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LIFETIMES OF HEAVY LEPTONS AND HADRONS*

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ABSTRACT

Recent measurements of the lifetimes of the τ lepton and charm and beauty particles are reviewed, with emphasis on the experimental techniques used for vertex detection.

1. Introduction

In the past few years, decays of heavy leptons and hadrons carrying heavy flavour quantum numbers have become a fashionable topic, for theorists and experimentalists alike. In the framework of the standard electro-weak theory, the flavour-changing transitions among quarks and leptons are described by their coupling to the charged weak boson, $W^{\pm}$. The parton diagrams for heavy leptons or quarks are identical to $\mu^{\pm}$ decay, and thus apart from differences in the couplings of the $W^{\pm}$ to various partons, the decay rates of the heavy quarks Q and leptons ℓ are calculable and closely related to the muon decay time τ_{μ}, namely

$$\tau_{\ell} \;=\; \frac{192\pi^3}{G_F^2 m_{\ell}^5}\, BR(\ell^- \to e^- \bar{\nu}_e \nu_{\ell}\,) \;=\; \tau_{\mu}\left(\frac{m_{\mu}}{m_{\ell}}\right)^5 \, BR(\ell^- \to e^- \bar{\nu}_e \nu_{\ell}\,)$$

$$\tau_Q \;=\; \tau_{\mu}\left(\frac{m_{\mu}}{m_Q}\right)^5 \, BR(Q \to e^- \bar{\nu}_e q\,) \Big/ \sum_q |V_{qQ}|^2 \;,$$

where G_F is the Fermi constant, m represent the parton masses, and BR stands for the leptonic or semi-leptonic branching ratios. This simple relation is, however, only valid for free quarks and in the absence of flavour mixing and final state corrections due to the light quarks and gluons participating in the decay of a hadron. The differences in the couplings of the quarks to the $W^{\pm}$ are given by the Cabibbo-Kobayashi-Maskawa matrix elements V_{qQ}.[1] Precise measurements of the lifetimes of heavy leptons, mesons and baryons, combined with their branching ratios, can serve as a test of these simple assumptions, help to determine the elements of the quark mixing matrix V_{qQ}, and help in the formulation of theoretical models of weak decay.

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From the point of view of an experimentalist the lifetime measurements are attractive because they represent a major challenge to the design and operation of detectors and to the data analysis. The principle difficulty experimentalists face in the detection of heavy lepton and hadron decays are their small production rates in hadron and photon interactions, and their short decay lengths. Measurements of the branching ratios and lifetimes of the τ lepton have remained an unchallenged domain of e^+e^- experiments, which benefit from the copious production of $\tau^+\tau^-$ pairs resulting in a very clean event topology. Signatures for heavy flavour particles can be derived from their relatively high mass and the weak nature of their decay. Masses of 2 GeV/c^2 and above give rise to large transverse momenta of the decay secondaries and small branching ratios for any particular decay mode. The weak coupling causes the emission of leptons ($e^\pm, \mu^\pm, \tau^\pm$, and neutrinos) and strange particles due to Cabibbo enhancement. Thus an experiment with good sensitivity requires a large-acceptance spectrometer with excellent momentum resolution and good particle identification, preferentially both for hadrons and leptons, and a vertex detector with superb resolution and granularity. Furthermore, measurements of beauty particle lifetimes in hadron beams will not be possible without selective and efficient triggers, or at least the possibility of a fast off-line filter of events.

The standard method to determine particle decay times is to measure the particle momentum and decay path, and thus requires an accurate determination of the production and decay vertices. If the decay products are not fully detected the momentum is often estimated from an unconstrained kinematic fit or from the measured effective mass and the momentum sum of the measured decay tracks. The accuracy of the estimate is tested by Monte Carlo simulation assuming a specific shape of the production spectrum. A more model independent estimate is based on the study of the decay length measured in the plane transverse to the beam in fixed target experiments. This method uses the fact that the transverse momentum distributions are well known. Another method relies on the measurement of the so-called impact parameter ρ[2] which is defined as the distance of closest approach of a track to the production vertex. ρ is proportional to the product of the decay length and the decay angle, and in the relativistic limit becomes insensitive to the momentum of the decaying particle. The clear advantage of this estimator is that it does not require a fully reconstructed decay or estimate of momentum, and can use individual tracks from hadronic or semileptonic decays, thus avoiding unacceptable losses due to small branching ratios and limited detector acceptance. Monte Carlo simulation is needed to relate the impact parameter to the decay time; this can be done to an accuracy of about 10%.

In the following, recent measurements of the τ, and the charm and beauty lifetimes will be reviewed, more information about the experiments and earlier results can be found in more detailed review articles.[3,4]

2. The Lifetime of the τ Lepton

Though we now have evidence for the decay of the Z^o and $W^\pm$ into $\tau^\pm$ leptons from the UA1 experiment at the SPS collider,[5] measurements of the τ branching ratios and lifetimes have been exclusively performed at the e^+e^- storage rings PEP, PETRA, DORIS and CESR, where large $\tau^+\tau^-$ pair production produces a clean event topology. All these experiments have improved the accuracy of the charge particle tracking by the installation of high precision drift chambers mounted on the outside of a thin-walled beam pipe. At present, the major limitation on the lifetime measurements is due to the fact that the production vertex is not observed, but is located somewhere inside the beam-beam interaction region. Tracks have to be extrapolated over a distance of several cm, depending on the radius of the beam pipe.

The MAC collaboration[6] has extracted the τ lifetime from the impact parameter distribution of all well measured charged particle tracks from τ decay. The production point is found using, with appropriate weights, the interception of the tracks and the beam ellipse. The event sample is selected by simple topology cuts, and contains less than 4% background. The resulting distribution for 6533 tracks is shown in Figure 1(a). The large statistics gain considerable precision; a clear shift and excess of tracks on the positive side are visible.The trimmed average is 44.5 ± 2.4 μm, corresponding to a lifetime of

$$\tau(\tau^\pm) = 2.86 \pm 0.17 \pm 0.13 \cdot 10^{-13} \text{ s.}^\star$$

The advantage of the impact parameter measurement is that systematic effects cancel to a large degree, and the trimmed average does not depend on the error on the impact parameter measurement, as long as all errors are distributed symmetrically around zero. The remaining systematic error is dominated by the uncertainty in the factor α which relates the impact parameter and lifetime; α is determined by Monte Carlo simulation.

The Mark II[7] and HRS[8] groups have derived the τ lifetime from the measured decay length distribution which is taken as the distance between the centre of the e^+e^- collision region and the vertex formed by the three well measured charged particles tracks from the decay $\tau^- \rightarrow \pi^-\pi^+\pi^-\nu_\tau$. The data from the Mark II group are shown in Figure 1(b). A maximum likelihood method fit is performed which takes into account the individual error of each decay length. The average decay length of $635 \pm 36\mu$m translates to an average lifetime of

$$\tau(\tau^\pm) = 2.86 \pm 0.16 \pm 0.25 \cdot 10^{-13} \text{ s.}$$

The CLEO[9] and ARGUS[10] experiments have presented preliminary results based on very similar analyses for substantially larger samples of τ decays. Their data are

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$\star$ If there are two errors are quoted, the first represents the statistical, the second the systematic uncertainty.

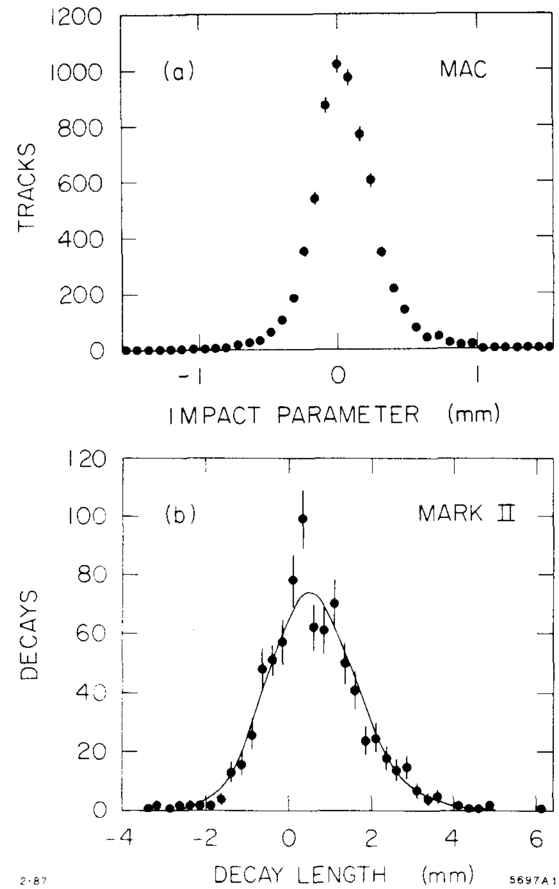

Fig. 1. Measurements of the $\tau^{\pm}$ lifetime: Distributions of (a) the impact parameter for 6533 tracks from the MAC, and (b) the decay lengths for 807 3-prong decays from the Mark II experiment.

recorded at lower energies, resulting in increased $\tau^+\tau^-$ production cross sections, reduced decay lengths and in larger background from hadronic final states.

