OBSERVATION OF SHORT LIFETIME

PARTICLES IN TRACK CHAMBERS

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The wide spread use of track chambers to examine details of the production vertex in high energy collisions is well known. Recall that strange particles were first identified in cloud chambers by Rochester and Butler[1] in 1947. So when the next flavor, charm, was discovered, it was inevitable that charmed particles would be studied in track chambers. I review here the information concerning the lifetime of these particles obtained in conventional bubble chambers and the preliminary results and potential of high resolution track chambers in this study.

The Technique

The most direct method of determining particle lifetimes is to measure the decay time distribution in the center of mass. Since this is impractical experimentally, we must measure the distance between production and decay vertex and the velocity. From these values we can infer the proper time according to

$$t = \frac{mL}{pc}$$

where L, m, p are the decay length, mass, and momentum of the particle respectively.

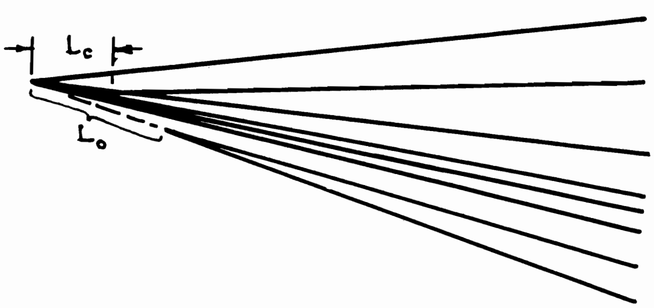


Figure 1. Schematic of event with charged and neutral decay.

The experimental problems are illustrated schematically in Figure 1. The decay length L_o of the neutral decay is clearly measurable, but the vertex of the charged particle decay is obscured by the forward jet. This "blind" region can be characterized by a confusion length L_c. Within this region most quantitative information is lost. Obviously, if smaller track size and higher resolution can be obtained, the region of confusion becomes smaller and shorter decay lengths can be distinguished.

Although in hydrogen charge conservation can be used to easily separate decay vertices from interactions, there is no sure way with nuclear targets. A significant reduction in this background can result from the use of low density targets or by the requirement that a single charged lepton (μ or e) be present in the decay.

Momentum analysis and/or kinematics must be used to eliminate strange particle events and to identify the type of parent charmed particle. Note that the mass must be known to uniquely determine the proper time.

Conventional Bubble Chambers

Although the production of charmed particles in neutrino interactions had been inferred since the observation of dilepton events in 1974[2], the first limits on the lifetime were reported by a BEBC collaboration[3] and the GGM collaboration[4] at the Oxford conference in 1978. The obtained the upper limits

$\tau < 3 \times 10^{-12}$ sec BEBC

$\tau < 1 \times 10^{-12}$ sec GGM

This year two positive results have been reported. Both experiments used the 15' Bubble Chamber at Fermilab. The Berkeley-Fermilab-Hawaii-Seattle-Wisconsin collaboration[5] (BFHSW) found four candidates in 80 dilepton events and the Brookhaven-Columbia group[6] (BNL-COL) found one candidate in 250 dilepton events. I refer you to the original papers for details but caution against a direct comparison of the rate since kinematic cuts, ν beam energy spectra etc. differ in the two experiments. The semi-leptonic decay is used to reduce the magnitude of the scanning effort as well as the interaction background. Unfortunately, however, the missing ν precludes kinematic identification of the parent particle.

As an example of these events one candidate of BFHSW is shown in Figure 2. The topologies of the events are:

C1 Single track decaying into an e^+ and two oppositely charged hadrons. (Shown in Figure 2.)

N1 Neutral decaying into e^+ and negative hadron.

C_{CB} Single track decaying into e^+ and two oppositely charged hadrons.

