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BUBBLE CHAMBER EXPERIMENTS ON CHARMED PARTICLE LIFETIMES*

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ABSTRACT

The three current bubble chamber experiments on charmed particle lifetimes are compared. Their most recently released results are discussed.

Although single charmed decay vertices have been seen in bubble chambers before, this discussion will cover the three current experiments. Two are at CERN and the third at SLAC. All use bubble chambers with relatively high resolution photographic techniques, coupled with downstream detector systems, and can measure lifetimes from decay length distributions.

The interest in such experiments increased after initial comparisons of the $D^{\pm}$ and D^{o} lifetimes. Theory, following the standard model, supposed that charmed particle decays would be dominated by processes involving $\Delta C = \Delta S = 1$ transitions of the charmed quark. Relevant diagrams are given in Fig. 1. An obvious consequence was that $\Gamma(D^{\pm}) = \Gamma(D^{o}) = \Gamma(F^{\pm})$, and that the semileptonic branching ratios should be the same. By comparison with muon decay a charmed lifetime could be obtained, $\tau \sim 5 \times 10^{-13}$ sec, in general agreement with what is found. Hard gluon effects calculated in leading log approximation did not substantially change these expectations.

Reports of differences in the semileptonic branching ratios of $D^{\pm}$ and D^{o} did change the picture. The results from DELCO and Mark II at SPEAR using different techniques, but using $D\bar{D}$ production at the Ψ'' resonance are indicated in Fig. 2. This graph of log likelihood against the ratio of branching fractions — or of lifetimes — originally came from the Mark II publication,[1] but an estimate of the DELCO result,[2] plotted

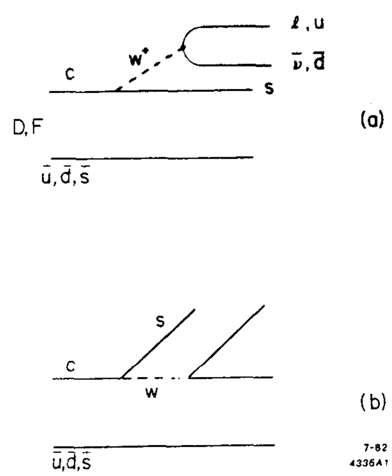

Fig. 1. Quark line diagrams for charmed meson decay — light quark spectator process.

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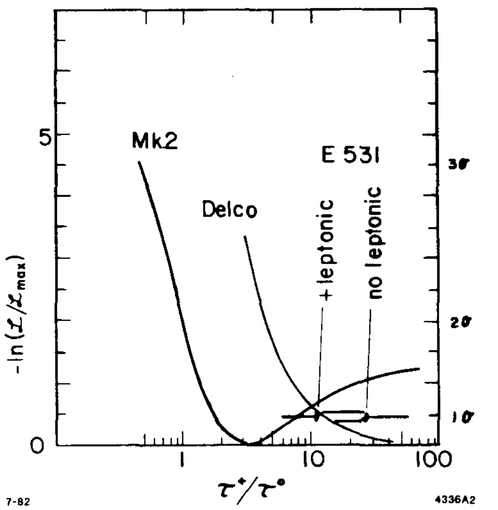


Fig. 2. Plot of -log (likelihood) against charged: neutral D lifetime ratio for Mark II and DELCO experiments. The error bars are for the neutrino emulsion experiment E531, with and without leptonic decays included. The standard deviation equivalent of the vertical scale is also given.

similarly, is shown. In addition, error bars are given for a neutrino-emulsion measurement of the ratio of the lifetimes, FNAL experiment E531.[3] In this case two values are shown. The larger ratio excludes semileptonic events which these experimenters now believe should be considered separately.

The large ratios suggested by these results brought some second thoughts to the theory of the decays. One approach sought a way to enhance the D^{o} decay rate without affecting the $D^{\pm}$ rate. A diagram available to D^{o}, but not to $D^{\pm}$ because of the quark content, is the W-exchange diagram of Fig. 3. Helicity mismatch of the light quarks should suppress this, but a new hypothesis[4] was that initial state emission of gluons could eliminate the helicity constraint. An alternative picture[4] considered the gluon component in the initial state wave function. Calculations allowed ratios $\tau(D^{\pm})/\tau(D^{o})$ = 1.7 ~ 7, depending on quark masses and coupling constants, with a preference for the range 2-3 or so. It should be noticed that the diagram Fig. 4 could similarly enhance the F decay, but this enhancement may be less marked, so that $\tau(D^{\pm}) \approx \tau(F^{\pm})$.

