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LIFETIMES OF HEAVY FLAVOUR PARTICLES*

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ABSTRACT

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

1. Introduction

In the past few years, measurements of lifetimes of particles carrying heavy flavour quantum numbers have become a fashionable activity among experimentalists. The theoretical interest in the decay rates of these particles has been discussed at length at this meeting and need not be repeated here. From the point of view of an experimentalist these 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 flavour decays are their small production rates in hadron and photon interactions, and their short decay lengths. 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[1] 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

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impact parameter ρ[2] which is defined as the distance of closest aproach 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 charm and beauty lifetimes will be briefly reviewed, more detailed information about the experiments and earlier results can be found in detailed review articles.[3,4]

2. Lifetimes of Charm Particles

Table I gives a compilation of the experiments measuring lifetimes of the charm mesons D^0, D^+, and F^+ (recently renamed D_s^+), as well as the charm baryon Λ_c^+.* The experiments are grouped as to the apparatus used for vertex detection.

Table I: Measurements of Lifetimes of Charmed Particles

		D^+		D^0		F^+		Λ_c^+	
Experiment	Ref	Decays	$\tau(10^{-13}s)$	Decays	$\tau(10^{-13}s)$	Decays	$\tau(10^{-13}s)$	Decays	$\tau(10^{-13}s)$
E-531	5	23	$11.1\pm^{4.4}_{2.9}$	58	$4.3\pm^{0.7}_{0.5}\pm^{0.1}_{0.2}$	6	$2.6\pm^{1.6}_{1.1}$	13	$2.0\pm^{0.7}_{0.6}$
WA-58	6	27	$5.0\pm^{1.5}_{1.0}\pm1.9$	44	$3.6\pm^{1.2}_{0.8}\pm0.7$			11	$2.3\pm^{0.9}_{0.6}\pm0.4$
SHF	7	48	$8.6\pm1.3\pm^{0.7}_{0.3}$	50	$6.1\pm0.9\pm0.3$				
NA-16	8	15	$8.4\pm^{3.5}_{2.2}$	16	$4.1\pm^{1.3}_{1.0}$			4	$1.9\pm^{1.4}_{0.7}$
NA-18	9	7	$6.3\pm^{4.9}_{2.3}\pm1.5$	9	$4.1\pm^{2.6}_{1.3}\pm0.5$				
NA-27	10	147	$10.6\pm^{1.3}_{0.9}$	129	$4.2\pm^{0.5}_{0.4}$				
NA-1	11,12	98	$9.5\pm^{3.1}_{1.9}$	51	$4.3\pm^{1.4}_{0.9}$				
NA-11	13,14	28	$10.6\pm^{3.6}_{2.4}\pm1.6$	26	$3.7\pm^{1.0}_{0.7}\pm0.5$	12	$3.1\pm^{1.2}_{0.8}$		
	15	69	$11.2\pm^{1.6}_{1.3}\pm0.8$						
NA-32	16,17,18	42	$9.6\pm^{1.9}_{1.5}$	42	$3.9\pm^{0.6}_{0.5}$	10	$4.3\pm^{1.9}_{1.2}$	11	$1.6\pm^{0.7}_{0.4}\pm0.3$
E-691	19	480	$10.9\pm^{0.8}_{0.7}\pm0.6$	672	$4.4\pm0.2\pm0.2$	35	$4.2\pm^{0.9}_{0.7}\pm0.6$		
DELCO	20				$4.6\pm1.5\pm^{0.7}_{0.6}$				
MKII	21	16	$8.9\pm^{3.8}_{2.7}\pm1.3$	66	$4.7\pm^{0.9}_{0.8}\pm0.5$				
HRS	22,23,24	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	25,26			13	$4.3\pm^{2.0}_{1.4}\pm0.8$	7	$3.4\pm^{2.9}_{1.6}\pm0.7$		
CLEO	27	247	$11.4\pm1.6\pm1.0$	317	$5.0\pm0.7\pm0.4$	37	$4.6\pm2.1\pm0.5$		
Total		1361	$10.29\pm^{0.54}_{0.43}$	1546	$4.43\pm^{0.19}_{0.17}$	170	$3.85\pm^{0.65}_{0.48}$	39	$1.8\pm^{0.4}_{0.3}$

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

2.1 *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 their total data samples recorded many years ago.