A compilation of recent measurements of the $\tau^{\pm}$ lifetime is given in Table I. None of the results listed has been published yet, and most of these measurements can be viewed as a calibration for the high precision drift-chamber and the technique applied to measure small decay distances or impact parameters. Typically, the measurement errors are comparable in size to the quantity used estimate the decay time, thus one observes a non-zero decay time as a shift of a Gaussian resolution function to positive values.

In the framework of the standard model the τ lifetime can be predicted, given the measured leptonic branching, $BR(\tau^- \to e^- \bar{\nu}_e \nu_\tau) = (17.93 \pm 0.36)\%$,[11] and the mass, $m_\tau = 1784.2 \pm 3.2$ MeV/c^2,[12] namely

$$\tau(\tau^{\pm})_{th} = 2.86 \pm 0.06 \cdot 10^{-13} \text{ s.}$$

All experiments listed in Table I are in good agreement with each other, and the average differs by one standard deviation from the prediction. In fact, the measurements can be used to set limits on possible deviations from the basic assumptions of the standard model. The measurements confirm the equality of the coupling of the τ and μ leptons to the charged weak current to a level of 2%. The measurements also constrain the mass of the ν_τ to be less than 195 MeV/c^2 at 90% confidence level; a limit which is not competitive with recent direct measurements. On the other hand, if the τ neutrino mixed with a neutrino of a mass greater than m_τ, the decay rate would be reduced by a factor of $\cos^2\theta$, where θ is the mixing angle. The present measurements can limit such mixing only to $\sin\theta < 0.3$, at 90% confidence level.

Table I: Measurements of the τ Lepton Lifetime

Experiment	Reference	Lifetime (10^{-13} s)
MAC	6	2.86±0.17±0.13
Mark II	7	2.86±0.16±0.25
HRS	8	2.85±0.15±0.11
CLEO	9	3.33±0.14±0.20
ARGUS	10	3.02±0.19±0.12
Average		2.97±0.10

3. Lifetimes of Charm Particles

In the following, an overview over experiments measuring lifetimes of the charm mesons, D^0, D^+, and D_s^+, (commonly referred to as F^+)* and charm baryons, Λ_c^+, Ξ_c^+, and Ω_c^0, will be given. The experiments are grouped as to the apparatus used for vertex detection.

3.1 Emulsion Experiments

In recent years, nuclear emulsions have been revived as active targets for lifetime experiments because of their superb spatial resolution (better than 1 μm) and granularity. With the addition of high resolution tracking external to the emulsion stacks, computer-aided scanning has substantially enhanced the analysing power of this technique. Two experiments have recently reported results based on data recorded many years ago.

* Throughout this report reference to particles like D^0, D^+, D_s^+ implies also the charge conjugate states $\overline{D}^0$, D^-, D_s^-, unless explicitly stated.

The E-531[13] experiment employed an emulsion in the ν beam at FNAL. The group recently published 58 D^0 decays and 47 decays of charged charm particles, among them 6 unique D_s^+, 13 unique Λ_c, and 28 decays that are consistent with D^+, but also compatible with the kinematics of D_s^+, and/or Λ_c^+ decay. This Λ_c^+ and D_s^+ contamination, which is estimated from a fit to the decay time distribution to be 4.8 ± 5.0 events, is responsible for the larger error in the D^+ lifetime. A likelihood fit to the observed decay time distributions results in

$$\tau(D^0) = 4.3 \pm^{0.7}_{0.5} \pm^{0.1}_{0.2} \cdot 10^{-13}\ \mathrm{s} \qquad \text{and} \qquad \tau(D^+) = 11.1 \pm^{4.4}_{2.9} \cdot 10^{-13}\ \mathrm{s}.$$

The lifetime ratio is calculated to be $2.6 \pm^{1.1}_{0.8}$. The average lifetimes of the fitted D_s^+ and Λ_c^+ decays are $2.6 \pm^{1.6}_{1.1} \cdot 10^{-13}$ s and $2.0 \pm^{0.7}_{0.6} \cdot 10^{-13}$ s, respectively.

The WA-58[14] group exposed a thin emulsion target to a photon beam at the CERN SPS. Their results, listed in Tables III and IV, are based on 45 events containing 27 D^+, 44 D^0, and 11 Λ_c^+ decays. While the observation of two secondary vertices in most of the events greatly enhances the purity of the charm selection, the identification of individual decay modes remains difficult, partially due to the limited mass resolution and particle identification of the Omega spectrometer. Only 8 D^+, 8 D^0, and 2 Λ_c^+ decays are identified by unambiguous fits to decay modes involving two or more charged and no neutral secondaries.

3.2 Bubble Chamber Experiments

The use of bubble chambers as active targets has the advantage that within a small fiducial volume, tracks can be accurately measured and clearly associated with the production or decay vertices. In the small bubble chamber LEBC, the single track resolution has been pushed to a few μm, by the introduction of laser optics, by improved HPD measuring machines, and by optimum operating conditions resulting in small bubble diameters and high bubble density. At Fermilab, holography is being used in the 15 feet bubble chamber.

The NA-27 group used the hydrogen bubble chamber, LEBC, in the European Hybrid Spectrometer and has recently completed the analysis of data recorded in a 360 GeV π^- beam.[18] The experimenters rely on the excellent vertex resolution and picture quality to select a sample of clean charm decays. They apply several different techniques to derive lifetime estimates for charm particle decays that cannot be constrained by kinematics. For instance, they estimate the total momentum from the effective mass and momentum of the measured charged particles associated with the decay, or they measure the distribution of impact parameters of the tracks associated with the charm decay. In both cases they infer the average lifetime from the measured distributions using Monte-Carlo methods. In addition, they have tried to reduce the model dependence by combining the distribution of decay lengths[19] measured in the plane transverse to the beam with the measured exponential form of the transverse momentum distribution. The transverse decay length distributions for the neutral and charged charm sample are shown in Figure 2.

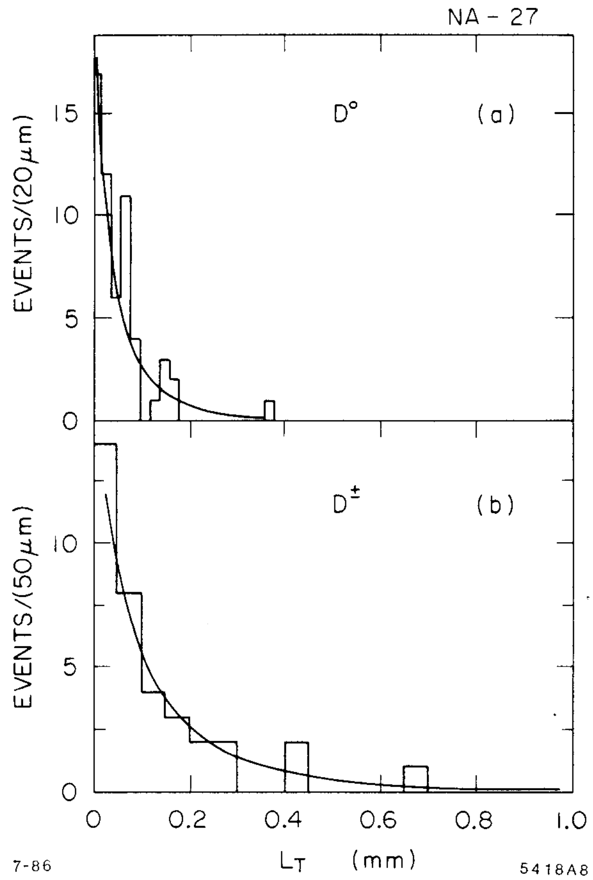

Fig. 2. NA-27: Transverse decay length distributions for selected D meson decays.

The length l_T has been corrected, event by event, for the minimum detectable length. The two distributions are clearly different. A maximum likelihood fit gives

$$\tau(D^0) = 4.1 \pm^{0.7}_{0.6} \cdot 10^{-13}\ \text{s} \qquad \text{and} \qquad \tau(D^+) = 10.7 \pm^{2.8}_{1.8} \cdot 10^{-13}\ \text{s}.$$

By applying different techniques to measure lifetimes to different, but overlapping, event samples the authors conclude that the transverse decay length is a robust estimator of the lifetime. Uncertainties in the measured transverse momentum distribution are included in the error. In the D^+ sample, there is no evidence for a short-lived component due to D_s^+ or Λ_c^+ contamination. The ratio of D^+ to D^0 lifetimes is $2.6\pm^{0.8}_{0.6}$.

The NA-27 has recently reported a result[20] on the Λ_c^+ lifetime, based on nine three prong vertices that have been unambiguously fitted to Cabibbo-favoured decay modes, $\tau(\Lambda_c^+) = 1.2 \pm^{0.5}_{0.3} \cdot 10^{-13}$ s.

3.3 *Experiments with Silicon Vertex Detectors*

The use of Silicon as an active target and as a high resolution tracking device was pioneered by two groups at CERN. The NA-1 group[21,22] uses a target made of

40 silicon wafers, 300 μm thick and spaced by 100 μm, to detect multiple vertices in an event with tracks reconstructed in the downstream spectrometer. Since there are two charm decays per event, the association of the decay length and the charged decay secondaries often remains ambiguous. This problem is overcome by selecting exclusive $D^0\overline{D}^0$ production and $D^{*+} \rightarrow D^0\pi^+$ decays.