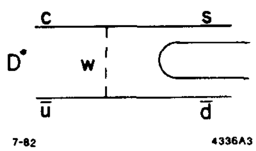


Fig. 3. W-exchange diagram for D^{o} decay.

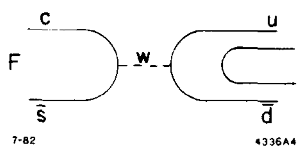


Fig. 4. Annihilation diagram for F decay.

A different viewpoint sees the D^{+} decay suppressed relative to the D^{o} and F^{+} decays. This is a "sextet dominance" model[5] which hypothesizes an enhancement of diagrams 1b) relative to 1a). 1b) are normally suppressed because of difficulty with color matching. If they can be enhanced, then for D^{+}, diagram 1a) and 1b) could interfere destructively, thus suppressing the D^{+} decays.

The three bubble chamber experiments are compared in Table 1, and in Figs. 5, 6, and 7. The resolved track widths, which are in the range 30-55 μm, are adequate to observe charm decays with reasonable efficiency. Two of the chambers use liquid hydrogen, the third chamber a Freon.

It can be seen that the small CERN chambers operate with no magnetic field, and the downstream spectrometers allow only ~90% efficiency for finding charged tracks. This has obvious consequences in reconstructing charmed decays. For the data reported, only the SLAC experiment had operating particle identification beyond

Table 1. Comparison of the three bubble chamber experiments.

	LEBC (EHS Collaboration)	SHF (SLAC Collaboration)	BIBC (BERN)
Liquid	H_2	H_2	C_4F_8
Track width	45 μm	55	30
Track bubble density	80 per cm	60	300
B.C. diameter	20 cm	110	6.5
Beam	π^-, p, 360 GeV/c	γ, 20	π^-, 340
Hybrid equipment	2 magnets drift chambers Pb. glass	P.W.C. Cerenkov Pb. glass	Streamer Chamber in magnet
Fraction of tracks momentum analyzed	90% of charm tracks ~50% of decays	100%	90%
π vs. (k,p) identification	small (ISIS consistency check)	~30%	small
Mass res. at D:			
No π^o	12 MeV/c^2	12	~40
With π^o	25	25	--
Mean charged multiplicity in CHARM events:			
At interaction	8	3.8	As LEBC
After decays	11	6.6	plus nuclear effects
Observed π^o	2.5	0.35	0
Observed K^o, Λ	?	0.23	?
Hadronic interactions:			
Total	πp 140K pp 250K	500K	94K
Analyzed	πp 70K pp 80K	200K	75K
Interactions per event in lifetime analysis	πp 5000 pp 9250	8000	5400

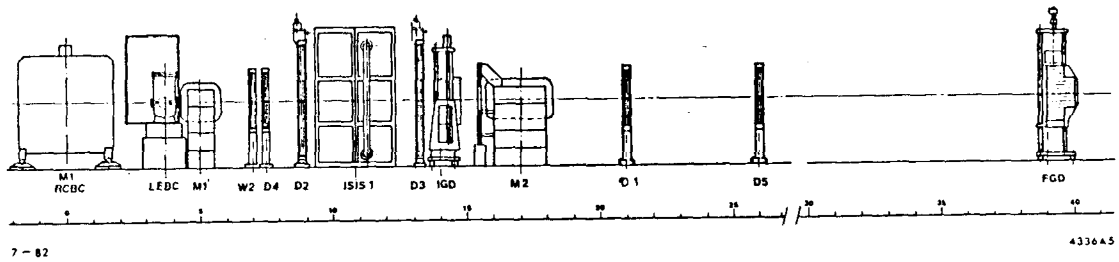


Fig. 5. EHS experiment layout. Behind LEBC are tracking chambers, magnets, ISIS and lead glass detectors.