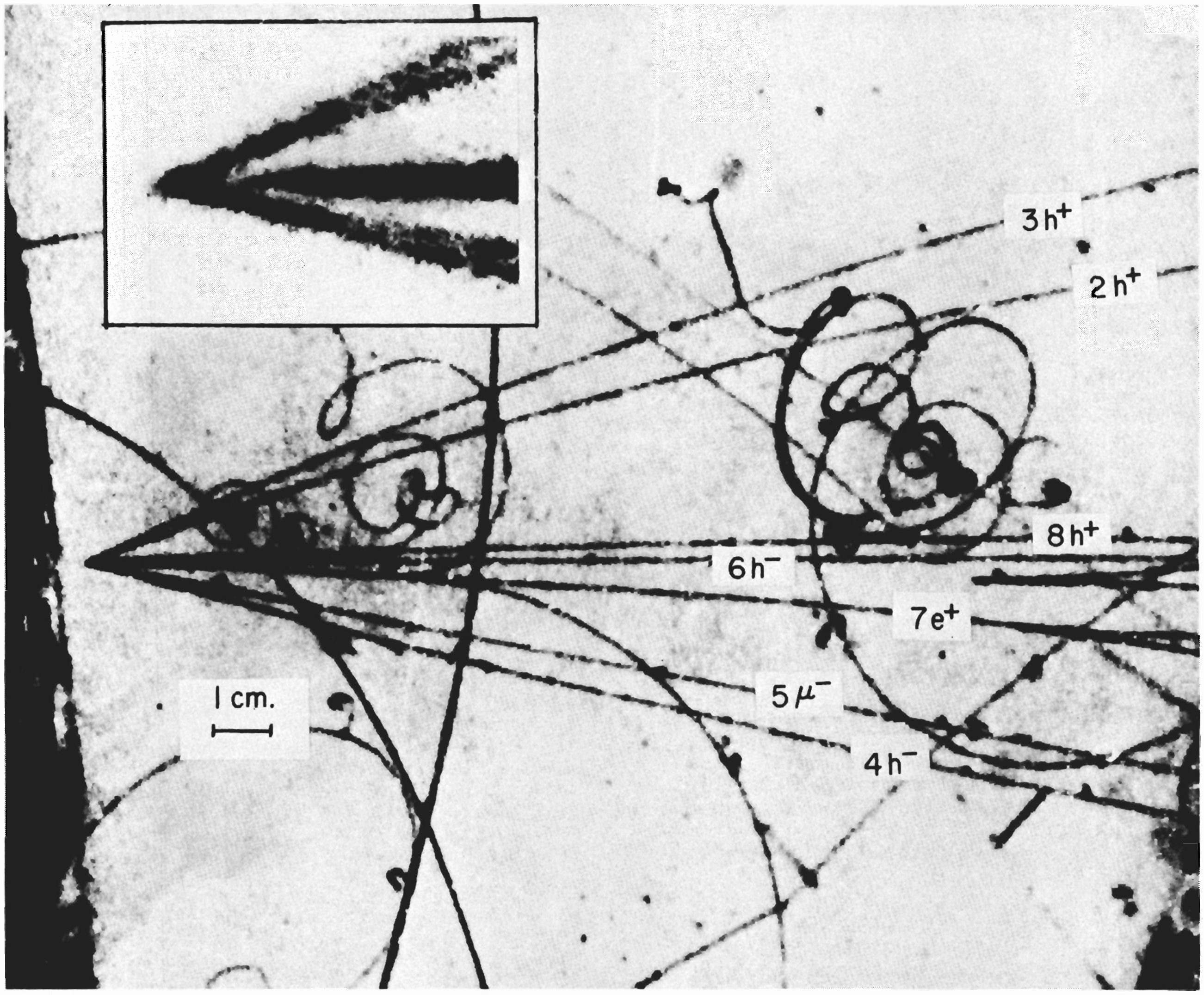


Figure 2. Candidate event for charm decay obtained in 15' Bubble Chamber (BFHSW)

N2 Neutral decaying into e^+ and negative hadron. How the decay vertex is obscured in all views, although the measured decay tracks do not extrapolate to the vertex. This event is considered to lie within the region of confusion and is not used in the lifetime calculation.

U1 An e^+ emerges from the forward jet with and angle and position that preclude its production at the primary vertex. As with N2 this event is not used in the lifetime calculation.

Some of the quantities measured in these events are shown in Table I. Note in the BFHSW events the invariant mass of the e^+ and the negative hadron interpreted as a π^- in each case is greater than the K mass. For the BNL-COL event the transverse momentum of the e^+ is impossible for a kaon decay. Thus a strange particle origin for the decays is eliminated. If the negative hadron is interpreted as a K^- then all events can be satisfactorily interpreted as decays of charmed particles - most probably D mesons.

The lifetime can be determined by maximizing the likelihood of the experimental results as a function of the mean lifetime. The probability either that the decay is observed with length L_D or that the decay occurred in the region of confusion L_C is calculated for each event and the product over all events is formed. The length of the confusion region was determined for each event by scanners and the distribution is shown in Figure 3.

Because the decay neutrino escapes unobserved only a lower limit of the momentum of the charmed particle can be determined for the seen decays. The momentum distribution for charmed particles is shown in Figure 4 as measured by the BNL-COL collaboration for $D^\circ \to K^\circ\pi^+\pi^-$ and the calculated spectrum for $dN/dz \sim$ constant and $dN/dz \sim e^{-3z}$ in the Quadrupole Triplet Beam. The results are not especially sensitive to the exact form of the distribution except that it must be hard (i.e. $dN/dz \sim$ flat).

EVENT	C1	N1	C_{cs}	N2	U1
E_{vis} GeV	233	39	43	74	82
p_μ GeV/c	16	22	6	12	54
L mm	6.2±0.8	6.7±1.2	11.±2.	8.7±1.6	3-6
$M_{e^+\pi^-}$	.58±.14	.65±.04	$p_T(e^+)$ =.45±.06	.85±.07	.85
$M_{e^+K^-}$	.75±.11	.82±.03	1.68	.98±.06	1.1
p_D GeV/c	111.-237.	8.-40.	35.-63.	38.-135.	---
t 10^{-12}sec	.16-.35	1.0-5.2	0.9-2.0	0.4-1.4	---

Table 1. Kinematic quantities for the 4 candidate events of BFHSW and the BNL-COL event.

