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An event representing the production and decay of the charmed F^+ meson has been identified by means of a 3-constraint fit to the decay hypothesis $F^+ \rightarrow \pi^+\pi^+\pi^-\pi^0$, in which both γ-rays from the π^0 converted. The event was produced by a charged current ν_μ interaction in an emulsion stack located inside the Fermilab 15-foot bubble chamber. The F^+ traveled 50 μm, corresponding to a proper time of 1.5 x 10^{-13} seconds, before decaying in flight. Its mass was determined to be 2017 ± 25 MeV.

Evidence for the charmed meson F(2030) was first presented by the DASP collaboration[1] which detected the decay $F \rightarrow \pi\eta$ following its production in e^+e^- annihilations. To date, however, there has been no convincing confirmation of this result from similar experiments at SLAC.[2] Another matter of considerable current interest is the determination of this, and other, charmed particle lifetimes which theoretical estimates[3,4] place in the range 10^{-12} to 10^{-14} seconds, and which require high spatial resolution to detect the track of the decaying particle.[5] In this paper we present an event which represents F^+ production and decay in an emulsion stack located inside the Fermilab 15-foot bubble chamber. The F^+ was produced by a charged current ν_μ interaction and was identified by means of a 3-constraint (3-C) kinematic fit to the decay hypothesis $F^+(2030) \rightarrow \pi^+\pi^+\pi^-\pi^0$ where both γ-rays from the π^0 converted. Treating the F^+ mass as unknown a 2-C fit found its value to be 2017 ± 25 MeV. The invariant mass of the $\pi^+\pi^-\pi^0$ system, using the slower of the two π^+, was 808 ± 20 MeV, not inconsistent with the ω mass. The F^+ traveled a distance of 50 μm, corresponding to a proper time of 1.5 x 10^{-13} seconds, before decaying in flight.

The data come from an exposure of the Fermilab 15-foot deuterium chamber, equipped with two-plane external muon identifer (EMI), to neutrinos from the wideband ν_μ beam with single horn. Twenty-two 1-liter stacks of Cryogenic Sensitized BR2 emulsions were contained in 2 stainless steel boxes mounted on the nose-cone flange just above and below the median plane of the chamber. About 320,000 bubble chamber pictures were taken at a machine energy of 350 GeV with an average of 1.6 x 10^{13} protons per pulse on target.

The bubble chamber pictures were scanned for tracks which leave the emulsion boxes and enter the chamber. These tracks were then measured and projected back to predict their common origin in the emulsion; events were subsequently found by scanning in the vicinity of the predicted vertex. The emulsion extends $\lesssim$ 5 cm along the beam direction and only 0.6 cm of steel, comprising the front face of the emulsion box, lies between the emulsion and the chamber liquid.

Fig. 1(a) shows the event as it appears in the emulsion. The particle of interest is produced at point A and travels to point B. The vertex B is clean, with no sign of nuclear excitation or recoil, as expected for a decay. The two unnumbered tracks at the primary vertex A are nuclear fragments each of which travels less than 500 μm before stopping in the emulsion. All other tracks from the primary vertex are consistent with minimum or plateau ionization and enter the bubble chamber; they are shown, appropriately labeled, in Fig. 1(b).

Of the tracks at the secondary vertex B, numbers 4.1 and 4.2 (both consistent with minimum/plateau ionization) are also seen in the bubble chamber. However track 4.3 does not enter the chamber, so that its charge and the magnitude of its momentum cannot be determined directly. It was possible to measure its ionization in the emulsion and thus determine $\beta = 0.65 \pm 0.06$. In addition, if the vertex B represents a decay then the charge of track 4.3 must be negative. This follows from the fact that tracks 4.1 and 4.2 are both known to be positive and a positive charge assignment to track 4.3 would imply an ionization $\geq$ 9 times minimum for track 4, contrary to its observed ionization.

There are 3 additional tracks which emerge from the box at point C but which are not seen in the emulsion. Of these, tracks 5 and 6 appear to be consistent with an e^-e^+ pair from a γ conversion (γ_1) while track 7 may be interpreted as an e^+ from another γ conversion (γ_2) in which the corresponding e^- does not enter the bubble chamber.

Table I presents a summary of track parameters for the event obtained from measurements both in the emulsion and in the bubble chamber; the ν beam direction is also included for reference. Tracks measured in the bubble chamber have all been swum back to their respective origins[6] and their angles transformed to the same reference frame as the emulsion data. There is good correspondence between the measured angles for those tracks seen in both the emulsion and the chamber. In addition the event was found well within errors of its predicted location.