The E-531[5] 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 F^+, 13 unique Λ_c, and 28 decays that are consistent with D^+, but also compatible with the kinematics of F^+, and/or Λ_c decay. This Λ_c^+ and F^+ 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

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

The lifetime ratio is calculated to be $2.6 \pm^{1.1}_{0.8}$. The average lifetimes of the fitted F^+ 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[6] group exposed a thin emulsion target to a photon beam at the CERN SPS. Their results, listed in Table I, 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. Furthermore, the limited thickness of this emulsion stack leads to substantial corrections for detection losses at proper times exceeding $3 \cdot 10^{-13}$ s.

2.2 *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 tested in the 15ft bubble chamber.

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† If there are two errors are quoted, the first represents the statistical, the second the systematic uncertainty.

The NA-27 group used the hydrogen bubble chamber, LEBC, in the European Hybrid Spectrometer and has just completed the analysis of data recorded in a 360 GeV π^- and 400 GeV proton beam.[10] 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 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 for the π^- beam data are shown in Figure 1.

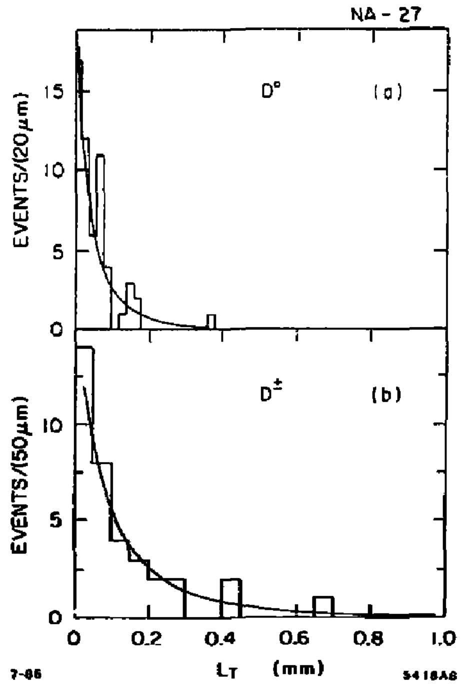

Fig. 1. NA-27: Transverse decay length distributions for selected D meson decays from the π^- data.

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 to the combined π^- and proton data sample gives

$$\tau(D^0) = 4.2 \pm^{0.5}_{0.4} \cdot 10^{-13}\ s \qquad \text{and} \qquad \tau(D^+) = 10.6 \pm^{1.3}_{0.9} \cdot 10^{-13}\ s.$$

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 F^+ or Λ_c^+ contamination. The ratio of D^+ to D^0 lifetimes is 2.5±0.4.

2.3 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[11,12] uses a target made of 40 silicon wafers, 300μm thick and spaced by 100μm, 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 $D^{*+} \to D^0\pi^+$ 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 5μm per plane.[13] 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 $D^+ \to \overline{K}^{*0}(890)\ e^+\nu_e$.[14] 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 $D^+ \to K^-\pi^+\pi^+$ 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.[19] 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 results are shown in Figure 2. 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

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

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

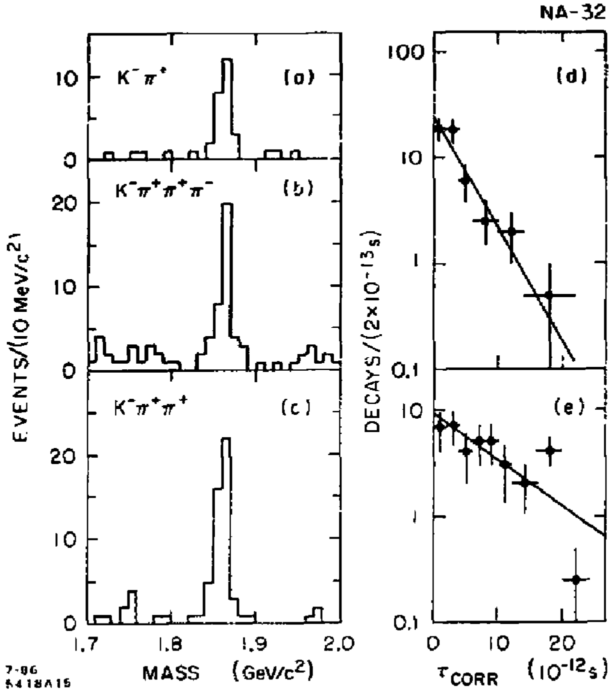

Fig. 2. NA-32: Effective mass and corrected decay time distributions for the selected D mesons.