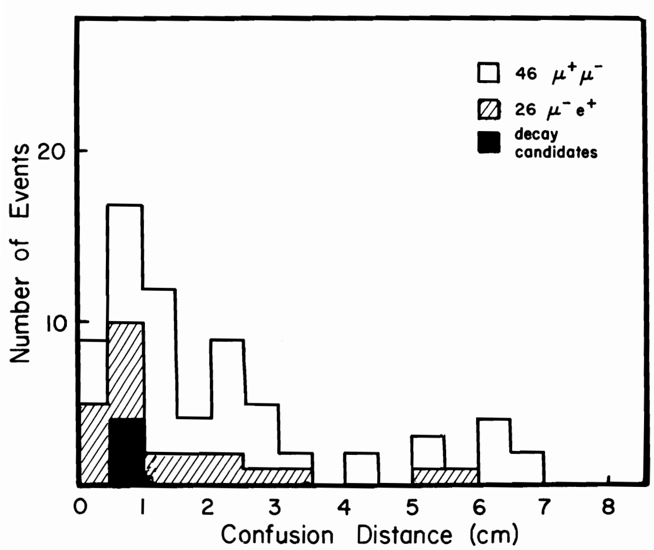


Figure 3. Distribution of confusion length determined for each dilepton event (BFHSW).

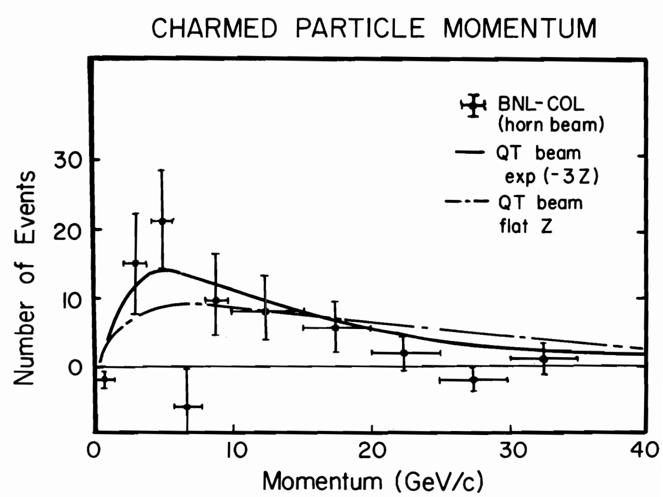


Figure 4. Momentum spectrum of charmed particles as observed by BNL-COL and as used in likelihood calculation by BFHSW.

The results of this analysis are shown in Figure 5 and 6 in which the likelihood distributions are shown for neutral (D°) and charged ($D^+F^+\Lambda^+$) charmed particles. The results of the best analysis for D° is shown together with calculations showing the sensitivity to change of the assumptions; increasing D momentum by a factor of 2, increasing "D" mass to 2.4 GeV/c^2, and adding 0.5 cm to each confusion length. In Figure 6 the likelihood distributed for the D^+ lifetime as determined by BFHSW alone is shown. Also I have combined this result with the result of BNL-COL and show the resultant distribution.

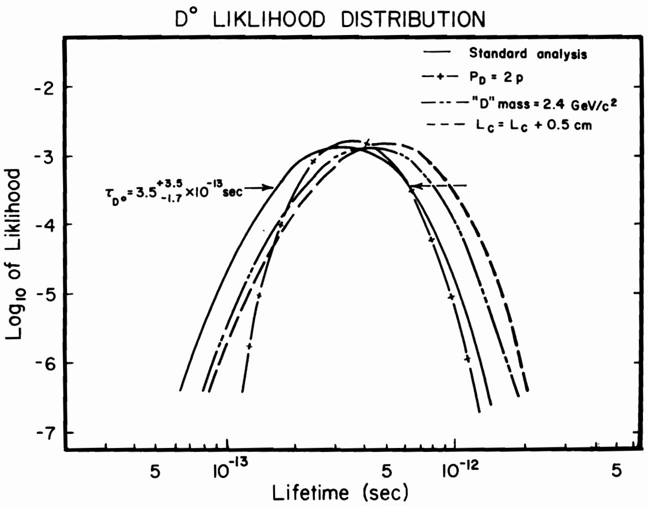


Figure 5. Likelihood of D° Lifetimes.

In summary the values obtained in this analysis are:

$$1.5 \times 10^{-13} \text{ sec} < \tau_{D^\circ} < 7. \times 10^{-13} \text{ sec}$$

$$2.0 \times 10^{-13} \text{ sec} < \tau_{D^+} < 6 \times 10^{-13} \text{ sec}$$

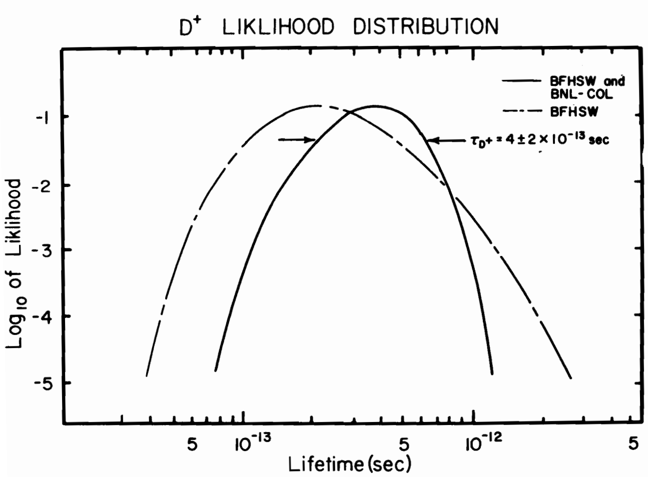


Figure 6. Likelihood of D^+ Lifetime.

