E546 Submitted to Physical Review Letters

FERMILAB-PUB-79-110-E

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JUL 6 1979
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OBSERVATION OF SHORT-LIVED PARTICLES PRODUCED IN HIGH ENERGY NEUTRINO INTERACTIONS

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ABSTRACT

Careful examination of a sample of 89 high-energy, neutrino-induced dilepton events produced in the Fermilab 15-ft bubble chamber has resulted in the direct observation of the production and semi-leptonic decay of short-lived particles. One charged decay, two neutral decays, and one decay candidate of undetermined charge are found. Assuming the decays are of D mesons, we obtain $\tau_{D^+} = 2.5^{+3.5}_{-1.5} \times 10^{-13}$ sec and $\tau_{D^o} = 3.5^{+3.5}_{-1.7} \times 10^{-13}$ sec.

Since the discovery of neutrino-induced dilepton events, evidence has mounted that such events result primarily from the production, via the weak charged-current, of short-lived charmed particles whose semi-leptonic decays yield the second lepton.[1] Direct observation of the production of short-lived particles by high-energy neutrinos has been reported by experiments[2-3] using emulsions. No direct observation of such particles in dilepton events has yet been reported; previous bubble chamber experiments[4-6] studying dimuon and muon-electron (μe) events have given only upper limits on charmed particle lifetimes. In this Letter we report the first direct observation of the semi-leptonic decays of short-lived particles in neutrino-induced dilepton events.

Our dilepton events come from a 326,000 picture exposure of the Fermilab 15-ft bubble chamber to the Quadrupole Triplet Neutrino Beam. Use of the two-plane External Muon Identifier (EMI)[7] yields 10,300 ν and 1,800 $\bar{\nu}$ charged-current events with muon momentum (P_μ) above 4 GeV/c. Experimental details and preliminary results on the dimuon sample have been reported.[7-9] An important difference between the dimuon and μe samples is that both leptons must have momenta above 4 GeV/c for dimuons but the electron momentum (P_e) can be as low as 0.8 GeV/c for the μe sample considered here. The average $\nu(\bar{\nu})$ event energy of 90 (60) GeV, considerably higher than that of previous bubble chamber experiments reporting dilepton events, is an important advantage for direct observation of short-lived particles.

The complete sample of 54 opposite-sign dimuon events (of which about 20 are background due mostly to π-μ decays) and a partial sample of 35 μe events have been examined under very high magnification by physicists for possible evidence of short-lived particles. One charged decay (C1), two neutral decays (N1 and N2), and one decay candidate (U1) of undetermined charge are observed. For events C1, N1, and N2, we have attempted to determine the positions of the primary and decay vertices in two ways. The first method is the usual corresponding point reconstruction and relies on the measurer's judgment of the locations of the vertices in each view. To reduce some of the possible biases in judging vertex locations, each event has been measured several times by different measurers. The decay lengths in Table I are the averages of the results of these measurements; the quoted errors are the root-mean-square (RMS) deviations. The second method uses only measurements on tracks and attempts to determine a vertex position by intersecting the tracks emanating from it. This method is free of the possible bias in judging the vertex location but depends upon the fitted trajectories which can be warped systematically by effects such as scattering or turbulence.

Event C1 appears (Fig. 1) quite clearly to have a charged particle decaying into an e^+ and two oppositely-charged hadrons (h^+ and h^-). The angles between the outgoing tracks are less than 5°, and the uncertainties in the track intersections from a single measurement are comparable to the apparent separation of the vertices. Therefore, one must rely on the visual evidence of a

difference in track density before and after the decay vertex. Examination of tracks in this event indicates that the random probability of a gap sufficient to produce the observed difference is about 0.005 for one track. The probability for gaps in the same position on two tracks is therefore $(0.005)^2$, which makes the visual evidence for a decay quite convincing.