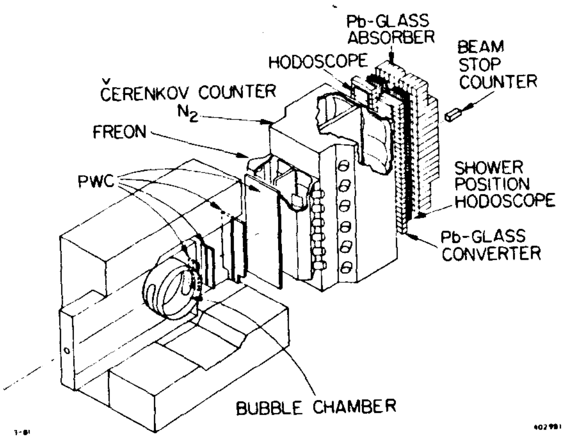


Fig. 6. SHF experiment layout.

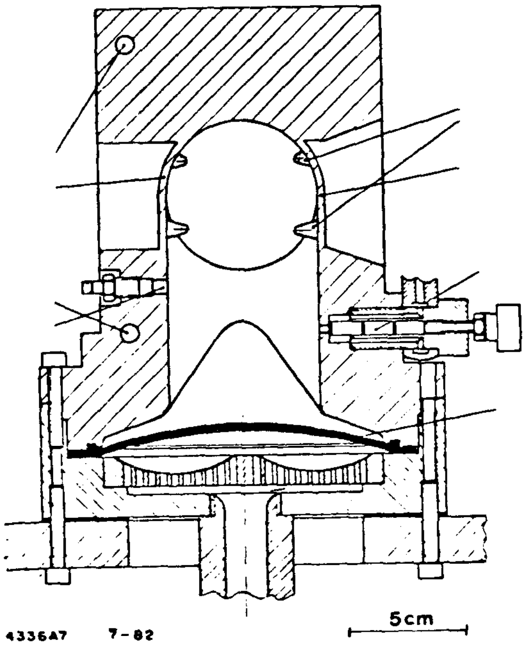


Fig. 7. The BIBC freon bubble chamber.

ionization of slow tracks in the chamber liquid. Even in this experiment the charmed decay track identification was limited to ~30% of tracks.

When full reconstruction was possible, mass resolutions were ~10 MeV/c^2 for the hydrogen experiments, but considerably poorer for the heavy liquid experiment which used a streamer chamber for momentum analysis. The resolution was a factor of two worse when π^0's were involved. These were measured in the lead glass arrays behind the two hydrogen experiments. It may be seen that the LEBC experiment had a relatively large number of showers from which to extract its π^0 signal, both because of its higher π^0 production and larger acceptance solid angle.

The 350 GeV/c momenta of the hadron beams of the CERN experiments also introduce a noteworthy difference in the topology of the events.

The multiplicity at the production vertex is twice as much as at SLAC energies. The track count increases, on average, by three after the charmed decay. The high energy experiments must live with a comparatively sharp forward collimation of their events, Fig. 8.

It is worth noting that the SLAC 20 GeV photon beam, although by no means unique, is somewhat unusual. It is produced by directing ultraviolet photon pulses from a laser against the SLED energy (30 GeV) electron beam. Compton backscattered photons are then collimated into the bubble chamber in a 3 mm diameter, almost monochromatic, pencil beam.

The statistics on the exposures serve to indicate that the LEBC and SLAC collaboration hydrogen experiments are ~40% analyzed, whereas the Bern statistics are almost complete (although their result is still preliminary).

The set of pictures from SLAC, Fig. 9, may be compared with those of the other experiments. The contrast has been slightly enhanced for ease of reproduction. As seen in a) and b), charmed events can be topologically very simple. Indeed the majority of D^+ decays are "kinks" as in a). However, mostly because of the large amount of missing energy, these are presently not used in the lifetime analyses. V^o topologies, like kinks, can be from strange particle decays. In both cases, events whose kinematics show they might be strange decays must be cut from the sample.