This technique is of limited value because of difficulties in uniquely identifying the type of charmed particle and in obtaining good statistics since the resolution, and thus the detection efficiency, is small.

A High Resolution Streamer Chamber

A Yale-Fermilab collaboration has begun a program to study decays of short lived particles using a high resolution streamer chamber. In a streamer chamber a large pulsed electric field is applied to a gas which has been partially ionized by the passage of a charged particle. A number of electron avalanches are formed along the particle trajectory which emit light that can be photographed. Because the light yield is very small, image intensifier tubes must be used to amplify the light without loss of the pattern information. A gain of about 10^4 is required. Details of the construction and performance of the streamer chamber have been given elsewhere.[7]

The achievement of high resolution depends on avalanche size which can be reduced by increasing the pressure of the gas. The normal operating pressure of this chamber is 24 atmospheres using a mixture of Neon-Helium (90%/10%) gas. The track widths obtained in early operation are 150 μm and point setting errors in trajectory measurements are ∿ 40 μm. The visible region is rather small ∿ 4 cm x 4 cm x 2 mm where the latter dimension is constrained by the depth of focus of the optical system.

The chamber has been incorporated in an experiment at FNAL to study short lifetime particles. The experimental arrangement is shown in Figure 7. A beam of 350 GeV protons is directed into the chamber. The application of the high voltage pulse is triggered by the production of one or more particles which penetrate the steel absorber. By requiring the muon, i.e. semi-leptonic charm decay, the trigger rate is enhanced by a factor of 30 over a simple interaction trigger. Muons are accepted with $p_\mu > 3.6$ GeV/c and 30 mrad $< \theta_\mu <$ 250 mrad. The multiwire proportional counters will uniquely correlate the triggering track (μ) to a track in the chamber. Unfortunately these chambers were not working in the initial running of the experiment and in general for this run it was not known which track triggered the apparatus. This problem, which will be remedied in future running, resulted in a significant background due to strange particles.

In the first operation 67,000 stereo pairs were recorded which will yield ∿ 1400 interactions in the gas. About 300 of these were taken without the muon trigger in order to study backgrounds and possible biases. The results presented here are based on analysis of about 750 events.[8]

Each event was measured separately in each view. These measurements were fit to straight lines and the hypothesis that all lines emanated from a single vertex was tested. Events for which multiple vertices could be visually

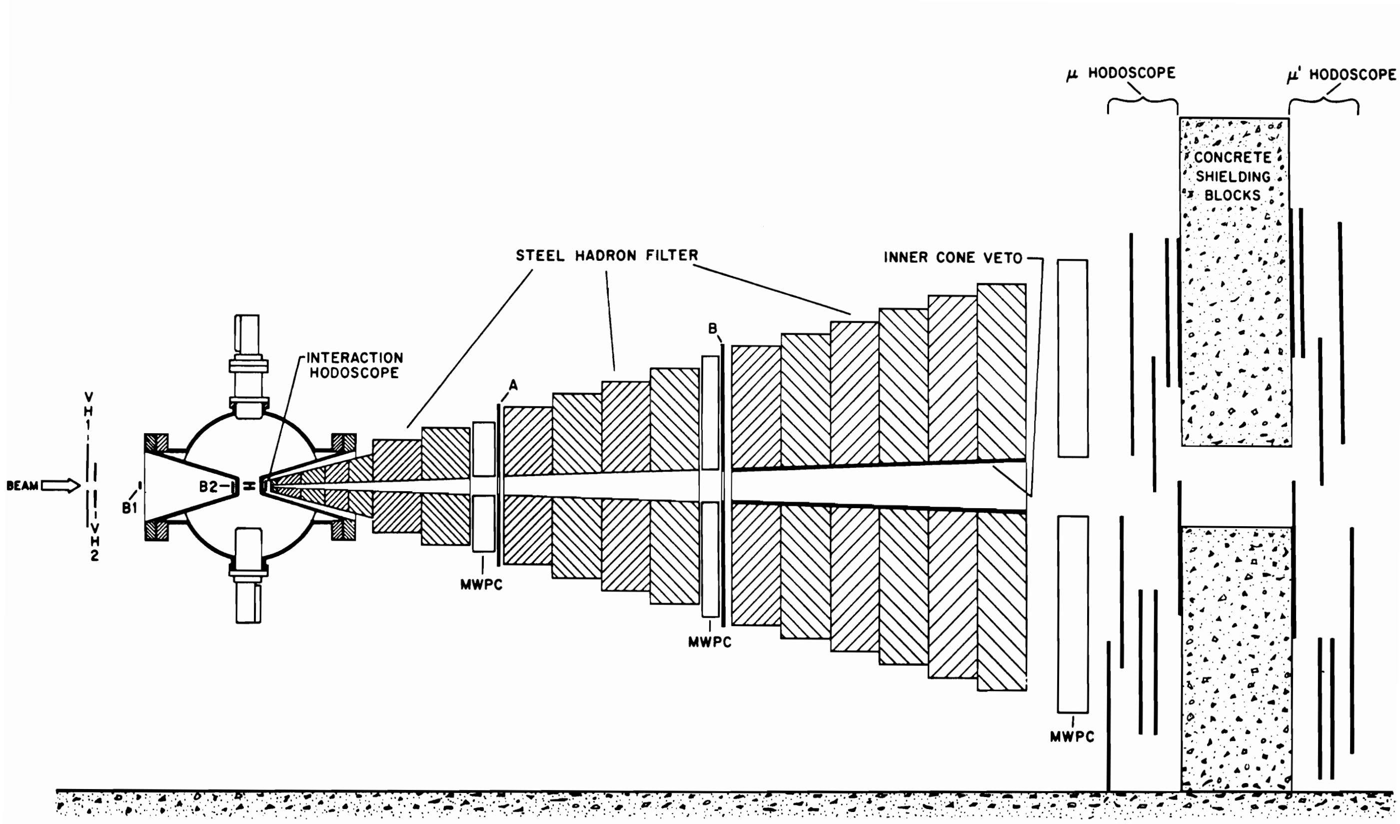
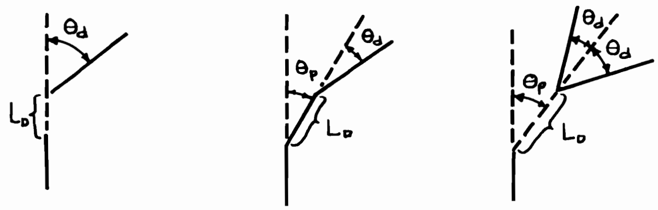