The NA-32 group[17] has applied the same analysis to search for the decay $F^+ \to K^-K^+\pi^+$ and finds 10 events above a background of less than one. The mass is 1973± 2.1 MeV/c². Due to ambiguities in the kaon and proton identification a few events are compatible with the decay modes $D^+ \to K^-\pi^+\pi^+$ or $\Lambda_c^+ \to K^-p\pi^+$. They are excluded from the sample. A fit to the corrected decay time distribution gives $\tau(F^+) = 4.3 \pm^{1.9}_{1.2} \cdot 10^{-13}$ s. If we combine these 10 decays with the 12 decays observed by NA-11 in the same detector the lifetime is

$$\tau(F^+) = 3.6 \pm^{1.1}_{0.7} \cdot 10^{-13}\ s.$$

In 1985 the NA-32 collaboration[18] improved the resolution and granularity of the vertex detector by the installation of two CCDs at a distance of 10 mm and 20 mm from a thin 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 F and Λ_c signals by about a factor of 12. This is the first use of Charged Coupled Devices as tracking detectors for minimum ionising particles. At present roughly 50% of the 5.8 million triggers have been processed, and the results are to be considered as preliminary. Figure 3c shows a decay $\Lambda_c^+ \to pK^-\pi^+$ as observed in the two CCDs. In spite of a track density of 2 hits/mm^2 the decay tracks are clearly separable from the primary tracks. The efficiency of the CCDs was measured to be 95%. There are a total of 11 Λ_c decays, including one background event, centred at a mass of 2285.0 ± 1.3MeV/c^2. The fitted lifetime is

$$\tau(\Lambda_c^+) = 1.6 \pm^{0.7}_{0.4} \pm 0.3 \cdot 10^{-13}\ s.$$

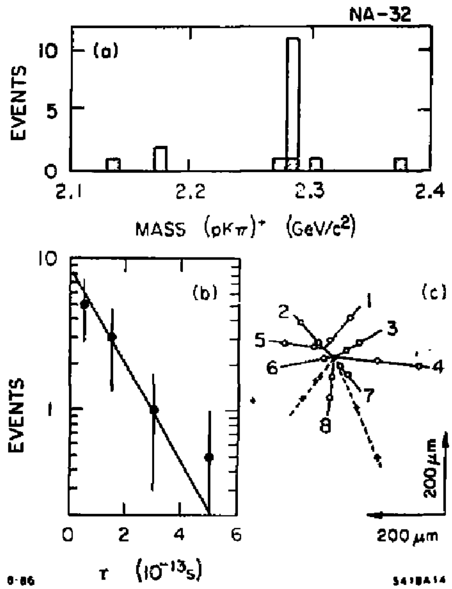

Fig. 3. NA-32: Measurement of the Λ_c lifetime, a) effective mass, b) decay time distribution and c) a display of a single event detected in the CCDs (tracks 1,2,5 result from a Λ_c decay).

At this conference, first results on charm meson lifetimes were reported by the E-691 group from Fermilab. The analysis is based on 15% of a total 10^8 interactions recorded by the Tagged Photon Spectrometer.[19] Inelastic interactions in the 5cm long Beryllium target were selected by a trigger on the transverse energy measured in the downstream calorimeters.