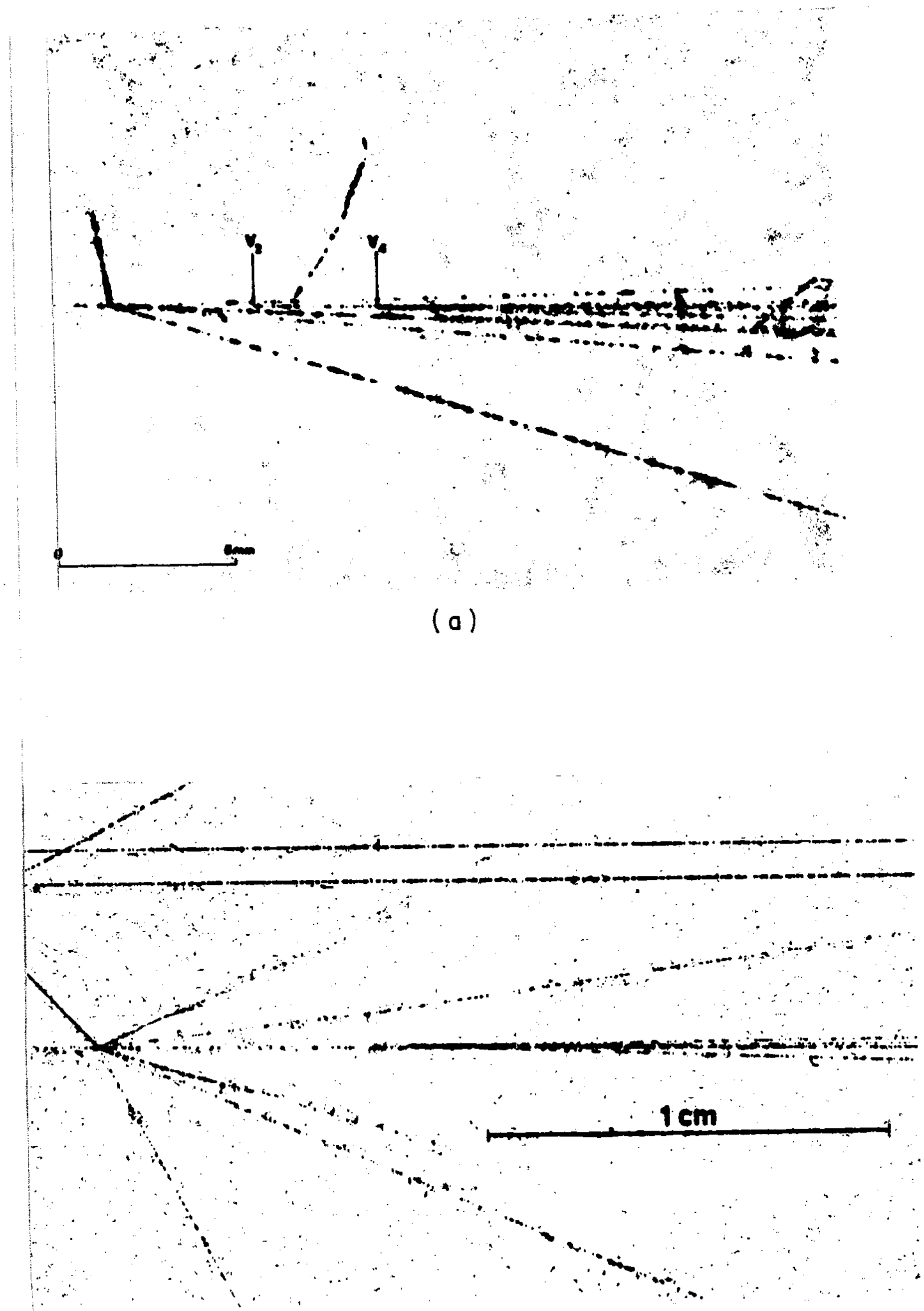
In Fig. 9c), a difficulty is illustrated. In a few events it is impossible to be sure which vertex (there are three!) several of the tracks come from. Thus it is possible, in this event, to reconstruct a Λ_c^+ and $\bar{D}^o$ — but not at the same time since the two hypotheses use common tracks. Another problem occurs in the event in Fig. 9d). Although topologically clear, the three-prong decay — which has a π and a K identified — can be reconstructed as a D^+ or F^+ depending on whether the third track is a π or a K. This ambiguity is characteristic of charmed vertex reconstruction. It is ameliorated by improved mass resolution and track identification, and will improve also when one feels confident in the mass of the F, and perhaps with better knowledge of the branching ratios.

The event in Fig. 9e) is a clear example of a charmed pair decaying. It is unfortunately particularly representative of the processes, because in both cases there is substantial missing mass. Neutral particles, π^o, K^o, Λ, n .... even if detected, cannot usually be allocated after reconstruction to a specific decay vertex.