Events N1 (Fig. 2) and N2 appear to have a neutral particle decaying into an e^+ and h^-. The striking feature of event N1 is that extrapolation of the e^+ backward through the apparent decay vertex significantly misses the primary vertex. The angle between the e^+ and h^- is 13° and the average separation of the vertices from 14 determinations by track intersections is 0.54 cm with a statistical uncertainty of 0.04 cm. The track lengths used are sufficiently short (40 cm on the h^- and 15 cm on the e^+) that the uncertainty in their intersection due to multiple scattering is only 0.05 cm. Therefore, the decay vertex determined by this method is significantly downstream of the primary vertex and is quite consistent with the result from corresponding point reconstruction.

Event N2 appears, from the difference in track density, to have a neutral decay; but the apparent decay vertex is obscured by another track in all views. Thus the RMS deviation of the decay length measurements underestimates the real uncertainty. In addition, the small (5°) angle between the e^+ and h^- from the apparent decay and the turbulence present in event N2 probably preclude a reliable vertex determination by track intersection. Therefore, we include this event in Table I as a likely neutral

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decay but treat it as unseen in the lifetime determination described below.

Event U1 has a forward jet of several tracks (including the μ^-) from which an e^+ emerges at a 20° angle and clearly downstream (by 0.6 cm) of the primary vertex. The tracks of the jet are too closely spaced to see a decay vertex or determine which tracks, if any, also come from the decay. The evidence for a decay in this event is that, in the clearest view, backward extrapolation of the e^+ track intersects the μ^- track at a distance (projected) of 0.28 ± 0.03 cm downstream of the primary vertex. The probability that this is due to a scatter on a primary e^+ is less than 10^{-6}.

Possible backgrounds which could simulate a decay vertex from which an e^+ emerges are summarized in Table II. Each process is required to occur more than 0.5 cm but less than 1.0 cm from the primary vertex; the various backgrounds are all roughly proportional to the length of the interval considered. The background from K_L^o decay is included for completeness but is ruled out for events N1, N2, and U1 because the $e^+\pi^-$ invariant masses (see Table I) are significantly greater than the K^o mass. For event C1 backgrounds from K_S^o or Λ decay superimposed on a primary e^+ are ruled out by invariant masses of the hadrons, and background from a neutral hadron interaction superimposed on a primary e^+ is negligible. The most serious background is that from asymmetric γ conversions giving an e^- with such low energy that it is undetectable. The minimum energy for the e^- to be detectable is taken conservatively to be 5 MeV, and thus the fraction f of asymmetric γ conversions for γ momentum > 0.8 GeV/c in which the e^- is undetectable is given by $f \leq 5/800$. (This value of f overestimates the

background for the observed candidates since the e^+ momenta all exceed 1.1 GeV/c.) In order to simulate a decay vertex, the conversion must also occur very near at least one of the hadron tracks which also happens to appear visually to originate downstream of the primary vertex. This accidental association probability α is estimated to be 10% for events N1 and N2 and 20% for event C1. In addition, the e^+ from a close asymmetric conversion will extrapolate back to the primary vertex in contrast to the appearance of events N1 and U1. The clearest case is event N1, where the extrapolation of the e^+ misses the primary vertex in the vertical direction by 0.17 ± 0.06 cm. Because the miss is in the vertical direction (parallel to the magnetic field), it cannot be due to a change in curvature caused by an early Bremsstrahlung. The e^+ would have to scatter more than 10° to produce this effect, and the probability for such a scatter on an electron of this momentum is less than 10^{-6}/cm.

In order to estimate the decay times from the observed decay distances, one must make some assumptions about the mass of the decaying particle and about neutral particles from the decay. The success of the charm model in describing the characteristics of dilepton events leads us to presume that we are observing the semileptonic decays of charmed particles. The D^o meson is the only known (or expected) weakly-decaying, neutral charmed particle but the D^+ and F^+ mesons and the Λ_c^+ baryon are all candidates for the charged decay in event C1. The invariant masses (see Table I) of