The NA-11 group was the first to use silicon microstrips to reconstruct secondary vertices and to demonstrate $> 99\%$ efficiency and single track resolution of 5 μm per plane.[23] A system of on-line processors was used to trigger on prompt electrons or more than one kaon, detected by a calorimeter and Cerenkov counters downstream. Recently, the group has presented a sample of 69 semi-leptonic decays $D^+ \rightarrow \overline{K}^{*0}(890)\ e^+\nu_e$.[25] The decay times are estimated using the observed invariant mass and momentum, and corrected for the minimum detectable decay time compatible with the vertex cuts. The resulting lifetime of $\tau(D^+) = 11.2 \pm^{1.6}_{1.3} \pm 0.8 \cdot 10^{-13}$ s compares well with the earlier result based on 28 $D^+ \rightarrow K^-\pi^+\pi^+$ decays.

In an attempt to detect secondary vertices at the trigger level, the same group, under the label NA-32, installed an active target of 14 finely segmented silicon counters.[26] While the on-line charm selection did not produce satisfactory results, a total of $38 \cdot 10^6$ were recorded with an interaction trigger in a 200 GeV hadron beam. At present 11 million π^- and 5 million K^- interactions have been analysed resulting in 98 fully reconstructed D decays. Two or more decay tracks are required to form a vertex that is separated from the interaction point by a distance of at least 3 mm. The D momentum must point back to the production point to within a few μm. Preliminary data, shown in Figure 3, demonstrate the cleanliness of the samples. There are 46 D^+ and 52 D^0 decays, above a background of 4 and 10 events, respectively. To correct for detection losses at short decay distances the measured decay times are corrected for the smallest detectable decay time, $t_{corr} = t - t_{min}$, compatible with the selection criteria. Maximum likelihood fits to the background subtracted time distributions yield

$$\tau(D^0) = 3.9 \pm^{0.6}_{0.5} \cdot 10^{-13}\ \text{s} \qquad \text{and} \qquad \tau(D^+) = 9.8 \pm^{1.9}_{1.5} \cdot 10^{-13}\ \text{s}.$$

The systematic errors are estimated to be substantially smaller than the statistical errors quoted. The measurements translate into a lifetime ratio of $\tau(D^+)/\tau(D^0) = 2.5 \pm 0.6$.

The NA-32 group[27] has applied the same analysis to search for the decay $D_s^+ \rightarrow K^-K^+\pi^+$ and finds 12 events above a background of less than one. The mass is 1972.82$\pm$2.1 MeV/c^2. Due to ambiguities in the kaon and proton identification a few events are compatible with the decay modes $D^+ \rightarrow K^-\pi^+\pi^+$ or $\Lambda_c^+ \rightarrow K^-p\pi^+$. They are excluded from the sample. A fit to the corrected decay time distribution gives $\tau(D_s^+) = 3.4 \pm^{1.3}_{0.9} \cdot 10^{-13}$ s. If we combine these 12 decays with the 9 decays

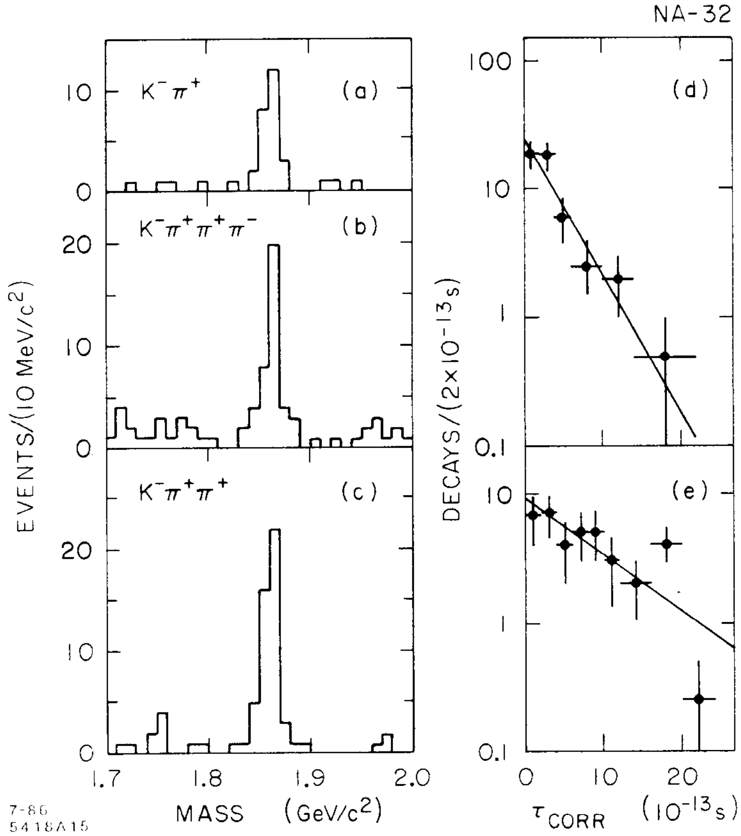

Fig. 3. NA-32: Effective mass and corrected decay time distributions for the selected D mesons.

observed by NA-11 in the same detector the weighted average is

$$\tau(D_s^+) = 3.3 \pm^{1.0}_{0.6} \cdot 10^{-13} \text{ s}.$$

In 1985 the NA-32 collaboration[28] improved the resolution and granularity of the vertex detector by the addition of two CCDs at a distance of 10 mm and 20 mm from a 2.5 mm thick Cu target, that was exposed to a 230 GeV negative hadron beam. The trigger required at least two particles without a signal in the threshold Cerenkov counters, thus increasing the D_s^+ and Λ_c signals by about a factor of 12. This is the first use of Charged Coupled Devices as tracking detectors for minimum ionizing particles. At present roughly 20% of the 16 million triggers have been processed and the results are presented in Figure 4. Figure 4(a) shows a decay $\Lambda_c^+ \rightarrow pK^-\pi^+$ projected on to a plane parallel to the CCDs. With an incident intensity of 10^6 particles per 2.5 s beam pulse there are on the average 2 hits/mm^2, compared to a cell density of 2100/mm^2 in the active area of 8.8×2.4 mm^2. The efficiency of the CCDs was measured to be 95%. The primary vertex is determined with a precision of 2 μm in the plane transverse and 60 μm along the direction of the incoming beam. A total of 14 Λ_c decays have been observed (including one background event), their masses are peaked at 2285.6 ± 1.1 MeV/c^2. Three decays with ambiguous particle identification are compatible with D^+ or D_s^+ decay to $KK\pi$ and they are excluded from the lifetime determination. A fit gives

$$\tau(\Lambda_c^+) = 1.4 \pm^{0.5}_{0.3} \pm 0.3 \cdot 10^{-13} \text{ s},$$

where the systematic error reflects the sensitivity of the fit to changes in the event selection and assumed position error.

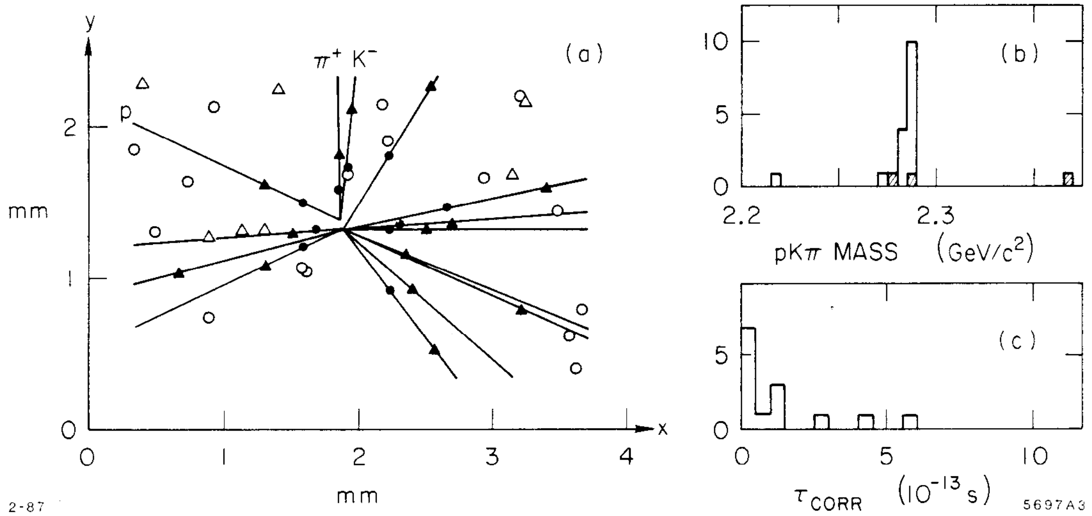

Fig. 4. NA-32: Measurement of the Λ_c lifetime, (a) display of a single event detected in the CCDs in the projection transverse to the beam, (b) effective mass and (c) decay time distribution. Hits in the first and second CCD are marked as triangles and circles, respectively. The open symbols mark hits that are not associated with this event. They are due to additional beam tracks passing during the active time of the CCDs.