The final example in the figure shows a 4-track neutral decay where two pions are identified and one track is a K^+ (or p). The hypothesis that the fourth track is a π gives a $\bar{D}^o$ mass, and there is no kinematic indication of a missing neutral. It appears to be a clean example of a $\bar{D}^o$. The interesting thing is its lifetime. At 23×10^{-13} sec it would have travelled ~10 lifetimes if certain of the reported D^o lifetime results are correct — a probability of $< 5 \times 10^{-5}$.

In comparing the various analyses there are several subtleties which we must pass over to concentrate on the more general issues.

First the strange particles are removed kinematically. The LEBC experiment believes they may have ~1 event background from a strange V^o. In the other experiments it should be substantially less.



(a)

(b)

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Fig. 8. Examples of events in a) LEBC and b) BIBC.

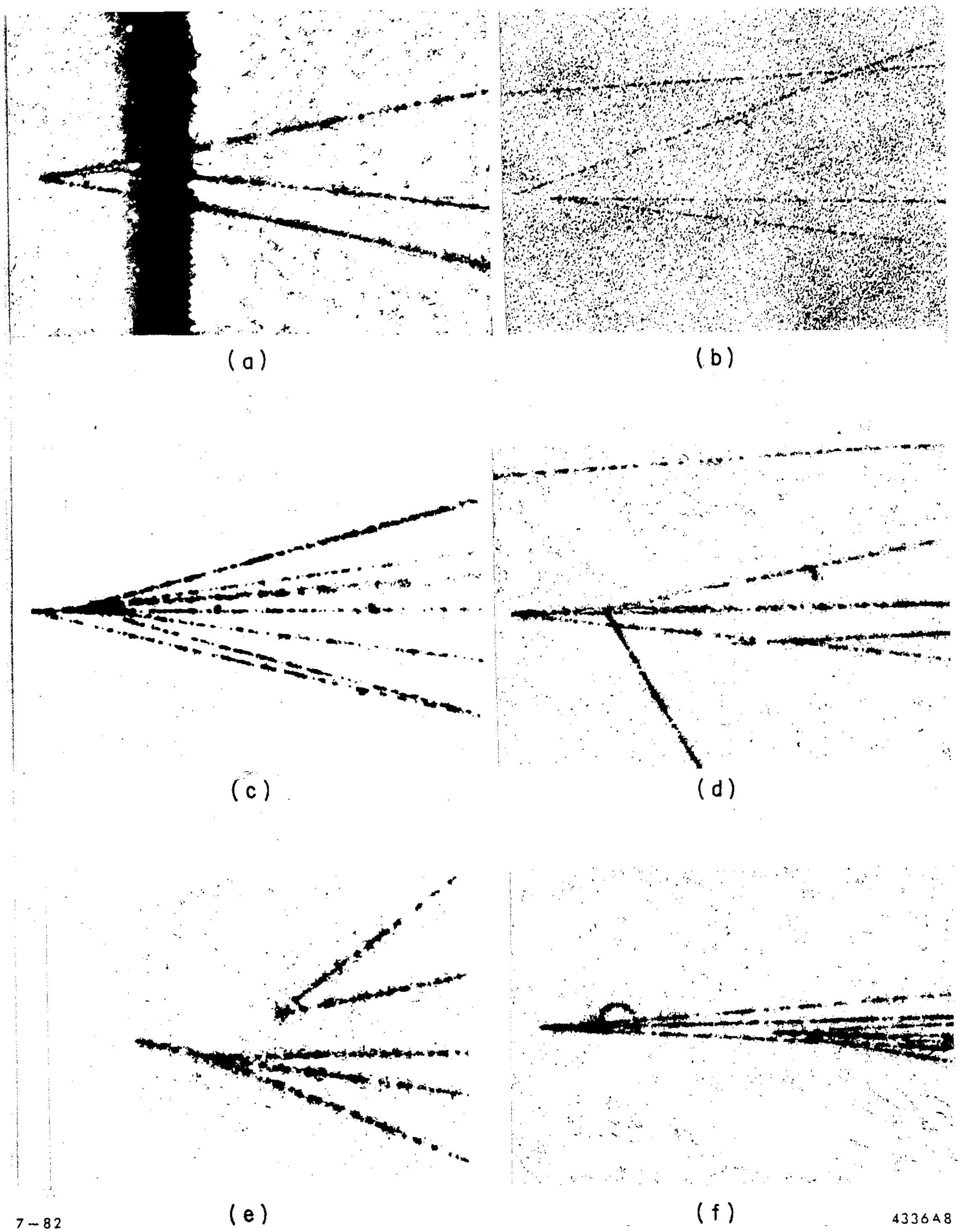

Fig. 9. Events from the SHF data.

