \to K^0\pi^+\underline{\pi}^-$	11.3	1819±80	1.77±.13	
3	27	+11	$\bar{D}^0 \to K^+\pi^+\underline{\pi}^-\underline{\pi}^-\pi^0$	9.2	1766±48	0.18±.02	
4	116	-4	$D^0 \to \pi^+K^-\pi^0\pi^0$	30.1	1935±132	0.24±.02	
5[b]	626	not seen	$D^0 \to K^-\pi^+\pi^0$	12.9	1856±79	3.02±.18	
6[b]	3307	not seen	$\bar{D}^0 \to K^+K^-$	47.7	1832±124	4.59±.19	
7	4056	-46	$D^0 \to \pi^+\pi^-\underline{\pi}^+K^-\pi^0$	23.6	1861±39	10.7±.34	
8	748	-200	$D^0 \to K^-\pi^+\underline{\pi}^+\pi^-$	13.5	1947±99	3.44±.21	D^{*+}
9	41	-10	$D^0 \to \pi^-K^-\underline{\pi}^+\underline{\pi}^+\pi^0$	15.4	1855±43	0.17±.01	D^{*+}
10	183	+27	$\bar{D}^0 \to \pi^-K^+\pi^0\pi^0$	22.4	1825±68	0.51±.05	
11[a]	6.5	-4	$D^0 \to \pi^+\underline{\pi}^+K^-\pi^-\underline{\pi}^-\underline{\pi}^+$	19.2	1923±46	.02±.003	
12	734	-26	$D^0 \to \underline{K}_S^0\underline{\pi}^+\underline{\pi}^-\pi^0$	12.4	1835±41	3.66±.19	D^{*+}
13	653	-73	$D^0 \to K^-\pi^-\underline{\pi}^+\pi^+$	55.2	1865±101	0.73±.04	
14	256	not seen	$D^0 \to K^-\pi^-\underline{\pi}^+\pi^+(\pi^0)$	12.9		1.24±.09	D^{*+}
15	67	-30	$D^0 \to \pi^+\underline{\pi}^-(\bar{K}^0)$	11.3		0.37±.04	D^{*+}
16	187	+34	$\bar{D}^0 \to K^+\underline{\pi}^-(\pi^0)$	6.8		1.71±.12	D^{*-}
17	5479	-83	$D^0 \to \pi^-\pi^+\underline{\mu}^+K^-(\nu)$	35.5		9.58±.36	
				58.5		5.72±.22	
18	4374	-59	$D^0 \to \underline{e}^+K^-(\nu)$	29.8		9.13±.44	
				62.7		4.33±.21	
19	2647	-26	$D^0 \to K^-\underline{\mu}^+(\nu)$	22.8		7.20±.37	
				38.7		4.24±.22	

[a] 1C fit.
[b] Events are an associated pair from the same interaction.

decays are looked for by scanning a volume 1 mm long with a radius of 300 μm downstream of the primary (interaction) vertex, and by following back unmatched spectrometer tracks into the emulsion (scanback).[8] The results are shown in Table I.

The analysis of the events is described in Refs. 6 and 7. The crucial requirement in the reconstruction of the decays is that momentum and energy be conserved at the decay vertex. The median transverse momentum error is 140 MeV/c so that the presence of a neutral secondary (π^0, K^0, ν, etc.) is readily inferred. Eleven of the events have three constraint fits with acceptable confidence levels (C.L. > 1%). Two events have a single constraint (1C), one because the decay distance is too short for momentum balance at the decay vertex to be useful, the other because a $\pi^0 \to \gamma\gamma$ secondary must be included to balance P_T and only one γ is observable in the detector. Three semileptonic (S.L.) decays are found. The remaining three events require a neutral hadron, unobserved because of wide angle or low momentum.

The events are listed in Table II. The event number is only for use in the context of this Letter. Seven of the events (3, 4, 9, 11, 15, 16, and 19) were previously published.[2] Final-state particles are underlined if unambiguously identified in the detector (no alternate hypothesis with C.L. > 10%). In the case of constrained events only the best hypothesis (having the highest C.L. on the assumption of D^0 decay) is listed. Other hypotheses are possible in some cases. In particular, for event 6, a $\bar{D}^0 \to K^+\pi^-$ hypothesis is also possible with a slightly larger χ^2 than the Cabibbo-unfavored decay listed in the table. The momenta in the table are those obtained from constrained fits to D^0 hypotheses; the masses are obtained after constraining momentum balance. The error in the decay time includes the uncertainty in flight path (usually < 5%). The unconstrained events are listed at the end of the table, with the S.L. decays last. We require $\Delta C = \Delta S$ for these decays. Assumed neutral secondaries are enclosed in parentheses. Additional missing neutrals are not likely for events 14, 15, and 16, but cannot be excluded for the S.L. decays.

The mass determined in this experiment for the D^0 is 1865 ± 14 MeV/c^2, quite consistent with results from e^+e^- colliders.[10] We assume $m = 1863.1$ MeV/c^2, in fitting. We have investigated D^* production by looking at all $D^0\pi^+$ and $\bar{D}^0\pi^-$ mass combinations for all the events. The resulting histogram is shown in Fig. 1. In the case of unconstrained events 14 and 16 where two momentum solutions are equally likely we plot $m(D^0\pi)$ closest to the D^*. Only this momentum solution has been listed in the table. There are six events having a mass within 1.5 MeV of the D^* and no other combinations within 40 MeV.