Figure 7. Arrangement of Yale - Fermilab experiment.

Figure 8. Example of event obtained in Yale - FNAL experiment.

detected were measured as such. All events with a large χ^2 per degree of freedom were closely examined by a physicist. This procedure resulted in a sample of 21 multivertex events. An example of the technique is shown in Figure 8 which is a reproduction of the interactive fitting program.

These events can be categorized by topology.



Short decay Kink Vee

Figure 9.

A short decay is defined as an event in which a measured track cannot be attributed to the primary vertex, but whose parent track and decay vertex lies in the region of confusion. The decay length of such short decays is calculated by assuming the parent is produced at zero degrees to the beam.

The results are best displayed by plotting decay length (L_D) vs. the projected decay angle (θ_D).

Recall the decay length can be written as

$$L_D = \frac{p_D C t}{M}$$

where p_D, M, t are the momentum, mass, and proper time of the particle. The decay angle is

$$\theta_D \sim \frac{p_\perp^*}{p_{\parallel}} \sim \frac{3p^*}{p_D}$$

where p* is the maximum transverse momentum of a daughter in the parent rest frame and the daughter lab momentum is about 1/3 the parent momentum (assuming a three body decay). Thus

$$L_D = \left(\frac{c}{3p_\perp^* M}\right) \frac{t}{\theta}$$

For fixed proper time $L_D \sim 1/\theta$. This relation is smeared somewhat by production and decay kinematics and by the exponential proper time distribution. The 21 events are plotted in Figure 10. For an assumed lifetime of 8 x 10^{-13} sec a complete calculation indicates that 95% of charmed particles produced with Feynman x less then 0.2 have decay which lie between the axes and the contour shown. The 12 events which lie outside the boundary are attributed to strange particles.

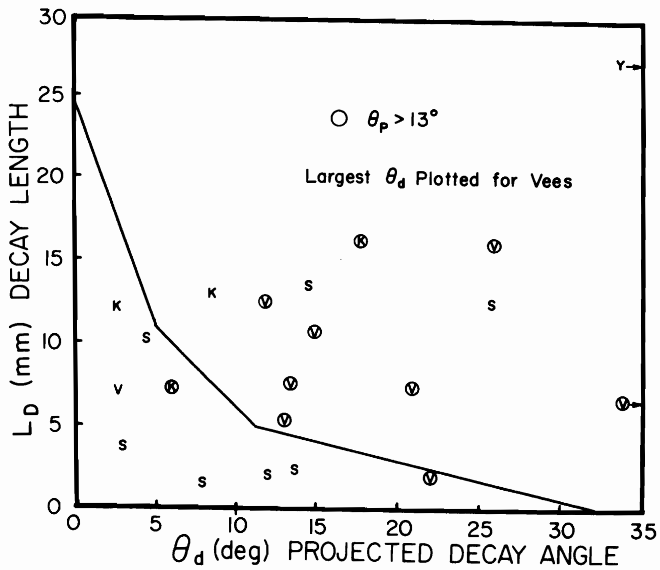


Figure 10. The plot of decay length vs. projected decay angle for candidate events in Yale - FNAL experiment.

A further criterion can be imposed, viz. the production angle θ_P is required to be less than 13°. This would correspond to a transverse momentum of about 2 GeV/c for a centrally produced charmed particle. This requirement should strongly inhibit acceptance of slow strange particles. That this is indeed the case can be seen in Figure 10. The seven events remaining within the boundary are candidates for charm decay.

The backgrounds due to fast strange particles, δ rays, and secondary interactions have been calculated together with the estimation of slow strange particle background obtained from the L_D-θ_D plot. The number of background events estimated is two. The authors conclude that the observed seven events cannot be attributed to background, hence a significant signal for charmed particles has been observed.