It is then necessary to define geometrical limits within which the charm detection efficiency is high and uniform. When tracks from a decay, projected back towards the original interaction, seem to miss it by more than about twice the track width, the scanners pick up the events efficiently. All groups agree on this. (The observed least distance of approach is termed the impact distance.) In some analyses a minimum flight length of 0.5 or 1 mm is required to reduce the reconstruction ambiguities from track overlap.

Given a clean sample, the lifetime comes from flight length and momentum. Of course the flight length must be corrected for the minimum distance the charmed particle must travel before it could be detected and accepted into the sample.

The momentum is a more difficult problem. Of 20 decays in the SLAC collaboration sample, 12 have substantial missing momentum. This difficulty has been handled in rather different ways in the experiments.

The European groups have sought events whose momentum vectors lie within errors of the line between the interaction and decay vertices, and for which some Cabibbo allowed permutation of track identities gives a charmed particle mass. If necessary, available neutral vertices are included. Then only events so classified are included in the lifetime distribution.

Figure 10 shows that selecting a π^0 from pairs of γ rays is not without background risks. Figure 11 shows that, when three-prong decays are selected to have some combination giving a charged D mass, then for the same events, with and without detected neutrals, there may be other possible charm selections. If the wrong one is chosen the charmed particle momentum will in general be wrongly estimated.

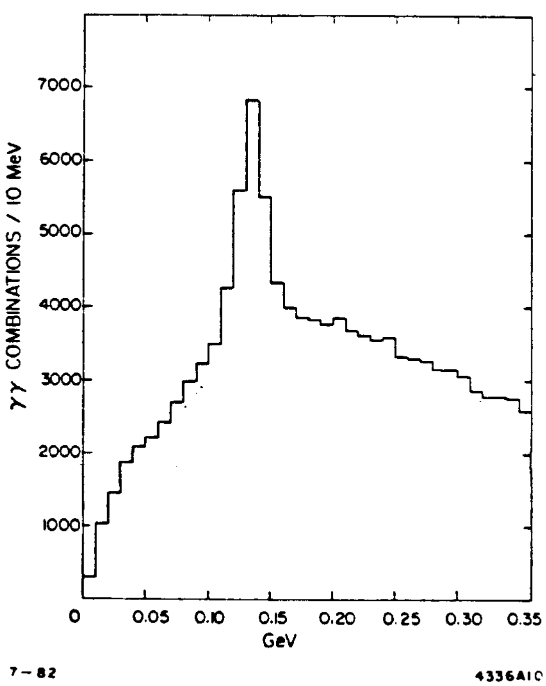

Fig. 10. Mass spectrum of γ pairs from lead glass data (EHS).

Because of worries that this situation is presently inadequately understood, the SLAC collaboration used a different procedure. At least at SLAC energies the visible momentum is usually within a factor of ~2 of the maximum possible momentum of the decaying particle. Therefore an estimate of the momentum cannot be wrong by too much (given the overall uncertainties on the lifetime). The estimate comes from

$$1/p_{EST} = (1/p_{VIS} + 1/p_{MAX})/2.$$

This estimate is then simulated in a Monte Carlo representation of the experiment. In fact, three independent Monte