Over the past six months, the E-691 group from Fermilab has reported lifetime measurements with high statistical and systematic accuracy.[29] The present analysis is based on up to 45% of a total 10^8 interactions recorded by the Tagged Photon Spectrometer. Inelastic interactions in the 5 cm long Beryllium target were selected by a trigger on the transverse energy measured in the downstream calorimeters. Three triplets of Silicon strip detectors with 50 μm spacing and digital read-out were installed to improve the charged particle tracking close to the target. The event selection is remarkably straight forward and designed to minimize systematic errors in the determination of the lifetimes. (1) Tracks from the decay of a charm particle are required to form a good secondary vertex, all other tracks are used to form the primary vertex. (2) The impact parameter of the reconstructed charm candidate relative to the primary vertex is not to exceed 80 μm. (3) The decay path was required to be larger than l_{min}. This distance was chosen to be typically 6-10 times the resolution σ_z, in order to reduce the background for each decay mode to an acceptable level. The proper time is calculated using the measured momentum and the distance from l_{min} to the decay vertex. (4) The particle masses had to be consistent with the Cerenkov counter pulse heights. The resulting four D meson samples are presented in Figure 5. There are three independent samples for the D^0 and one for the D^+, their statistics and the cleanliness are remarkable. The decay time distributions are fit to a sum of signal and background. The fit takes into account the resolution, acceptance, detection efficiency and the measured background distributions. The number of signal and background events, and the l_{min} cut are given in Table II. The three D^0 samples are statistically independent, they have different corrections and background. The fact that all three samples agree provides a check on the systematic uncertainties. The background subtraction for the two D^* modes is negligible; for the decay $D^0 \to K^-\pi^+$ it causes a shift by 0.05 ps. The total acceptance correction amounts to -0.030 ± 0.007 ps. A global fit to all three subsamples gives

$$\tau(D^0) = 4.35 \pm 0.15 \pm 0.10 \cdot 10^{-13} \text{ s.}$$

The D^+ decay time distribution shows a clear deviation from the expected exponential; this is due to the limited length of the decay region and the longer average lifetime. The correction due to acceptance and resolution is -0.050 ± 0.015 ps, the background subtraction amounts to 0.25 ± 0.025 ps, and absorption in the target causes a shift by -0.030 ± 0.005 ps. A fit to the data results in a lifetime of

$$\tau(D^+) = 10.6 \pm 0.5 \pm 0.3 \cdot 10^{-13} \text{ s.}$$

The charged D meson lifetime exceeds the lifetime of the neutral D meson by a factor of $2.44 \pm 0.14 \pm 0.08$.

Table II: Results from Experiment E-691 at FNAL

Decay Mode	Vertex Cut ℓ_{min}/σ_z	Decays	Background	Lifetime (10^{-13} s)
$D^o \to K^-\pi^+$	8	746	450 ± 10	4.3 ± 0.2
$D^{*+} \to D^o\pi^+ \to K^-\pi^+\pi^+$	5	385	16 ± 2	4.6 ± 0.3
$D^{*+} \to D^o\pi^+ \to K^-\pi^+\pi^+\pi^-\pi^+$	7	228	25 ± 3	4.0 ± 0.3
$D^+ \to K^-\pi^+\pi^+$	10	969	383 ± 9	10.6 ± 0.5
$D_s^+ \to \phi\pi^+$	6	61	21 ± 3	$4.9 \pm^{0.8}_{0.7}$
$D_s^+ \to \overline{K}^{*o}K^+$	10	38	15 ± 3	$4.6 \pm^{1.0}_{0.8}$
$\Lambda_c^+ \to pK^-\pi^+$	6	65	100 ± 10	$2.0 \pm^{0.5}_{0.4}$

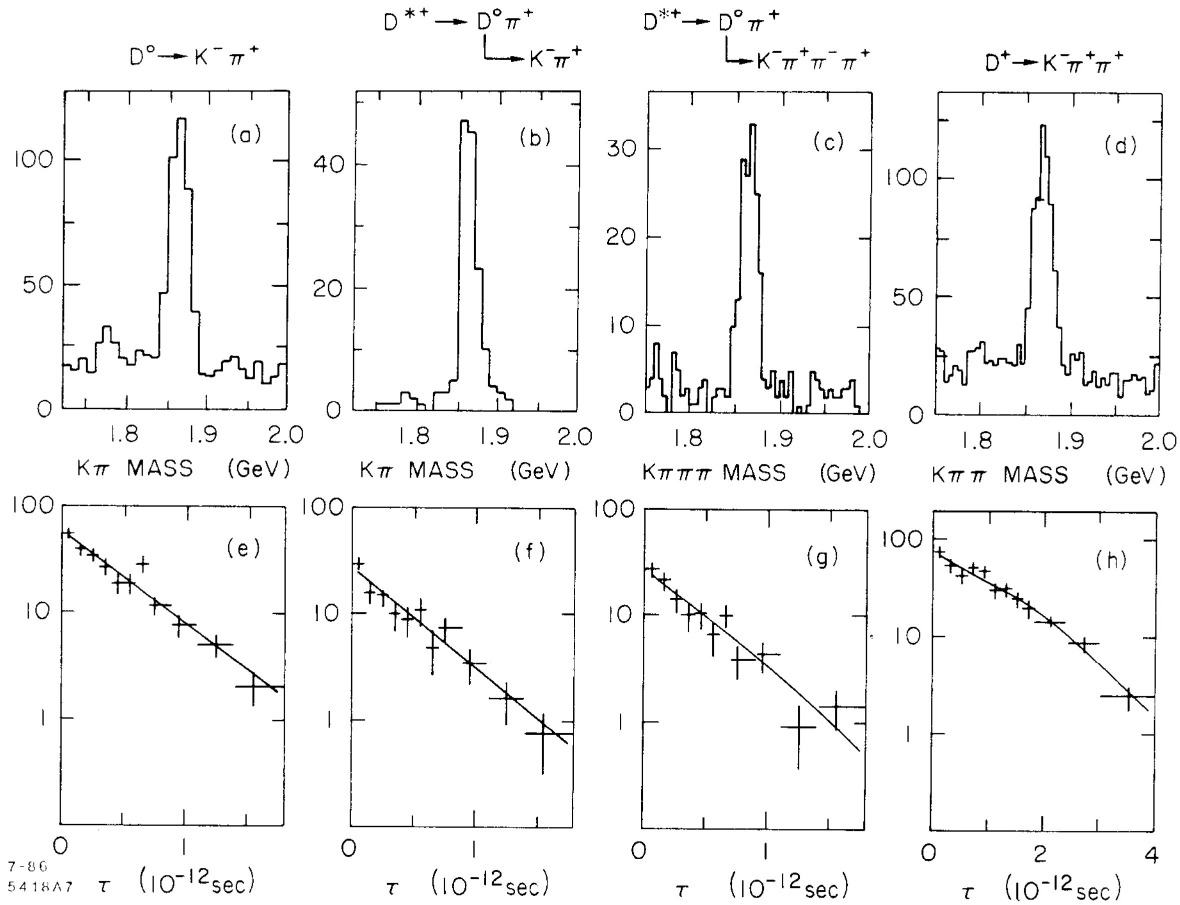

Fig. 5. E-691: Effective mass and decay time distributions for selected D decays.

The same data sample was used to study the D_s^+ lifetime.[30] The D_s^+ mesons were identified by two different decay modes, $D_s^+ \to \phi\pi^+ \to K^-K^+\pi^+$ and $D_s^+ \to \overline{K}^{*o}K^+ \to K^-K^+\pi^+$. The mass spectra and corrected decay time distributions for the two sample are shown in Figure 6. There are two well separated mass peaks, one from the Cabibbo-suppressed decay of the D^+, the other from the decay of the D_s^+. The decay time distributions include only decays within the mass region 1.953 – 1.985 GeV/c^2. The number of signal and background events are given in Table II. A maximum likelihood fit to the total sample of 99 D_s^+ decays gives a mean lifetime of

$$\tau(D_s^+) = 4.8 \pm^{0.6}_{0.5} \pm 0.2 \cdot 10^{-13} \text{ s}.$$

The main contributions to the systematic error arise from the corrections for efficiency and resolution, –0.050±0.017 ps, and from the background subtraction, ±0.12 ps. Decays $D^+ \to K^-\pi^+\pi^+$ and $\Lambda_c \to pK^-\pi^+$ are estimated to contribute less than one background event to the total D_s^+ sample.

At this conference, the E-691 group[31] presented the first, still preliminary results on the lifetime of the Λ_c^+ (cdu) baryon, based on 50% of the total data sample. The analysis follows the same procedure outlined above for charm mesons.

The results, based on the decay mode $\Lambda_c^+ \to pK^-\pi^+$, are given in Table II and in Figure 7. The background is substantially larger than for the charm meson decays, because of the smaller production cross section and the shorter lifetime. The systematic error, quoted as $\pm 0.3 \cdot 10^{-13}$ s, is still under study.