Before discussing kinematic fitting at the secondary or decay vertex B, two important features of the event should be noted: (a) the transverse momentum of track 4.1 (relative to the direction of track 4) is $\sim$ 600 MeV/c which is much higher than corresponding momenta encountered in the decays of non-charmed "stable" particles, and (b) it is not possible to balance transverse momentum using only the charged particles observed at vertex B. These expectations are confirmed by kinematic fitting using the tracks at B and ignoring tracks 5, 6, and 7. In kinematic fitting, track angles measured in the emulsion were used whenever available; all possible identities were tried for the charged particles[7] and fits were attempted to a variety of charmed meson and baryon decay hypotheses as well as to the decay of non-charmed particle states. Only fits to $D^+(1868)$, F^+, and $\Lambda_c^+(2257)$ were obtained, all of which were 0-C fits involving a missing neutral such as ν, γ or π^0.

It is clearly essential that there be a missing neutral at vertex B, and we proceeded to try kinematic fits including γ_1 (which yielded the e^-

e^+ pair represented by tracks 5 and 6) and γ_2. For the latter, only the e^+ (track 7) from the conversion was seen, and it was used to determine the direction (but not the magnitude) of the momentum of γ_2. Only 3 fits were obtained, namely $F^+ \to \pi^+\pi^+\pi^-\pi^o$, $F^+ \to K^+\pi^+\pi^-\pi^o$, and $\Lambda_c^+ \to p\pi^+\pi^-\pi^o$, where in each case $\pi^o \to \gamma_1\gamma_2$; none of the previous fits for $D^+(1868)$ survive to give a fit when γ_1 and γ_2 are included. If one ignores the incomplete γ_2 one obtains a fit to the additional hypothesis $F^+ \to \pi^+\pi^+\pi^-\gamma_1$. These 3-C fits are shown in Table II. The only one of these fits with an acceptable χ^2 is $F^+ \to \pi^+\pi^+\pi^-\pi^o$ which has $\chi^2 = 3.77$; of all the hypotheses tried, it is the only one that satisfactorily accounts for all the observed tracks.(8) A summary of the results for this fit is presented in Table III.

We next consider the question of whether the event can be explained as an interaction rather than a decay. The probability of finding such an interaction in our event sample may be calculated from a knowledge of (a) the interaction mean free path in emulsion for event configurations with an odd number of prongs and no sign of nuclear excitation or recoil,(9) (b) the average multiplicity of relativistic hadrons produced in ν interactions, and (c) the average distance each track is followed in the emulsion. The probability thus calculated is $< 10^{-3}$ making such an interpretation unlikely.

Although no kinematic fits were possible at the production vertex A, there are nevertheless several characteristics of the production process that can be established. The 12 GeV/c negative particle (track 1) is identified as a μ^- on the basis of the EMI data. In addition, track 3 is most likely due to a π^-, on the basis of its observed ionization in the emulsion. The total visible energy release at production is $\gtrsim$ 16 GeV. In addition, we find $Q^2 = 2.3 \pm 0.4$ $(GeV/c)^2$, and x_{vis} = 0.30 ± 0.05, $y_{vis} = 0.26 \pm 0.01$ for the usual scaling variables.[10]

In summary, we conclude that the event represents the production of F^+ by ν_μ in a charged current reaction, with the subsequent decay $F^+ \rightarrow \pi^+\pi^+\pi^-\pi^o$ occuring after 1.5×10^{-13} sec.

We thank the 15-foot bubble chamber crew as well as our scanning and measuring staffs for their help. We are also indebted to Dr. Lubomilov for processing the emulsion, and the IIT-Maryland-Stony Brook-Tohoku-Tufts collaboration for making the bubble chamber film available. This work was supported by the U.S. Department of Energy and the National Science Foundation.

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5. There are a number of experiments utilizing emulsions to study such decays. See, for example: review by L. Voyvodic, Proceedings of the Ninth International Symposium on Lepton and Photon Interactions at High Energies, 1979, Ed. H. Abarbanel, T. Kirk (to be published); J. D. Prentice, Ibid.

6. The vertices A and B (which serve as origins for all tracks except 5, 6, and 7) are only $\sim$ 8mm upstream of the point of emergence C and so the results are relatively insensitive to the details of the swimming procedure. The common origin of tracks 5 and 6 (which come from the conversion of γ_1) was not directly observed and was found by swimming the tracks back 3.2 mm into the steel wall of the emulsion box where the opening angle of the 2 tracks was a minimum. At this location the spatial separation of the two tracks is also a minimum and the line of flight of γ_1 from vertex B is consistent with the direction of the vector sum of the momenta of tracks 5 and 6. The origin of track 7 (the e^+ from the γ_2 conversion) was found by swimming the track 1.6 mm back into the steel where agreement between the track direction and the line of flight of γ_2 is optimal; the angles taken for track 7 (and

hence γ_2) were the weighted average of the angles for the line of flight of γ_2 and track 7 at this point.