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the charged particles from the neutral decays are consistent with decay of a D^o meson. Event C1 is consistent with $D^+ \to e^+K^-\pi^+\nu$ ($M_{e^+K^-\pi^+} = 1.28 \pm 0.11$ GeV) and barely with $\Lambda_c^+ \to e^+\pi^-\pi^+\Lambda\nu$ ($M_{e^+\pi^-\pi^+} = 1.20 \pm 0.12$), but not with $F^+ \to e^+K^-K^+\nu$ ($M_{e^+K^-K^+} = 2.49 \pm 0.21$), nor with $\Lambda_c^+ \to e^+K^-p\nu$ ($M_{e^+K^-p} = 4.37 \pm 0.40$). Other decay modes or decays of other massive particles cannot be ruled out as explanations of the observed decays. In the following analysis we assume that the observed decays are of D mesons, but the results depend only on the masses of the decaying particles being near the typical charmed particle mass of about 2 GeV. Assuming the observed events are examples of $D^o \to e^+K^-\nu$ and $D^+ \to e^+K^-\pi^+\nu$, one can calculate the minimum and maximum D momentum using only the information on the charged particles from the decay. These values are given in Table I. The range of decay times quoted in Table I corresponds to the entire range of allowed D momenta and does not rely on the poorly-determined D direction.

Since it is quite plausible that we are observing the decays of D mesons, we attempt to determine the D^o and D^+ lifetimes separately by maximizing the likelihood functions that express the products of the probabilities (P_S) for the seen decays and the probabilities (P_U) for not detecting decays in events where none are seen. For this determination, events N2 and U1 are treated as unseen decays. The background (i.e. no charmed particles) probabilities are taken to be 0.35 for dimuon[8] and zero for μe events.

The charmed particles are assumed to be an equal mixture of D^o and D^+, and the probability that the D^+ decays to only one charged particle is taken to be 2/3. The maximum decay distance (ℓ_{MAX}) for an unseen decay is obtained by judging how far from the primary vertex a decay into at least two charged particles would have to occur so that it is evident that not all tracks originate at the primary vertex. The D momentum spectrum from our dilepton Monte Carlo[10] is used to estimate average values for the exponential terms in the probabilities P_S and P_U.

We have studied the sensitivity of the likelihood functions to the estimates of ℓ_{MAX} and the D momenta for the unseen decays and to the uncertainties in the decay distances and D momenta for the observed decays. Taking these uncertainties into account, the most probable values for the D^+ and D^o lifetimes are $\tau_{D^+} = 2.5^{+3.5}_{-1.5} \times 10^{-13}$ sec and $\tau_{D^o} = 3.5^{+3.5}_{-1.7} \times 10^{-13}$ sec, where the errors represent 1σ variations. The 2σ limits are $6 \times 10^{-14} < \tau_{D^+} < 1.3 \times 10^{-12}$ sec and $1.0 \times 10^{-13} < \tau_{D^o} < 1.2 \times 10^{-12}$ sec. These limits are quite consistent with upper limits obtained by bubble chamber experiments,[4-6] with the decay times for the charged decays seen in emulsion experiments,[2-3] and with recent theoretical estimates.[11]

We gratefully acknowledge the efforts of the many people at Fermilab and the other institutions who have contributed to this experiment. Special thanks are given to the scanners and measurers whose dedication and perserverence on these and countless other

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events are essential to a successful experiment. This work is supported in part by the U.S. Department of Energy and the National Science Foundation.

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TABLE CAPTIONS

Table I: Kinematic and decay quantities for the observed decay candidates. The invariant masses for event U1 result from combining the e^+ with the two negatively-charged hadrons in the forward jet.

Table II: Estimated backgrounds for the decays of short-lived particles. An interaction length of 193 cm and γ conversion length of 68 cm are used. Rates for K^o and K^+ production are taken to be 0.15 and 0.14 respectively. An average of 4.2 γ (42% of which have energies above 0.8 GeV), 0.15 interacting neutral hadron, and 5 interacting charged hadrons per event with 1 π^o per hadron interaction are also assumed. The Lorentz factor $\eta = P/m$ for kaons is taken to be ≥ 2 and the fraction of asymmetric conversions $f \leq 5/800$. The accidental association probability α is estimated to be 10% for events N1 and N2 and 20% for event C1.