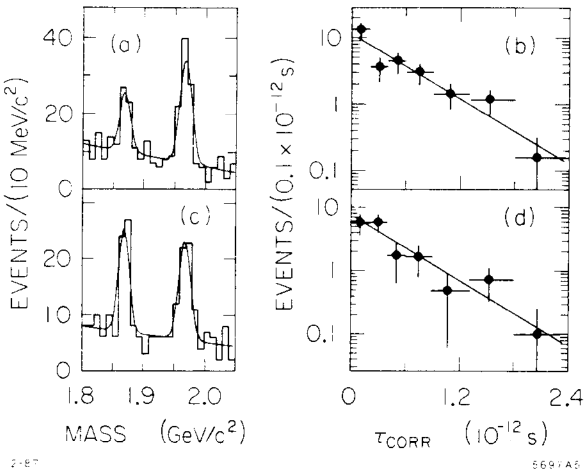

Fig. 6. E-691: Effective mass and decay time distribution for the decays $D_s^+ \to \phi\pi^+$ and $D_s^+ \to \overline{K}^{*o}K^+$.

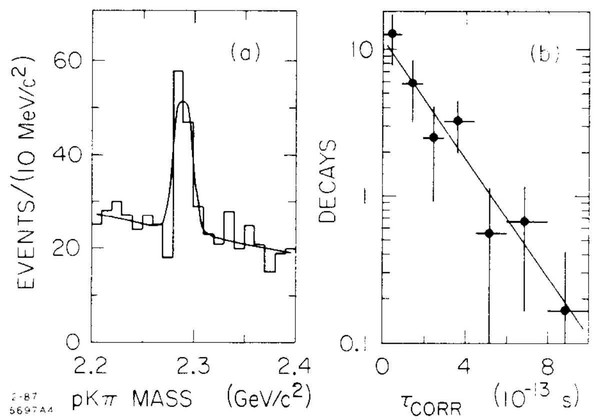

Fig. 7. E-691: Effective mass and decay time distribution for selected Λ_c^+ decays.

The E-400 group at Fermilab presented a first result on the production and lifetime of the Ξ_c^+ (csu) baryon at this conference.[32] The data were recorded in a high energy neutron beam by a large spectrometer with two magnets and three Cerenkov counters, placed downstream of a segmented target and a vertex detector of Silicon wafers and 9 planes of MWPC with 0.25 mm wire spacing. The resolution of the impact parameter was typically 60 μm, the average error on the longitudinal position of the interaction point was 1 mm. Figure 8 shows the $\Lambda^o K^-\pi^+\pi^-$ effective mass for candidates for the decay of the Ξ_c^+ baryon. For these candidates, the $K\pi\pi$ vertex is required to be separated by 3σ from the primary vertex and the Λ^o momentum has to exceed the momentum of both pions and point back to the secondary vertex. The mass distribution shows two narrow peaks, separated by 72 ± 8 MeV/c^2. There are 32 ± 8 and 27 ± 11 events in two peaks. They are interpreted as two Cabibbo-favoured decays, $\Xi_c^+ \to \Lambda^o K^-\pi^+\pi^-$ and $\Xi_c^+ \to \Sigma^o K^-\pi^+\pi^-$. The separation of the two peaks corresponds to the energy of the missing photon from the decay $\Sigma^o \to \Lambda^o\gamma$. A maximum likelihood for a sum of a polynomial background and two Gaussian peaks yields a Ξ_c^+ mass of 2448 ± 5 MeV/c^2. The uncertainty of the absolute mass scale is estimated to be 30 MeV/c^2. The average lifetime for all decays was determined from a comparison of signal and background events with Monte Carlo simulations, the result,

$$\tau(\Xi_c^+) = 6.2 \pm^{1.8}_{1.6} \cdot 10^{-13} \text{ s},$$

compares well with an earlier measurement from the CERN hyperon experiment.[33]

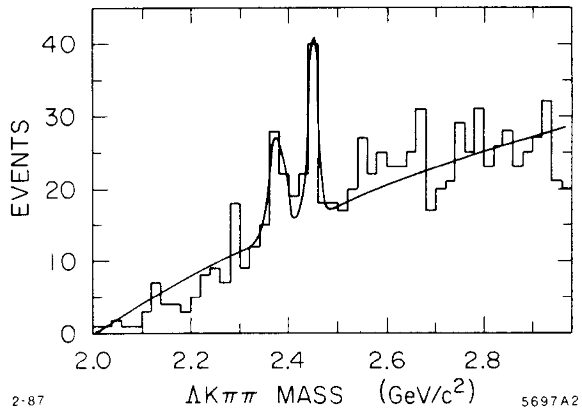

Fig. 8. E-400: Effective mass of candidates for the decays of the Ξ_c^+ baryon. The curve represents the result of a maximum likelihood fit taking into account the experimental resolution.

3.4 e^+e^- Experiments

The advantage of e^+e^- experiments is the fact that 45% of the hadronic final states contain heavy flavour particles, and clean samples of charm particle decays can be obtained on the basis of kinematics alone, avoiding losses at short decay distances.

The DELCO group has published[34] a measurement of the D^0 lifetime based on the measurement of the impact parameter of the K^- and π^+ relative to the beam centre that is monitored by a set of four electrodes placed inside the vacuum chamber. A multi-cell Cerenkov counter and a very loose cut on the $D^{*+} - D^0$ mass difference are employed to select the decay modes $D^0 \to K^-\pi^+ +$ neutrals. The average impact parameter of 151.7 ± 42.5 μm translates to a lifetime $\tau(D^0) = 4.6 \pm 1.5 \pm^{0.7}_{0.6} \cdot 10^{-13}$ s. Systematic studies show that the measurement is largely bias free and insensitive to small errors in alignment or resolution.

The Mark II collaboration[35] recently published a measurement of the D^0 and D^+ lifetimes, the HRS,[36-38] TASSO,[39,40] CLEO,[41] and ARGUS[42] groups presented preliminary results on D^0, D^+, and D_s^+ lifetimes at recent conferences. Since space is limited and the analyses are similar for these experiments, only the CLEO analysis will be described in detail. The charged particle tracking in the CLEO detector relies on two cylindrical drift chambers, a 10 layer vertex chamber with a 90 μm resolution and a larger volume chamber with 17 layers and 140 μm resolution. The chambers are operated in a 10 kGauss magnetic field and are instrumented to measure drift time and specific ionization. The extrapolation error for a single high momentum track is approximately 100 μm. Candidates for the following charm meson decay modes are selected (a) $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$, (b) $D^+ \to K^-\pi^+\pi^+$, and (c) $D_s^+ \to \Phi\pi^+$, $\Phi \to K^-K^+$. The kaons are identified by time-of-flight measurements or by dE/dx in the drift chamber gas. Appropriate mass cuts are applied to select the D^{*+} and Φ decays. Additional cuts on the particle momenta and angles further enhance the signals. The decay point of a charm meson candidate is determined as the fitted intersection of all charged secondaries. The fitting procedure incorporates the uncertainties due to multiple scattering, spatial resolution and track finding, and only vertices with χ^2/dof less than 6 are retained. The decay length is measured as the distance between the fitted decay vertex and the average beam position, which is monitored on a run-by-run basis. The size of the interaction region is 150 μm (FWHM) in the vertical and 1200 μm (FWHM) in the horizontal plane. The decay lengths are converted to proper flight distances $c\tau$ using the measured momenta. In Figure 9 the distributions in effective mass and decay distance are shown for the three decay modes measured by the CLEO collaboration. There are 247 D^0, 317 D^+ and 87 D_s^+ decays above backgrounds of 28, 279, and 54, respectively. Although the measurement of the decay distances is limited by the detector resolution and the beam size, the displacement of the nearly Gaussian distributions to positive values is apparent. The observed distributions are fitted to a sum of two contributions, the charm particle decay distribution and the background distribution. The background contribution is measured separately from candidate decays that pass all the selection criteria except for having an invariant mass outside the signal region. Their decay time distributions are centred on zero (within errors). The results are still preliminary, $\tau(D^0) = 5.0 \pm 0.7 \pm 0.4 \cdot 10^{-13}$ s, $\tau(D^+) = 11.4 \pm 1.6 \pm 1.0 \cdot 10^{-13}$ s, and $\tau(D_s^+) = 4.6 \pm 2.1 \pm 0.5 \cdot 10^{-13}$ s. The systematic errors include the uncertainties in the detector resolution, the background subtraction, and the beam position. The lifetime ratios are

$$\tau(D^+)/\tau(D^0) = 2.3 \pm 0.5 \qquad \text{and} \qquad \tau(D_s^+)/\tau(D^0) = 0.9 \pm 0.5.$$

2.5 Summary on Charm Particle Lifetimes

A compilation of lifetime measurements of charm mesons is given in Table III. There are now 16 experiments contributing 2414 D^0, 1743 D^+, and 320 D_s^+ decays, substantially more than a year ago. The improvement is mainly due to the high statistics, high resolution results from the E-691 experiment at Fermilab. In attempting to combine the available information, averages and combined errors have been calculated. All individual results, whether final or preliminary, have been weighted by the inverse square of the fractional error, a recipe that in the limit of perfect resolution and negligible acceptance corrections corresponds to the number of events in the sample, which is the correct weight for an exponential distribution. (For large Gaussian errors like in e^+e^- experiments, however, the inverse square of the total error is the more appropriate weight.) Using the combined statistical and systematic errors quoted, the best estimate for the lifetime of the charmed mesons are, in units of 10^{-13} s,

$$\tau(D^0) = 4.42{\pm}^{0.15}_{0.14}\ , \qquad \tau(D^+) = 10.3 \pm 0.4\ , \qquad \tau(D_s^+) = 4.4\ {\pm}^{0.5}_{0.4}\ .$$