7. On the basis of the observed ionization in the emulsion track 4.2 is not likely to be more massive than a pion.

8. It is, of course, possible to account for γ_1 or γ_2 by ascribing them to the production vertex A since it is clearly not possible to distinguish whether a γ points to vertex A or B, only 50 μm apart. However this would require one to dismiss, as fortuitous, the highly constrained fit that was obtained.

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10. These variables are defined as $y_{vis} = (E_\nu - E_\mu)/E_\nu$ and $x_{vis} = Q^2/2m(E_\nu - E_\mu)$ where E_μ is the energy of the muon, E_ν is the total visible energy of the final state particles (exclusive of nucleon rest mass), and m is the nucleon mass. The quantity Q^2 is the magnitude of the four-momentum transfer squared from the neutrino to the muon, assuming the neutrino energy to be the visible energy E_ν. In calculating E_ν we have assumed that track 2 is due to a proton, consistent with its observed ionization after scattering outside the field of view of Fig. 1(b).

TABLE I
Measured Track Parameters for Event

TRACK	EMULSION DATA		BUBBLE CHAMBER DATA*			
	AZIMUTH (deg.)	DIP (deg.)	AZIMUTH (deg.)	DIP (deg.)	MOMENTUM (GEV/c)	CHARGE
ν	-3.0 ± 0.5	-2.5 ± 0.5				
1	2.8 ± 0.1	-5.0 ± 0.3	2.3 ± 0.5	-5.5 ± 0.5	12.02 ± 0.11	-
2	8.4 ± 0.1	-18.7 ± 0.5	8.2 ± 0.7	-18.3 ± 0.7	1.37 ± 0.01	+
3	30.4 ± 0.1	-28.4 ± 0.5	28.7 ± 2.8	-26.1 ± 2.4	0.314 ± 0.005	-
4†	-28.8 ± 0.2	4.4 ± 0.7				
4.1	-45.1 ± 0.2	11.7 ± 0.4	-44.3 ± 0.6	10.4 ± 0.6	2.01 ± 0.01	+
4.2	-2.3 ± 0.3	41.3 ± 0.3	-1.3 ± 3.2	38.8 ± 2.5	0.299 ± 0.003	+
4.3	86.4 ± 0.4	-62.4 ± 0.4			$\beta = 0.65\pm0.06$††	
5			33.4 ± 1.9	-20.3 ± 1.7	0.257 ± 0.007	-
6			32.7 ± 3.0	-20.3 ± 2.6	0.160 ± 0.007	+
7			3.9 ± 6.9	-37.4 ± 4.7	0.049 ± 0.020	+

* Tracks have all been swum back to their respective origins[6] and their angles transformed to the same reference frame as the emulsion data.

† This track decays after traveling 50 ± 1 μm.

†† This track does not enter the bubble chamber. The value for β is obtained from ionization measurements in the emulsion.

TABLE II
3-C Fits Obtained

$F^+(2030)$	$\rightarrow$	$\pi^+\pi^+\pi^-\pi^0$ $\quad\llcorner\rightarrow \gamma_1\gamma_2$	$\chi^2 = 3.77$
		$K^+\pi^+\pi^-\pi^0$ $\quad\llcorner\rightarrow \gamma_1\gamma_2$	$\chi^2 = 12.7$
		$\pi^+\pi^+\pi^-\gamma_1$	$\chi^2 = 16.7$
$\Lambda_c^+(2257)$	$\rightarrow$	$p\pi^+\pi^-\pi^0$ $\quad\llcorner\rightarrow \gamma_1\gamma_2$	$\chi^2 = 11.7$

TABLE III

Fit Results for $F^{+}(2030) \rightarrow \pi^{+}\pi^{+}\pi^{-}\pi^{o}$, with $\pi^{o} \rightarrow \gamma_1\gamma_2$

TRACK	IDENTITY	AZIMUTH (deg.)	DIP (deg.)	MOMENTUM (GeV/c)
4	$F^{+}(2030)$	-28.7±0.2	5.1±0.4	2.37 ±0.03
4.1	π^{+}	-45.2±0.2	11.5±0.4	2.01 ±0.01
4.2	π^{+}	-2.3±0.3	41.3±0.3	0.299±0.003
4.3	π^{-}	86.4±0.4	-62.4±0.4	0.133±0.018
	π^{o}	25.0±2.2	-28.2±1.6	0.568±0.028
	γ_1	32.1±1.9	-22.8±1.6	0.415±0.010
	γ_2	3.5±3.4	-39.7±3.9	0.169±0.029