TABLE I

	C1 (16040581)	N1 (16441094)	N2 (14651459)	U1 (15131206)
$\vec{P}_{VIS} \cdot \hat{\nu}_{BEAM}$ (GeV/c)	233	39	74	82
P_μ (GeV/c)	16.1 ± 0.3	21.6 ± 0.5	12.4 ± 0.2	53.7 ± 1.0
$P_\mu^\perp$ (GeV/c)	2.9	3.8	1.1	1.2
$P_{MISS}^\perp$ (GeV/c)	0.5	2.4	0.3	0.7
P_{e^+} (GeV/c)	3 ± 1	1.1 ± 0.1	2.9 ± 0.4	1.3 ± 0.2
$M_{e^+\pi^-}$ (GeV/c^2)	0.58 ± 0.14	0.650 ± 0.041	0.852 ± 0.065	{0.947 ± 0.074 0.824 ± 0.072
$M_{e^+K^-}$ (GeV/c^2)	0.75 ± 0.11	0.824 ± 0.034	0.984 ± 0.057	{1.097 ± 0.067 1.114 ± 0.068
DECAY LENGTH (cm)	0.62 ± 0.08	0.67 ± 0.12	0.87 ± 0.16	0.3–0.6
P_D (GeV/c)	111-237	8-40	38-135	--
DECAY TIME (10^{-12} sec)	$0.16 < t < 0.35$	$1.04 < t < 5.20$	$0.40 < t < 1.42$	--
Q^2 (GeV^2/c^2)	123	27	7.2	2.3
x	0.28	0.77	0.06	0.04
y	0.93	0.45	0.83	0.35
W (GeV/c^2)	12	6.2	8.6	7.9

TABLE II

Background Process	Estimated Background Events in 12000 Charged-Current Events: Neutral Decays	Charged Decays
$K_L^o \to e^+\pi^-\nu$	$0.06/\eta \leq 0.03$	$0.06\ \alpha/\eta \leq 0.01$
$K_S^o \to \pi^o\pi^o$, $\pi^o \to$ Asymmetric Dalitz	$1.20\ \alpha f/\eta \leq 0.001$	$1.20\ \alpha^2 f/\eta < 0.001$
Neutral Hadron Int. $\to \pi^o\pi^-X$, $\pi^o \to$ Asymmetric Dalitz	$0.03\ f \leq 0.001$	$0.03\ \alpha f \leq 0.001$
Neutral Hadron Int. $\to K^+\pi^-X$, $K^+ \to e^+$(collinear) $\pi^o\nu$	$0.001/\eta < 0.001$	$0.001\ \alpha/\eta \leq 0.001$
Asymmetric γ Conversion	$156\ \alpha f \leq 0.10$	$156\ \alpha^2 f \leq 0.04$
$K^+ \to e^+\pi^o\nu$	$0.11\ \alpha/\eta \leq 0.006$	$0.11/\eta \leq 0.05$ (1-prong dec
Charged Hadron Int. $\to \pi^o$, $\pi^o \to$ Asymmetric Dalitz	$0.90\ f \leq 0.006$	$0.90\ f \leq 0.006$
TOTAL	≤ 0.14	≤ 0.11

FIGURE CAPTIONS

Fig. 1: High magnification view of event C1. Tracks 6, 7, and 8 appear to come from the decay of a charged particle 0.6 cm from the primary vertex. Track 6 undergoes an interaction whose visible energy exceeds 100 GeV; the momentum of track 8 is determined from curvature to be 5.5 GeV/c.

Fig. 2: High magnification view of event N1. Tracks 7 and 8 appear to come from the decay of a neutral particle. Another view (not shown) reveals that track 2 is clearly not associated with the vertex from which tracks 7 and 8 emerge. Track 8 has a momentum determined from curvature of 6.9 GeV/c and undergoes an interaction that produces a K_S^o.