Further corroboration of this interpretation is obtained from the muon detector scintillation counters. For two events within the charm region the decay track is the only track which intercepts the counters which triggered the event.

Since the decay length is proportional to proper time, a lower limit for the lifetime can be inferred from the L_D-θ_D plot. If the lifetime were chosen to be 2-3 x 10^{-13} sec about half the charm candidates would be excluded. From preliminary analysis of detection efficiency the authors estimate the charm production cross section to be $\gtrsim$ 20μb/nucleon and the average charmed particle lifetime $\tau = \gtrsim 3 \times 10^{-13}$ sec.

The experiment is expected to run again in Summer 1980 with the Multiwire Proportional Chambers and several improvements to the streamer chamber. It is hoped the track size can be reduced to ∿ 75 μm. Background due to slow strange particles should be eliminated. About 500 charmed particle decays should be detected.

A Small High Resolution Bubble Chamber

Results have recently been obtained from preliminary operation of LEBC (Little European Bubble Chamber) which heralds the appearance of an innovative new type of instrument to study short lifetime phenomena.[9] A small hydrogen bubble chamber has been constructed by a CERN-Rutherford Laboratory collaboration in the astonishingly short time of one year. This was possible largely because of the technology developed for the Track Sensitive Target program at Rutherford Laboratory.

The chamber is rapid cycling (30-50 Hz), operated without a magnetic field, and is equipped with two cameras (∿ 17° stereo). The active volume of the chamber is a cylinder 20 cm in diameter and 3.5 cm in depth. Bubble sizes of ∿ 50 μm have been achieved in recent operation.

A collaboration of groups at Brussels, CERN, Oxford, Padova, Trieste, Rome and Rutherford have mounted experiment NA-13 at the CERN super proton synchrotron. A test run of the chamber was made in May 1979 in which a beam of 340 GeV π^- mesons was directed into the chamber. For this test run only one camera was used.

Pictures were taken whenever an interaction occurred. Some 60,000 events were obtained with the bare chamber which should be fully analyzed in 3-4 months and should yield 40-50 double decays.

The chamber performance during this run was:

Bubble size	50 μm
Bubble density	70-100/cm
Precision (residuals of fit to line)	5-10 μm

To date 12,000 events have been scanned which correspond to ∿ 0.6 events/μb. If the cross section for charm production were ∿ 40 μb/nucleon, and the lifetime ∿ 5×10^{-13} sec, several events with both charmed particles decaying should have been observed. Five such events have been recorded. A typical event is shown in Figure 11. By attributing to multiple coulomb scattering the residuals determined in fitting one of the tracks in Figure 11 a lower limit to the momentum of 3 GeV/c is found. The transverse momentum so established eliminates a strange particle origin.

The determination of the scanning efficiency is the most troublesome aspect of the analysis. The authors have used the ultimate in Monte Carlo calculations in which they simulate not only the kinematics and geometry of an event, but also the actual position, size, etc. of the bubbles.[10] One of these Monte Carlo pictures is shown in Figure 12. The pictures can be scanned and efficiencies can be precisely measured.

As indicated the technique is sensitive to lifetimes $\tau \gtrsim 10^{-13}$sec. Finally, the systematic errors are well understood and analysis should be rapid even though each picture must be scanned.

Within the next year LEBC will be operated as an active target together with an external spectrometer. The spectrometer will have a momentum analysis precision of ∿ 1%, photon detection, and some particle identification. A 60 ev/μb exposure is planned equally divided between protons and π^- at 350 GeV. Such an exposure should yield ∿ 1000 double decays.

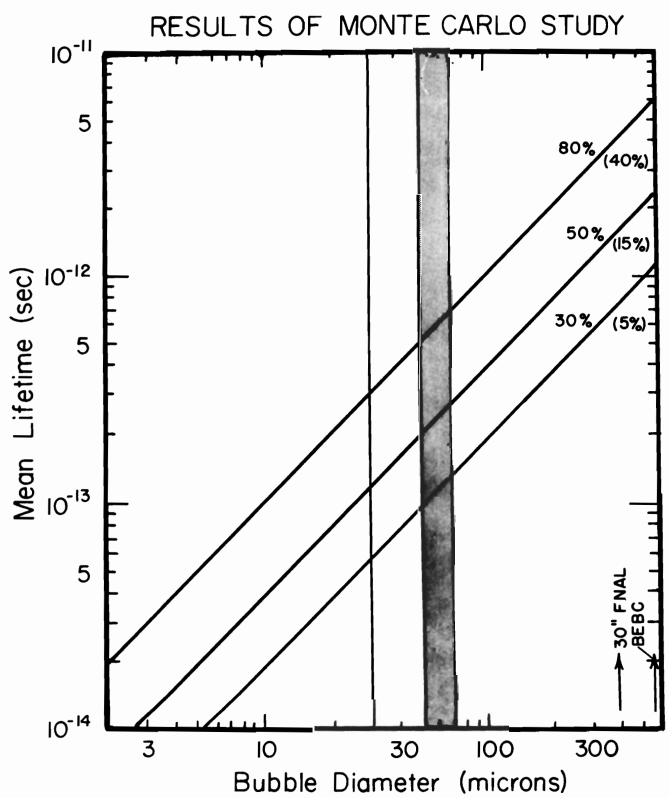


Figure 13. The relation between lifetime sensitivity and bubble diameter in LEBC.