FIGURE CAPTION

Fig. 1 (a) Camera Lucida drawing of the event as is appears in the emulsion. The ν interaction takes place at point A and the charmed meson (track 4) travels to point B where it decays. The plane of the emulsion is vertical. (b) Bubble chamber photograph showing the tracks as they emerge from the emulsion box at point C. Track 4.3 from the decay does not enter the bubble chamber. Tracks 5, 6, and 7 are not seen in the emulsion and are electron and positron tracks from γ-ray conversions. Note that track 6 (interpreted as e^+) has a very large δ-ray at point D. The bubble chamber photograph is a projection on a horizontal plane.

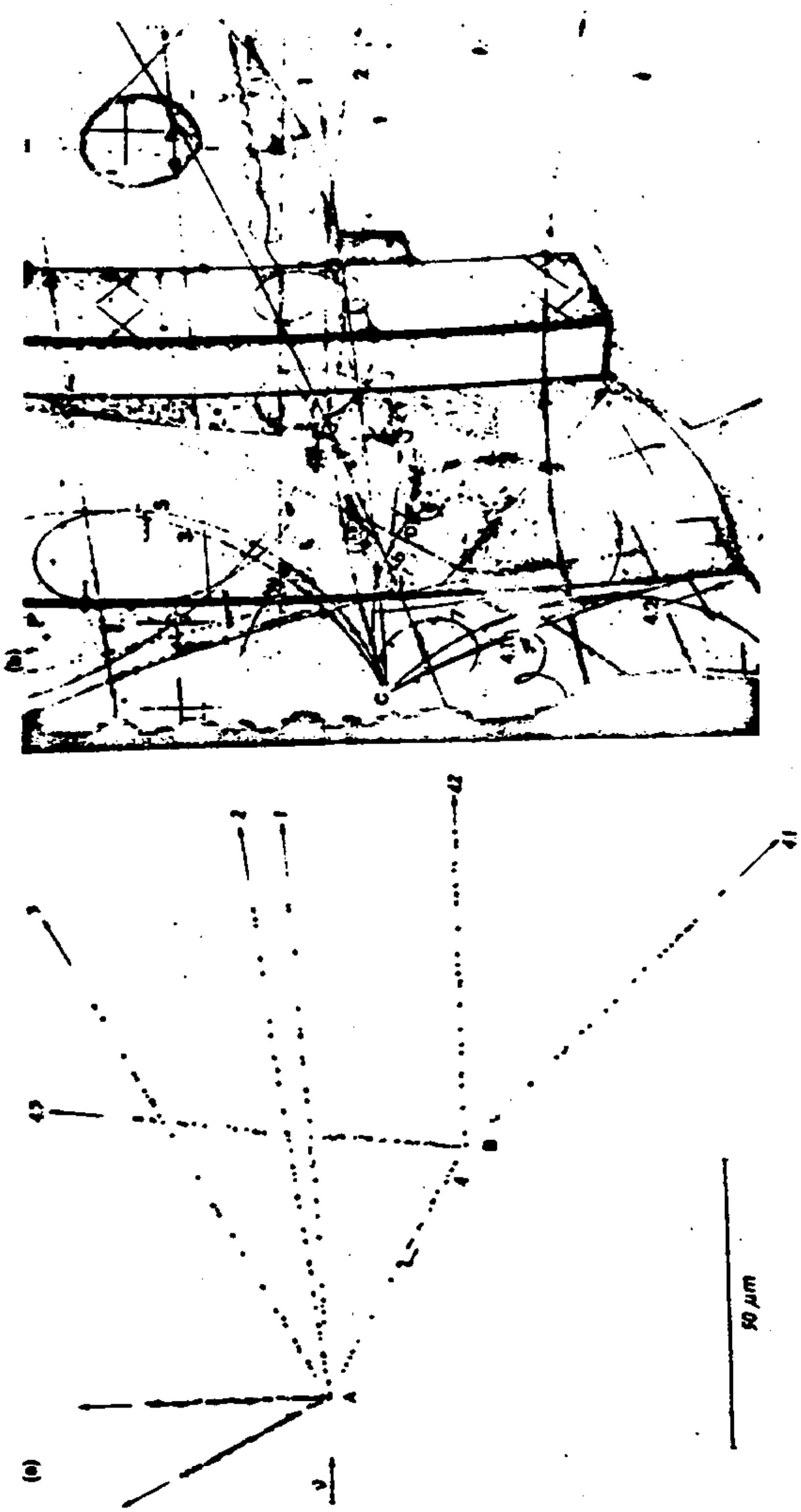

FIG. 1