The lifetime for the charged and neutral D mesons are clearly different, the average

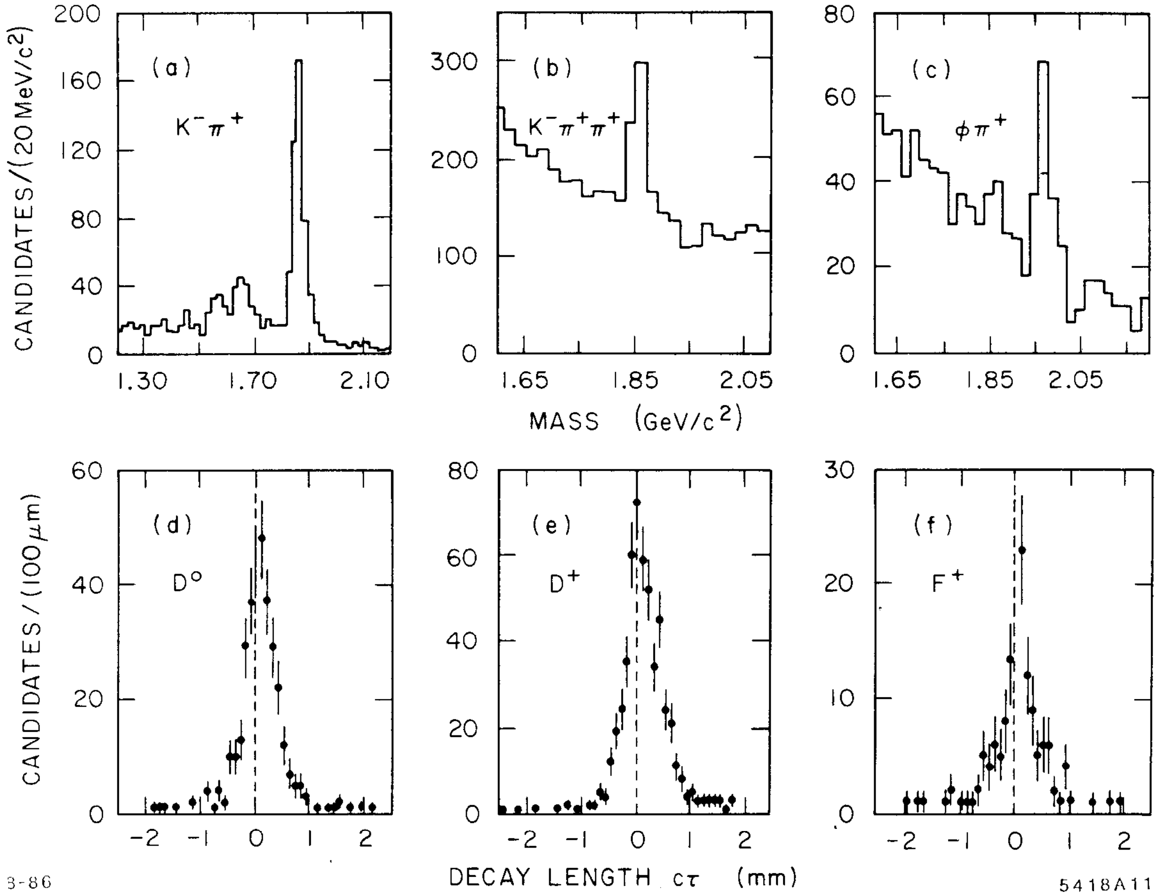

Fig. 9. CLEO: Effective mass and decay length distributions for D^0, D^+ and D_s^+ decays.

of the ratio measured by individual experiments is

$$\tau(D^+)/\tau(D^0) = 2.27 \pm 0.13 \ .$$

This average is strongly affected by the very low ratio of $1.4 \pm 0.3 \pm^{0.2}_{0.1}$ from the photo-production experiment using the SLAC Hybrid Facility. If we exclude this measurement – though there is no good reason – the average of this ratio increases to 2.40 ±0.13. The D^+/D^0 lifetime ratio can also be inferred from the semi-leptonic branching ratios. The Mark III group[43] has reported $BR(D^+ \to e^+X) = 0.170 \pm 0.019 \pm 0.007$, and $BR(D^0 \to e^+X) = 0.075 \pm 0.011 \pm 0.004$, and the ratio $BR(D^+ \to e^+X)/BR(D^0 \to e^+X) = 2.3 \pm^{0.5}_{0.4} \pm 0.1$, in agreement with the ratio from the direct measurements. Since the purely leptonic widths of the charm mesons are negligible and the semi-leptonic partial widths of the D^0 and D^+ should be nearly equal (unless Cabibbo-suppressed processes play a major role in D^+ decay), a difference in the lifetime and semi-leptonic branching ratios implies a difference in the non-leptonic width of the two states. Numerous theoretical explanations have been proposed to either enhance the D^0 or suppress the D^+ hadronic width and they were discussed at length at this conference. A resolution of this and other questions will require detailed study of exclusive decay modes.

Table III: Measurements of Lifetimes of Charmed Mesons

Experiment	Ref.	D^+ Decays	D^+ $\tau(10^{-13}$ s)	D^0 Decays	D^0 $\tau(10^{-13}$ s)	D_s^+ Decays	D_s^+ $\tau(10^{-13}$ s)
E-531	13	23	$11.1\pm^{4.4}_{2.9}$	58	$4.3\pm^{0.7}_{0.5}\pm^{0.1}_{0.2}$	6	$2.6\pm^{1.6}_{1.1}$
WA-58	14	27	$5.0\pm^{1.5}_{1.0}\pm1.9$	44	$3.6\pm^{1.2}_{0.8}\pm0.7$		
SHF	15	48	$8.6\pm1.3\pm^{0.7}_{0.3}$	50	$6.1\pm0.9\pm0.3$		
NA-16	16	15	$8.4\pm^{3.5}_{2.2}$	16	$4.1\pm^{1.3}_{1.0}$		
NA-18	17	7	$6.3\pm^{4.9}_{2.3}\pm1.5$	9	$4.1\pm^{2.6}_{1.3}\pm0.5$		
NA-27	18	40	$10.7\pm^{2.8}_{1.8}$	60	$4.1\pm^{0.7}_{0.6}$		
NA-1	21,22	98	$9.5\pm^{3.1}_{1.9}$	51	$4.3\pm^{1.4}_{0.9}$		
NA-11	23,24	28	$10.6\pm^{3.6}_{2.4}\pm1.6$	26	$3.7\pm^{1.0}_{0.7}\pm0.5$	9	$3.2\pm^{1.5}_{1.0}$
	25	69	$11.2\pm^{1.6}_{1.3}\pm0.8$				
NA-32	26,27	42	$9.8\pm^{1.9}_{1.5}$	42	$3.9\pm^{0.6}_{0.5}$	12	$3.4\pm^{1.3}_{0.9}$
E-691	29,30	969	$10.6\pm0.5\pm0.3$	1360	$4.35\pm0.15\pm0.10$	99	$4.8\pm^{0.6}_{0.5}\pm0.2$
DELCO	34				$4.6\pm1.5\pm^{0.7}_{0.6}$		
MKII	35	16	$8.9\pm^{3.8}_{2.7}\pm1.3$	66	$4.7\pm^{0.9}_{0.8}\pm0.5$		
HRS	36,37,38	114	$8.1\pm1.2\pm1.6$	53	$4.2\pm0.9\pm0.6$	13	$3.5\pm^{2.4}_{1.8}\pm0.9$
TASSO	39,40			13	$4.3\pm^{2.0}_{1.4}\pm0.8$	7	$3.4\pm^{2.9}_{1.6}\pm0.7$
CLEO	41	247	$11.4\pm1.6\pm0.7$	317	$5.0\pm0.7\pm0.4$	87	$4.6\pm2.2\pm0.5$
ARGUS	42			249	$4.89\pm0.65\pm0.60$	86	$4.4\pm1.4\pm1.0$
Total		1743	$10.29\pm^{0.44}_{0.40}$	2414	$4.42\pm^{0.15}_{0.14}$	319	$4.37\pm^{0.48}_{0.38}$

Measurements of the D_s^+ lifetime have in the past suffered from extremely low statistics and the contamination from D^+ and Λ_c^+ decays. New data from the fixed target experiments E-691 and NA-32 show that the D_s^+ and D^0 lifetimes are comparable.