The precision and potential of the small bubble chamber can be seen from Figure 13. The results of the Monte Carlo efficiency study and the bubble size observed in the test run are combined to show the region of lifetimes that can be studied.

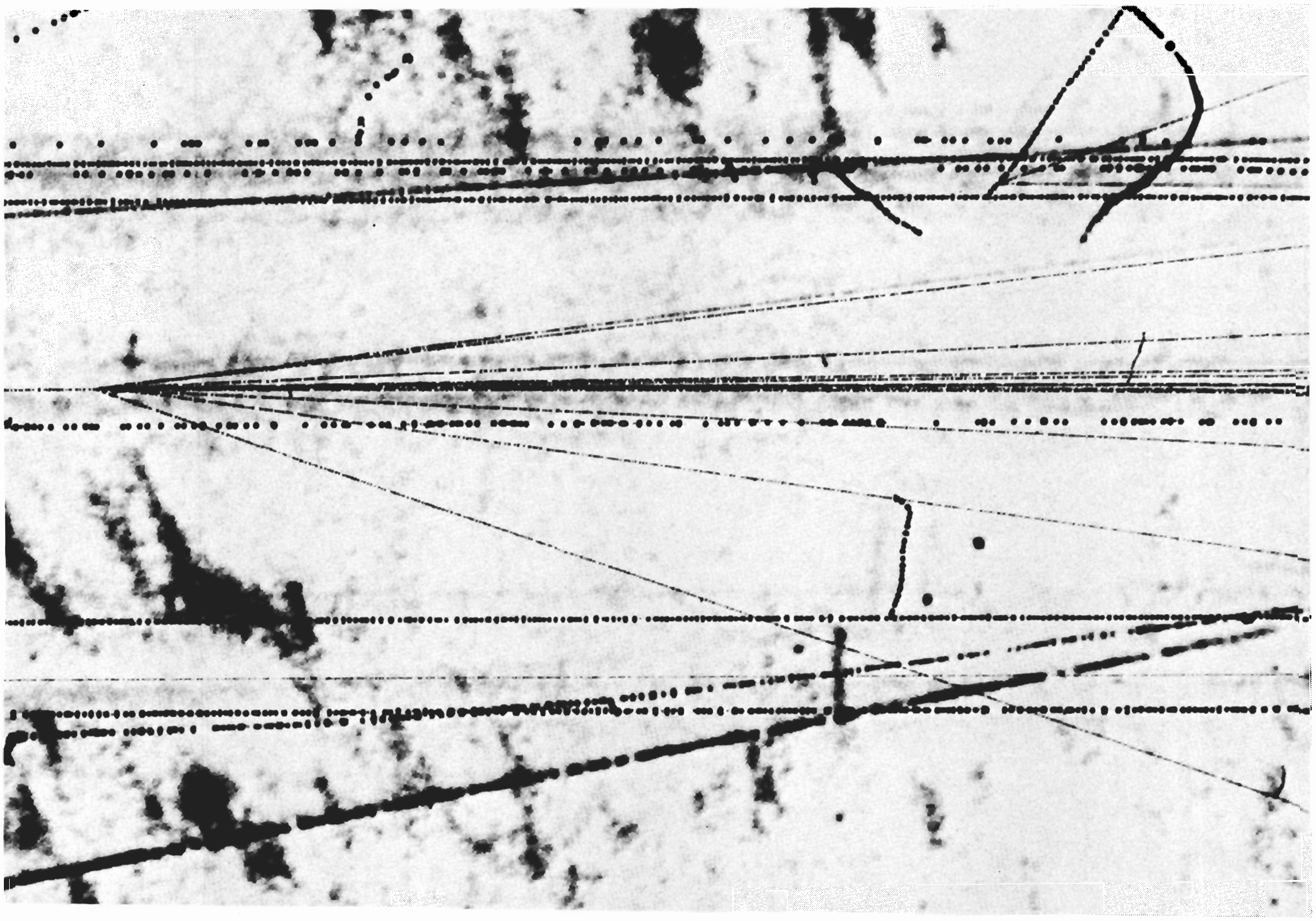


Figure 11. Example of a candidate for charm decay obtained in LEBC at CERN.