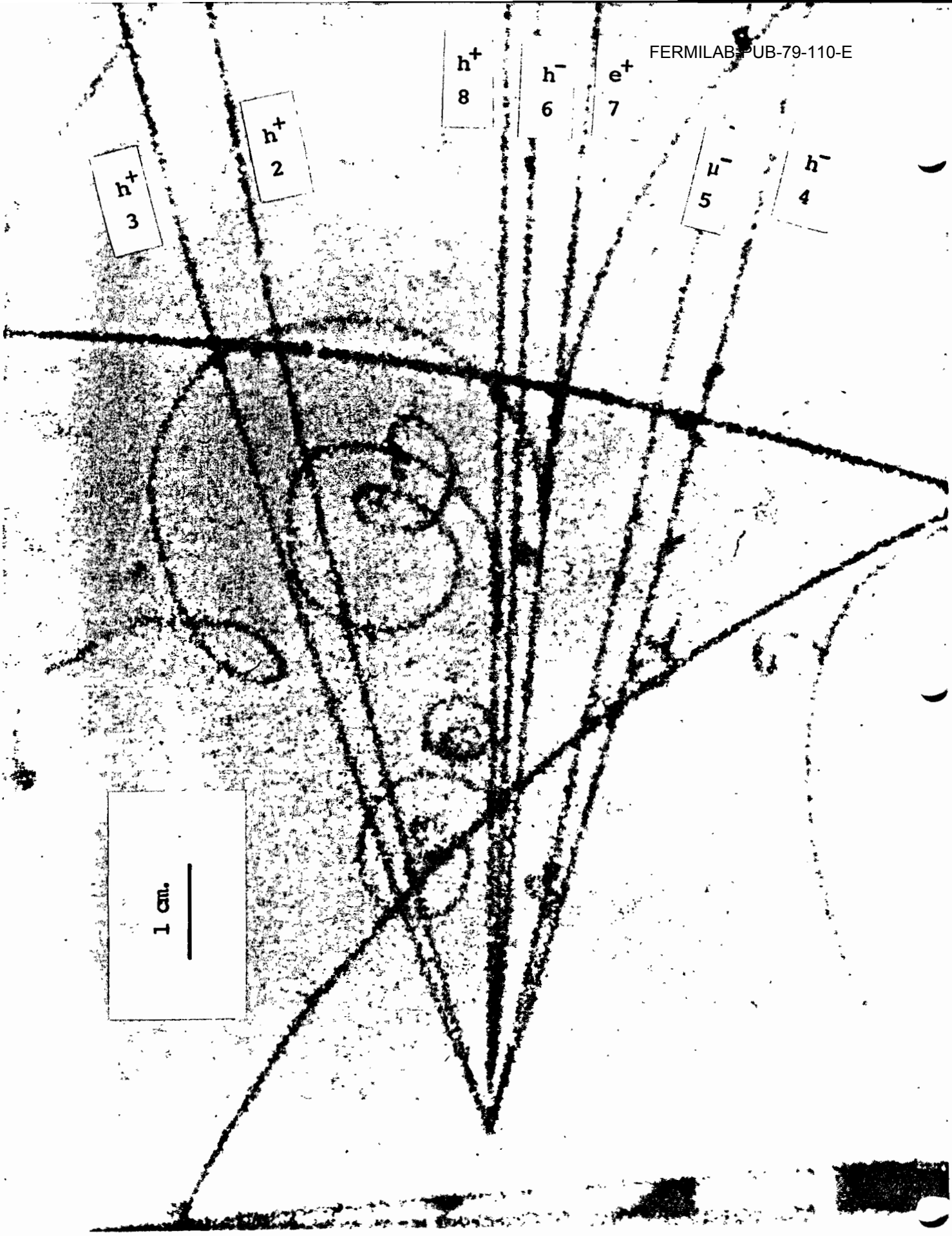

Fig. 1

Fig. 2