Among the ten $J^P = 1/2^+$ charmed baryon states predicted by SU_4 only the lowest mass state, Λ_c^+ (cud),* is well established at a mass of 2285.6±1.8 MeV/c^2.[44] Five experiments have contributed to the measurement of the Λ_c^+ lifetime, in particular NA-32 with high resolution data recorded with a set of CCDs. The CERN hyperon experiment WA-62[45] was the first to present evidence for the strange charm baryons Ξ_c^+ (csu) at a mass of 2460 ± 15 MeV/c^2 and Ω_c^0 (css) at 2740 ± 10 MeV/c^2. The experimenters observe a clear shift to positive values in the background subtracted decay length distribution for the decay $\Xi_c^+ \to \Lambda^0 K^- \pi^+ \pi^+$. A fit yields $\tau(\Xi_c^+) = 4.8 \pm^{2.1}_{1.0} \pm^{2.0}_{1.0} \cdot 10^{-13}$ s. The three reconstructed decays $\Omega_c^0 \to \Xi^- K^- \pi^+ \pi^+$

* The quark contents of the hyperon states is indicated to explain the nomenclature.

have an average decay time of $7.9 \pm 2.8 \pm 2.0 \cdot 10^{-13}$ s. Theoretical estimates for the ratio of the Ξ_c^+ to Λ_c^+ lifetimes vary between two and four.[46]

Table IV: Measurements of Lifetimes of Charmed Baryons

		Λ_c^+		Ξ_c^+		Ω_c^o	
Experiment	Ref.	Decays	$\tau(10^{-13}$ s)	Decays	$\tau(10^{-13}$ s)	Decays	$\tau(10^{-13}$ s)
E-531	13	13	$2.0\pm^{0.7}_{0.6}$				
WA-58	14	11	$2.3\pm^{0.9}_{0.6}\pm0.4$				
NA-27	22	9	$1.2\pm^{0.5}_{0.3}$				
NA-32	28	14	$1.4\pm^{0.5}_{0.3}\pm0.3$				
E-691	31	65	$2.0\pm^{0.5}_{0.4}\pm0.3$				
E-400	32			59	$6.2\pm^{1.8}_{1.6}$		
WA-62	33,44			82	$4.8\pm^{2.1}_{1.0}\pm^{2.0}_{1.0}$	3	$7.9\pm2.8\pm2.0$
Total		112	$1.8\pm^{0.3}_{0.2}$	141	$5.7\pm^{1.6}_{1.1}$	3	7.9 ± 3.4

4. Lifetimes of Beauty Particles

It has been four years since the MAC[47] and Mark II[48] collaborations first reported lifetimes of beauty particles in the range of 10^{-12} sec, substantially longer than anticipated. These first measurements were confirmed by other experiments at PEP and PETRA, and now updates of earlier results with additional data, improved detectors and refinements in the analysis are available. Recent measurements from the four PEP experiments are shown in Figure 10.

The MAC collaboration[49] has completed an analysis based on the total data sample collected at PEP, 30% of which was recorded with a high resolution vertex detector. This device was installed on the outside of a vacuum pipe of 3.5 cm radius, and consists of 6 layers of thin-walled tubes counters and is operated at a pressure of 4 atmospheres. Each tube provides a position measurement with a resolution of 50 μm. The error on the impact parameter was improved from 350 μm for data recorded without the vertex chamber to 90 μm for the data with the vertex chamber. Multiple scattering contributes 360 μm/p(GeV) and 65 μm/p(GeV), respectively, to these errors. Hadronic events containing beauty particles were tagged by a muon or electron with a large transverse momentum, with respect to the thrust axis. The sample consists of 462 events, 152 with the vertex chamber in operation, and is expected to contain 70% $b\bar{b}$ and 16% $c\bar{c}$ events. The impact parameters of all well-measured tracks with momentum above 0.5 GeV/c were measured in the plane transverse to the beam. There are 1558 and 441 tracks in the two data samples with impact parameters of less than 4 mm and 3 mm, respectively. The B production point was determined from remaining tracks in the event. This reduces the uncertainty in the impact parameter by about a factor of three compared to the

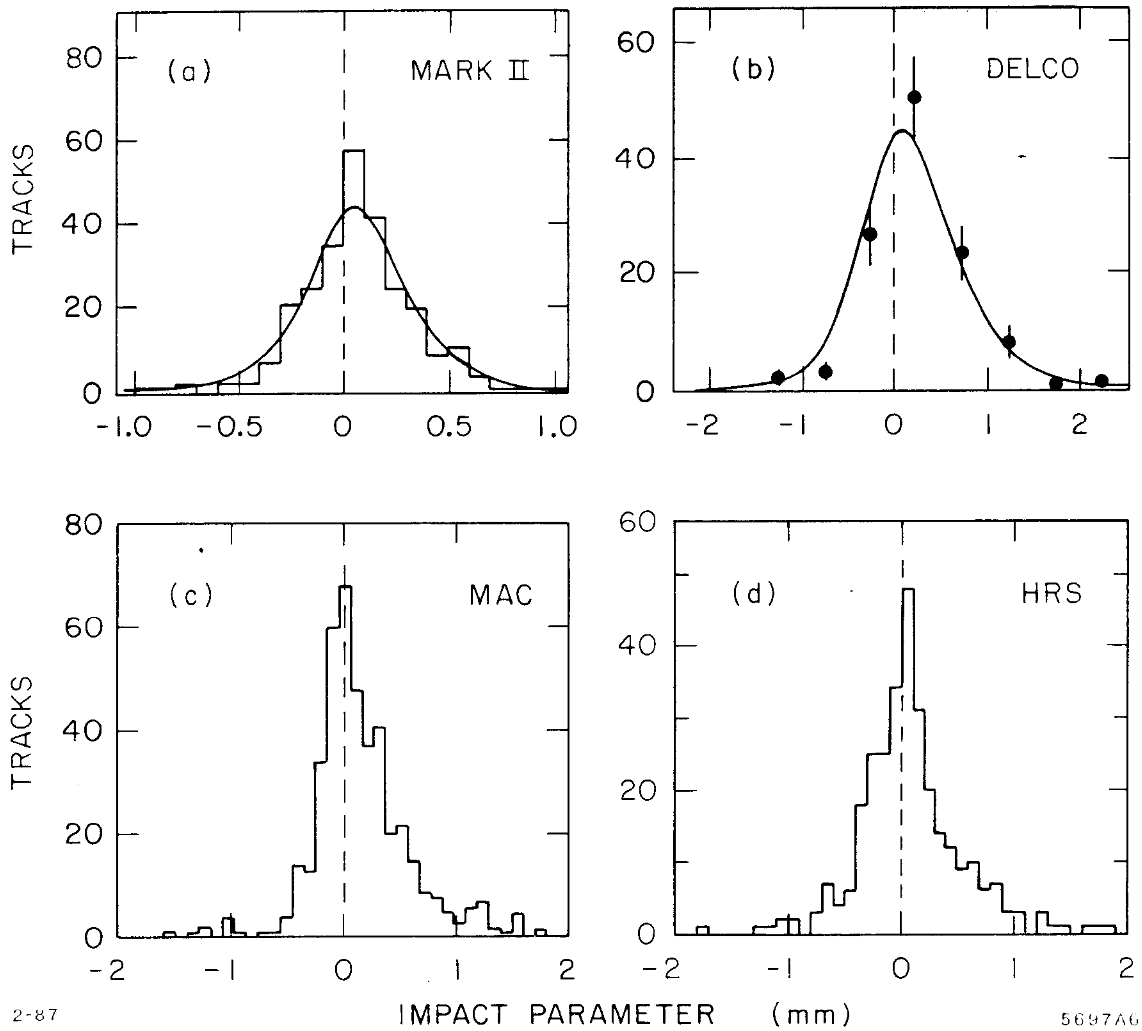

Fig. 10. Measurements of the beauty lifetime: Impact parameter distributions of the four PEP experiments.

measurement relative to the beam centre. The more precise vertex chamber data show not only a positive displacement, but also a clear tail on the positive side. To provide a robust and precise measure of this distribution the means were determined after 10% of the tracks were removed symmetrically from the tails. The trimmed means are 154 ± 20 μm for the early data and 129 ± 14 μm for the vertex chamber data. B lifetimes were obtained by adjusting its value in the Monte Carlo simulation to reproduce the measured trimmed means. The results are $\tau(B) = 1.24 \pm 0.29$ ps and $\tau(B) = 1.35 \pm 0.30$ ps, for the two subsamples, and for the total sample the lifetime is

$$\tau(B) = \{1.29 \pm 0.20(stat) \pm 0.07(syst)\} \cdot (1.00 \pm 0.15) \text{ ps.}$$

The complete electron sample yields 0.92±0.35 ps, while the muon data yield 1.30±0.25 ps. The systematic error has been separated into an additive term and an overall scale factor. The uncertainty in the trimmed mean of the impact parameter distribution is mainly due to the uncertainty in the B fragmentation. This is estimated to cause a 10% error in the overall scale. The uncertainty in the purity of the sample arises from errors in the measured leptonic branching ratios and detection efficiencies, it is estimated to contribute $\pm 7\%$. The uncertainty in the determination of the B production point adds $\pm 7\%$ to the scale error. Present uncertainties in the lifetimes of the charm particles contribute only ± 0.05 ps to the systematic error.