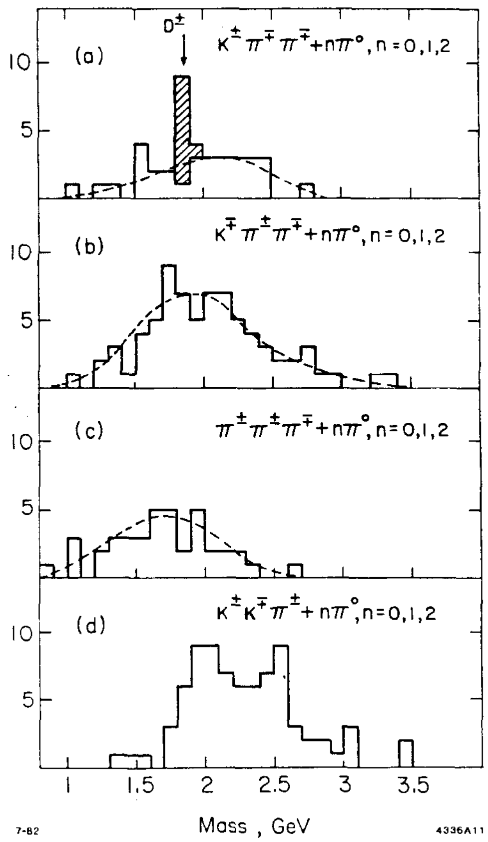

Fig. 11. Reconstructed masses for three-prong plus (n π^o) events (EHS). Events are selected to have a three-prong mass at the D mass, and other Cabibbo-allowed masses are plotted.

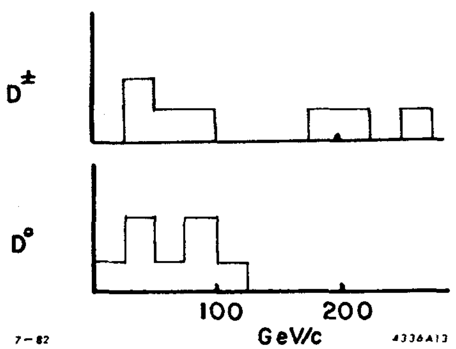

Fig. 13. Spectra of $D^{\pm}$ and D^o's from EHS.

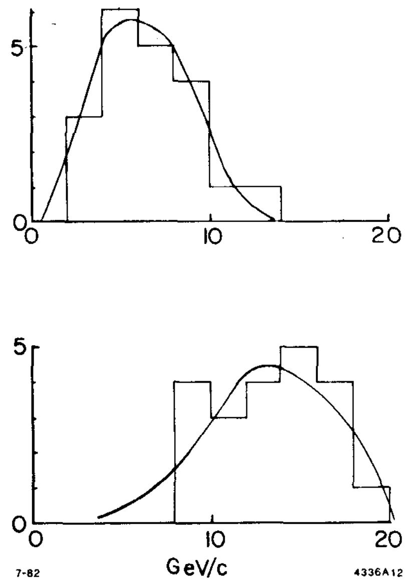

Fig. 12. Spectra of (upper plot) momenta visible at decay vertices and (lower plot) total visible momentum of SHF events. Smooth curves are from the Monte Carlo analysis.

Carlos have been compared with the data and represent it very well. The momentum representation is particularly important and examples of total visible momentum and decay vertex visible momentum plots are given in Fig. 12.

It is interesting to compare this with the broad momentum distributions for the $D^{\pm}$ and D^o events from the EHS (LEBC) collaboration (Fig. 13). The reason for, or the significance of, the difference between the charged and neutral spectra from the EHS is obscure to the writer.

Each charmed decay is compared with the Monte Carlo and a maximum likelihood found as a function of lifetime. The measureable quantities compared are: the impact distance (which measures lifetime essentially independent of momentum); the decay length, and the effective lifetime using the momentum estimate. A maximum likelihood for the ensemble of events is also obtained.

Before comparing the results, some useful checks can be reported. The possibility that some of the "decays" are actually interactions with a recoil track so short as to be invisible, has been evaluated by the SLAC collaboration. That background is $\lesssim 0.1$ event, but may be larger for higher energy experiments. In BIBC, the heavy liquid complicates matters. They estimate a background of 1.5 events. Another test concerns the experimental sensitivity to the minimum accepted separation between primary and decay vertices. The SLAC group has varied its impact distance and decay length cuts by a factor of two, up and down. This led to no significant changes in the lifetime results.

Lifetime distributions are available for SLAC and EHS collaborations, and are superimposed in Fig. 14. A disparity is evident in the neutral lifetimes. The current results of the three experiments are given in Table 2. The first thing to notice is the relative level of agreement in the $D^{\pm}$ lifetime numbers. Again there is some disagreement between the values for the D^{o}'s. It is perhaps noteworthy that the few Λ_c and F examples found were relatively long lived.

In an attempt to relate these results to the study with which the talk started, we return to the lifetime ratio plot. In this case, Fig. 15, the neutrino-emulsion (E531) result has been updated with their most recent neutral decay result.[6] Again two results are given: for all decays; and, after the exclusion of semileptonic events. The three bubble chamber results are super-imposed with approximately calculated likelihood lines. The congested figure suggests that a lifetime ratio in the neighborhood of 2.5-3.0 would suit all of the experiments with the exception of DELCO. That one would disagree at a level of perhaps 2.5-3.0 standard deviations. Such a ratio, we recall, would also be well received by present theory.