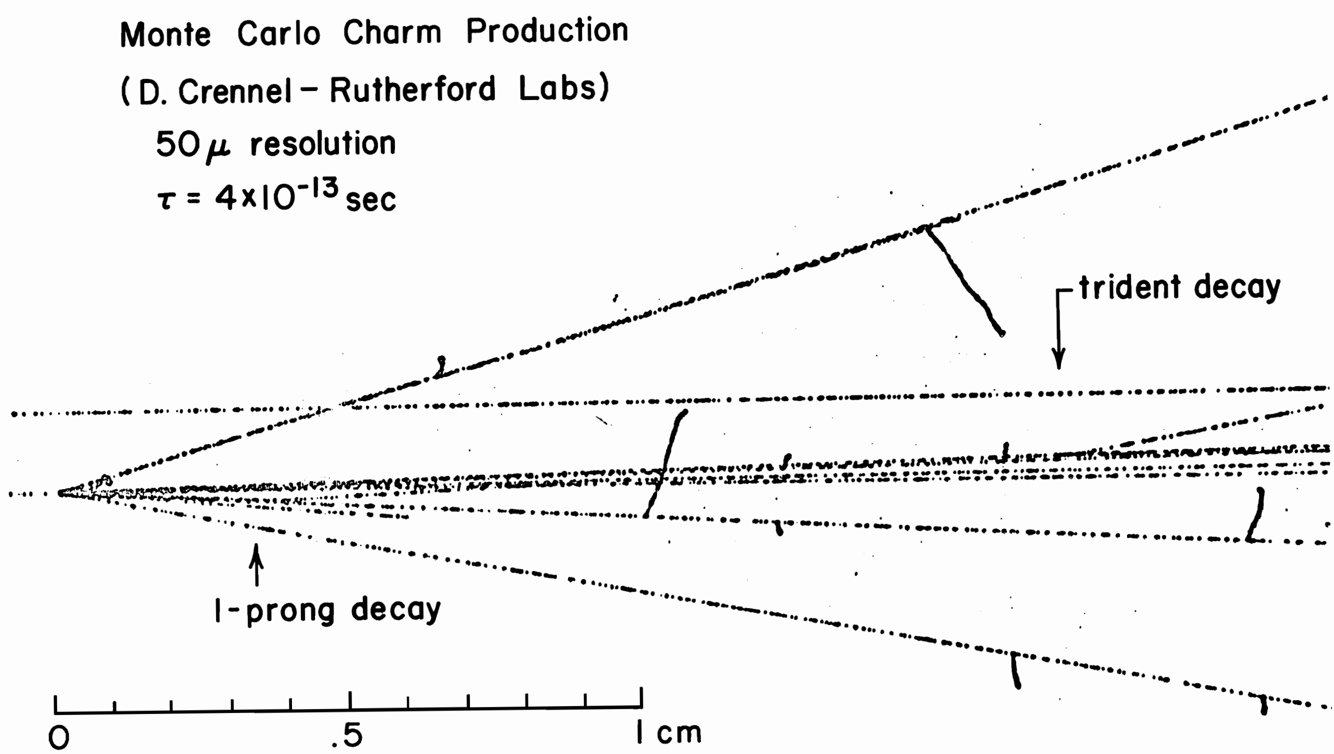


Figure 12. Example of an event contained particle decays as simulated by Monte Carlo in LEBC.

The shaded region indicates the bubble size obtained in test running. The line indicates the minimum attainable size. The diagonal lines are contours of constant scanning efficiency. The analysis efficiency is shown in parentheses.

This technique is extremely promising and has a number of important features. The chamber has equal efficiency in detecting neutral and charged decays, thus eliminating the bias found in some emulsion experiments. The use of hydrogen as the working liquid enables charge conservation to separate interactions (net charge increases by 1) and decays (net charge remains unchanged).

Conclusions

From the investigations using conventional Bubble Chambers the lifetime of charmed particles has been established within an order of magnitude.

$$10^{-13}\text{ sec} < \tau < 10^{-12}\text{ sec}$$

This result applies to an unknown mix of D°, D^{+}, F^{+}, Λ_C, etc. This value is corroborated by the embryonic results of the streamer chamber experiment.

Furthermore, the techniques of high resolution track chambers - both streamer and bubble - have been proved. Their use with spectrometers is an extremely promising method of studying short lifetimes. One can expect analyses involving about one hundred events to be completed within a few months. Within about one year about 1000 events will be analyzed with identification of charmed species.

I would like to acknowledge the cooperation of my colleagues at Berkeley, Fermilab, Hawaii, Seattle and Wisconsin as well as members of the other large conventional bubble chamber collaborations. In addition I wish to express my thanks and appreciation to J. Sandweiss, J. Shepherd and P. Cooper for information on the Streamer Chamber and Colin Fisher for information concerning LEBC.

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10. D. Crennell, Rutherford Laboratory, performed this admirable Monte Carlo calculation.

Q. (Diambrini, Genoa) If I understood you, LEBC still does not use stereo views. As long as you don't use stereo pictures, then I think you admit that V°_{S} could be confused with tridents, because you're projecting on only one plane. For example, your V° could be projected on single tracks so that you could in principle confuse a trident with a V°.

A. That's certainly true and the problem of confusion is one reason that the LEBC people are not saying they've made a measurement at this time. In the 60,000 event exposure I think they do have the stereo and they will be able to resolve this overlap problem. The other experiments all have stereo.

Q. (Kirkby, SLAC) I'm confused about your confusion distance plot in the first experiment. I would've thought that you couldn't set a lower limit on the lifetime of the charmed particles you are looking at because below 1/2mm or something there's infinite confusion. So if there is something with a short lifetime which may have spilled over into your sensitive region, you wouldn't really be measuring it carefully. Is this correct or not?

A. The idea is that you have a certain number of charmed particles. If they're characterized by a lifetime distribution and a confusion distance, there will be a certain number predicted that will be efficiently detected as separable vertices. If the lifetime were an order of magnitude shorter then there should be no events detected. So it's the fraction of seen events to the total number of events which gives rise to the lower limit.

Q. (Perkins, Oxford) In the E546 experiment are the secondary decay vertices based on measurement or some just on visual inspection.

A. They are based on both measurement and visual inspection.