The excellent electron identification of the DELCO experiment[50] leads to a very clean $b\bar{b}$ sample, and allows for a looser cut on the lepton transverse momentum, namely 1 GeV/c. The impact parameter for the 113 electron tracks is measured relative to the beam centre, the average is 259 ± 49 μm The B lifetime is determined from a maximum likelihood fit taking into account the measured resolution, including the non-Gaussian tails, the measured contributions from charm and background events in the sample, and the ± 3 mm cut on the impact parameter. The principle systematic errors arise from the uncertainty in the experimental resolution, $\pm^{0.07}_{0.04}$ ps, the fragmentation function and leptonic branching ratios, $\pm^{0.07}_{0.12}$ ps, and the Monte Carlo modelling of the jet axis, $\pm^{0.03}_{0.00}$ ps. The authors choose to add these errors linearly, leading to a result on the average B lifetime of

$$\tau(B) = 1.17 \pm^{0.27}_{0.22} \pm^{0.17}_{0.16} \text{ ps.}$$

The Mark II group[51] has tripled the data sample since its first publication. The analysis is very similar to that of the DELCO group. A final publication with substantially improved resolution is in preparation.

The HRS group[52] has just completed the B lifetime analysis. They measure an average impact parameter of 80 ± 27 μm for 301 electrons with high transverse momentum.

The JADE experiment,[53] combines dE/dx information from the drift-chamber with the lead glass signals associated with a track to obtain good electron identification. In addition, the group eliminates three-jet events to reduce the contamination of the electrons by high p_t hadrons and to assure a correct determination of the thrust axis. The lifetime is derived from the average impact parameter by comparison with Monte Carlo simulated events.

The TASSO collaboration[54] has recently presented an update on their B lifetime measurement based on twice the number of events previously published.[55] The $b\bar{b}$ events are selected by a cut on the product of the sphericities of the two jets in a frame that approximates the rest frame of the produced B mesons. This technique gives a higher efficiency but lower purity than the selection of leptons with high transverse momentum. The impact parameter distribution of all tracks in the B enriched sample shows a marked excess at positive values compared to the B depleted sample. The average B lifetime is determined by comparing the average impact parameter of 91 ± 17 μm with the Monte Carlo predictions for different $\tau(B)$. The systematic error is dominated by the uncertainty in the purity of the sample.

In addition the TASSO group explored two other methods to determine the decay distance in B decay, using only the more recent data with the vertex drift chamber in operation. The new measurements are not independent, because they are based on the same data and the same Monte Carlo programs. For both of these methods no particular cuts were applied to select $b\bar{b}$ events, but the complete hadron sample was included. Consequently, these measurements rely on a Monte Carlo simulation to reproduce the B decay multiplicities and fragmentation as well as the detector resolution and details of the track fitting. The main systematic errors stem from the uncertainties in this simulation. The results are still preliminary and should be considered as a check and confirmation of the impact parameter measurement.

The first method selects the best 3-prong vertex in each jet and calculates the decay length using the sphericity axis as the approximate B direction. There are 3106 vertices, the mean decay length is 141 ± 16 μm. A Monte Carlo prediction with the B lifetime and fragmentation function as free parameters is adjusted to fit the measured distribution. The fit yields $\tau(B) = 1.50 \pm^{0.37}_{0.29} \pm 0.29$ ps.

In the second method the decay vertex is defined as the weighted mean intersection of all tracks in each jet with the sphericity axis. In addition to the track error and angle, its rapidity is used as a weight to enhance to the contribution from high momentum tracks. The dipole moment is defined as the weighted distance between the vertices of the two jets. On the average 8 tracks per event, with an impact parameter resolution of typically 200 μm, are used. The measured distribution for 4874 events has a mean of 328 ± 28 μm. The lifetime is estimated to be $\tau(B) = 1.62 \pm^{0.33}_{0.29} \pm 0.25$ ps.

A compilation of the six recent measurements of the average lifetime of B hadrons produced in e^+e^- annihilation is given in Table V. The experiments agree very well, though the systematic errors remain substantial because of uncertainties in the sample purity, resolution, fragmentation and decay of B hadrons. Many features of the modelling of the hadronic final states are common among the experiments, as are some aspects of detector design and analysis, leading to errors that are not totally independent. The weighted average of the measurements is

$$\tau(B) = 1.17 \pm 0.14 \cdot 10^{-12} \text{ s.}$$

The only information on the lifetimes of individual B mesons has been obtained by the CLEO collaboration.[56] The number of di-lepton events from B-decays translates to a limit $0.48 < \tau(B^0)/\tau(B^+) < 1.9$.

The B lifetime can be related to the Cabibbo-Kobayashi-Maskawa matrix elements V_{cb} and V_{ub} which represent the coupling of the b quark to charged weak

Table V: Measurements of the Average Lifetimes of Beauty Particles

	MARK II	MAC	DELCO	HRS	JADE	TASSO
Luminosity pb^{-1}	200	220	214	200	63	25
Vertex Chamber Inner Radius (cm)	10.1	4.8	12.1	9.0	40.0	8.1
ID Lepton e	Pb/LA	Pb/Gas	Cerenkov	Pb/Scint.	Pb/Glass	Pb/LA
μ	Fe	Magn. Fe			Fe	Fe
Cuts p (GeV/c)	2.0	2.0	1.0	2.0	2.0	
p_t (GeV/c)	1.5	1.5	1.0	1.5	1.8	
# Leptons	284	561	113	301	113	
Signal Fraction	0.64	0.70	0.79	0.53	0.75	0.30
Resolution (μm)	90	50	150	100	450	140
Impact Parameter (μm)	80±17	129±19	249±49	80±27	282±66	92±17
Lifetime (10^{-12}s)	0.85 ± 0.17	1.29 ± 0.20	$1.17\ ^{+0.27}_{-0.22}$	$1.02\ ^{+0.41}_{-0.37}$	$1.80\ ^{+0.51}_{-0.30}$	1.57 ±0.32
Syst. Error	±0.21	±0.17	$^{+0.17}_{-0.16}$		±0.40	$^{+0.37}_{-0.34}$

current, in particular,

$$1/\tau_b = [A \cdot |V_{cb}|^2 + B \cdot |V_{ub}|^2] \ / \ BR(b \to Xe\nu) \ \cdot \ 10^{14} \ \mathrm{sec}^{-1},$$

where the coefficients depend on the quark masses m_u, m_c, m_b and QCD corrections. They have been calculated and reproduce the lepton spectra in semileptonic decays of charm and beauty mesons, $A = 0.58$ and $B = 1.18$.[57] Using the average of the semi-leptonic branching ratios of B mesons of $(11.8 \pm 0.3 \pm 0.6)\%$[58] one obtains

$$\tau_b = [4.9 \cdot |V_{cb}|^2 + 10.0 \cdot |V_{ub}|^2]^{-1} \ \cdot \ 10^{-14} \ \mathrm{sec}.$$

In the limit of no $b \to u$ transitions one obtains

$$|V_{cb}| = 0.044 \pm 0.003 \pm 0.005,$$

where the first error quoted represents the experimental, the second the theoretical uncertainties. Based on the conservative limit on the $b \to u$ transitions presented here by the CLEO group, we obtain

$$|V_{ub}| < 0.012 \qquad (90\% \ \mathrm{C.L.}).$$

With this additional input and the unitarity condition, the absolute values of all elements of the Cabibbo-Kobayashi-Maskawamatrix can be determined or severely constrained. In fact, the matrix becomes almost diagonal, and thus there is very little mixing between the second and the third generations of quarks.[59] The small value of $|V_{cb}|$ imposes constraints on the top mass, the ratio ϵ'/ϵ in K^0 decay and CP violation in beauty meson decay.

4. Conclusion

The present status of lifetime measurements of heavy flavour particles can be summarized as follows:

- Lifetimes of different charm particles are different,

$$\tau(D^+) > \tau(D^0) \geq \tau(\Lambda_c).$$

  This observation indicates either problems with the naive parton description including short distance QCD effects or the need for W exchange and annihilation diagrams, or both. There is new information on many exclusive decays available from the Mark III and ARGUS experiments. In particular, the observation of $D^0 \rightarrow K_s\Phi$ supports contributions from W exchange, while the relatively large branching ratios for $D^0 \rightarrow \overline{K}^0\pi^0$ and $D^+ \rightarrow \Phi\pi^+$ suggest the absence of colour suppression. The large rate of $D^+ \rightarrow \overline{K}^0 K^+$ relative to $\overline{K}^0\pi^+$ could be explained by interference in D^+ decay and may be contributing to its reduced hadronic width.

- Six measurements at e^+e^- storage rings agree on an average lifetime of the B hadrons produced of (1.17 ± 0.14) ps. There is still only one directly observed, hadro-produced $B^-\overline{B}^o$ event.[60]

In summary, measurements of charm particle lifetimes have substantially improved over the last year, but orders of magnitude more data are needed to study lifetime of individual charm baryons and beauty mesons. There are many experiments presently under way, NA-14 and NA-32 at CERN, E-653, E-687, E-690 and E-769 at Fermilab, and ARGUS at DESY and CLEO at Cornell. At SLC and LEP substantial production rates and high precision vertex detectors will become available. Thus, before the end of this decade, measurements of heavy quark lifetimes and couplings, possibly including the top, can be expected. It is an enormous effort, but it has been and will continue to be fun!

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