For the future, we note that, although the heavy liquid experiment has almost run its course, the two hydrogen experiments expect to more than double their statistics. This will allow them to study systematic biases in their data as well as reducing fluctuations.

The EHS has undergone a substantial upgrading. Particle identification has been introduced using aerogel and helium

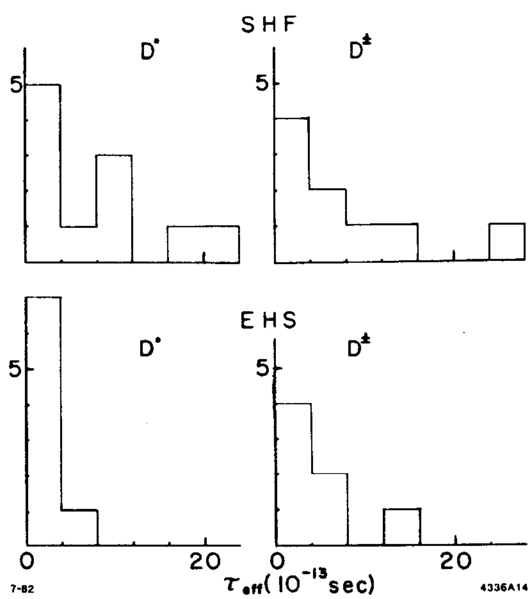

Fig. 14. Effective lifetime plots for $D^{\pm}$ and D^{o} from SHF and EHS.

Table 2. Comparison of results of the three bubble chamber experiments. Units 10^{-13} sec.

	D^0	$D^\pm$	$D^\pm/D^0$	$F^\pm$	Λ_c^+
LEBC	$2.1\ ^{+1.3}_{-0.7}$ (8 decays)	$6.5\ ^{+4.7}_{-2.1}$ (7 decays)	$3.1\ ^{+2.9}_{-1.4}$	5.5 (1 decay)	7.7 (1 decay)
SHF	$6.7\ ^{+3.5}_{-2.0}$ (11)	$8.2\ ^{+4.5}_{-2.5}$ (9)	$1.2\ ^{+0.9}_{-0.5}$	--	--
BIBC	$3.8\ ^{+2.4}_{-1.2}$ (8)	$6.3\ ^{+6.0}_{-2.5}$ (5)	$1.65\ ^{+1.9}_{-0.9}$	8.3 (1)	--

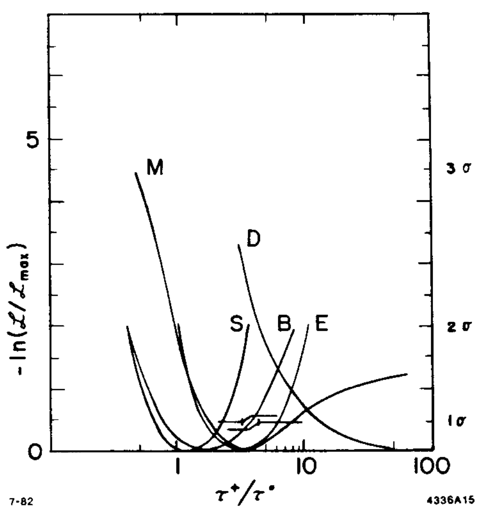

Fig. 15. Figure 2 updated. Experiments are identified by letters: M — Mark II, D — DELCO, S — SHF, B — BIBC, E — EHS. The E531 neutrino emulsion experiment's most recent results are given by the error bars: lower ratio with leptonic decays included, higher ratio without leptonic decays.

Cerenkov counters, as well as a full scale ISIS ionization sampling device, and a transition radiation detector. Upgraded tracking has been included, and perhaps most significant, a new small bubble chamber, HOLEBC, has been made to give resolved track widths of 20 μm with conventional optics. This system has already had its first run.

The SHF collaboration also plans to run again with improved track resolution and particle identification. In two years or so these groups should statistically better their first experiments but with substantially improved systematics.

I wish to thank my various colleagues in the SLAC collaboration, and particularly Dr. G. Kalmus, for useful discussions about this topic.

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