Including the D^* mass as a constraint we are thus able to determine the correct momenta for events 1–16. For the S.L. decays there is no reliable procedure to select which momentum solution is right on an event-by-event basis[11] and we therefore do not include these events in the restricted D^0 sample. In Fig. 2 we plot dN/dt, the weighted number of decays per unit time, where the weight used is the reciprocal of the decay finding efficiency. The curve in the figure is from a maximum-likelihood fit which yields

$$\tau = 2.3^{+0.8}_{-0.5} \times 10^{-13} \text{ sec}$$

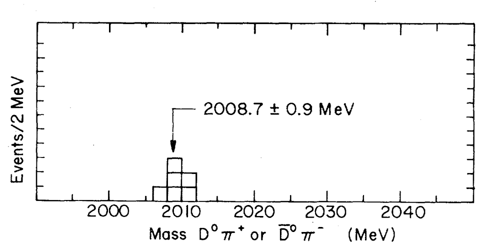

FIG. 1. Histogram of $D^0\pi^+$ and $\bar{D}^0\pi^-$ masses. The D^0 mass is taken to be 1863 MeV.

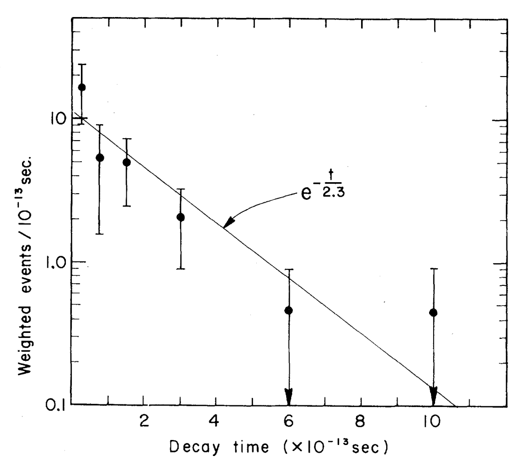

FIG. 2. Number of decays per 10^{-13} sec. The events are weighted by the reciprocal of the scanning efficiency for charm decays. The curve is from a maximum-likelihood fit to the data.

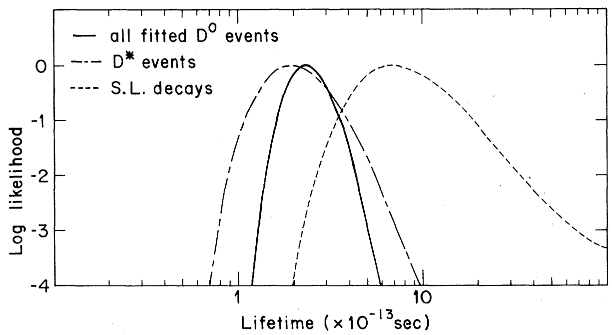

FIG. 3. Likelihood function for the D^0 lifetime. The solid curve is for the sixteen fitted decays. We also show results for the six events from this sample where the D^* is observed, and for the three unconstrained S.L. decays.

for the sixteen fitted events.[12] If we include the S.L. decays, using the average decay times of these events, the lifetime estimate increases by one standard deviation.

Figure 3 shows the likelihood function for the fitted D^0 sample (solid curve) together with the function for the three S.L. decays (dashed curve). The broken curve is for the six D^0's resulting from D^* decays; it is consistent with the solid curve. The tight clustering around the accepted D^* mass (Fig. 1) makes alternative hypotheses for these events unlikely. The most probable lifetime for the three S.L. events is about 3 times that for the fitted sample. These decays have a 2% probability of having the same lifetime as the fitted decays. While not statistically compelling, the above result together with our neutral long-lived baryon candidate (Table I) and long-lived D^0 events seen in a bubble chamber[13] suggest that more than one type of massive neutral particle may decay weakly.

Some of these questions may well be resolved by the results of our second run which contains a much larger data sample.

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[1]R. H. Schindler *et al.*, Phys. Rev. D 24, 78 (1981); W. Bacino *et al.*, Phys. Rev. Lett. 45, 329 (1980).

[2]N. Ushida *et al.*, Phys. Rev. Lett. 45, 1049 (1980).

[3]N. Ushida *et al.*, Phys. Rev. Lett. 45, 1053 (1980).

[4]D. Allasia *et al.*, Nucl. Phys. B176, 13 (1980).

[5]M. I. Adamovich *et al.*, Phys. Lett. 99B, 271 (1981).

[6]M. Gutzwiller, Ph.D. thesis, Ohio State University, 1981 (unpublished).

[7]S. Errede, Ph.D. thesis, Ohio State University, 1981 (unpublished).

[8]K. Niu, in *High Energy Physics—1980*, edited by Loyal Durand and Lee G. Pondrom, AIP Conference Proceedings No. 68 (American Institute of Physics, New York, 1981), Vol. 1, p. 352.

[9]For characteristics of interactions in emulsion, see, e.g., H. Winzler, Nucl. Phys. 69, 661 (1965).

[10]R. L. Kelly *et al.* (Particle Data Group), Rev. Mod. Phys. 52, Pt. 2, S1 (1980).

[11]It would be possible to assign phase-space-generated weights to the high- and low-momentum solutions of the missing neutrino if this were the only missing particle. Since we cannot unequivocally show that this is the case, the weighting procedure is not very useful.

[12]The lifetime quoted here is 1.8 standard deviations higher than that determined by us in Ref. 2 using seven events from a completely scanned set of 685 interactions. None of the new decays come from rescanning this first sample.

[13]M. Aguilar-Benitez *et al.*, in Proceedings of the 1981 European Physical Society International Conference on High Energy Physics, Lisbon, 9–15 July 1981 (to be published).