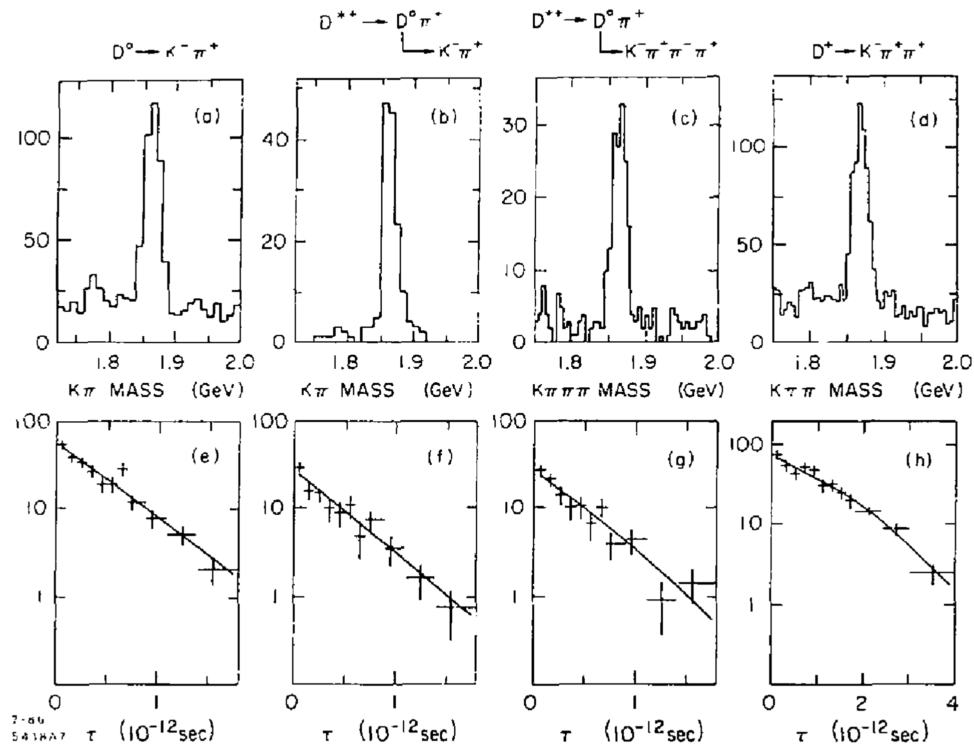

Fig. 4. E-691: Effective mass and decay time distributions for selected D decays.

Three triplets of Silicon strip detectors with 50μm 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 minimise 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 80μm. 3) The decay path was required to be larger than l_{min}. This distance was chosen to be typically 6-10 times the resolution, 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 pulseheights. The resulting four D meson samples are presented in Figure 4. 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 ± 0.015 ps. A global fit to all three subsamples gives

$$\tau(D^0) = 4.4 \pm 0.2 \pm 0.2 \cdot 10^{-13} \text{ s}.$$

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 -0.09 ± 0.04 ps, the background subtraction amounts to 0.20 ± 0.04 ps, and absorption in the target causes a shift by -0.04 ± 0.01 ps. A fit to the data results in a lifetime of

$$\tau(D^+) = 10.9 \pm^{0.8}_{0.7} \pm 0.6 \cdot 10^{-13} \text{ s}.$$

The charged D meson lifetime exceeds the lifetime of the neutral D meson by a factor of $2.5 \pm 0.2 \pm 0.1$.

Table II: Results from Experiment E-691 at FNAL

Decay Mode	Vertex Cut ℓ_{min}/σ_z	Decays	Background	Lifetime ($10^{-13}s$)
$D^o \to K^-\pi^+$ $D^{*+} \to D^o\pi^+$	8	350	165	4.50±0.30
$D^o \to K^-\pi^+$ $D^{*+} \to D^o\pi^+$	5	198	7	4.30±0.35
$D^o \to K^-\pi^+\pi^+\pi^-$	7	123	17	4.20±0.45
$D^+ \to K^-\pi^+\pi^+$	10	480	140	$10.9\pm^{0.8}_{0.7}$
$F^+ \to \phi\pi^+$	6	19	4	$4.0\pm^{1.2}_{0.8}$
$F^+ \to \bar{K}^{*o}K^+$	10	16	7	4.6±1.4

The same data sample was used to study the F^+ lifetime. The F^+ mesons were identified by two different decay modes, $F^+ \to \phi\pi^+ \to K^-K^+\pi^+$ and $F^+ \to \overline{K}^{*0}K^+ \to K^-K^+\pi^+$. The mass spectrum for the $\phi\pi$ sample is shown on Figure 5a. There are two well separated peaks, one from the Cabibbo-suppressed decay of the D^+, the other from the decay of the F^+. Figure 5b gives the decay time distribution for the events in the mass region 1.95-1.98 GeV/c^2.

There are 19 events above a background of 4 events. A similar selection leads to a sample of 16 $\overline{K}^{*0}K^{+}$ decays above a background of 7 events. A maximum likelihood fit to the total sample of 35 F^+ decays gives a mean lifetime of

$$\tau(F^+) = 4.2 \pm^{0.9}_{0.7} \pm 0.6 \cdot 10^{-13}\ s.$$

The estimate of the systematic error is preliminary. It is expected to decrease substantially, once the full sample is available and more detailed studies of the sensitivity of the result to the selection criteria are possible.

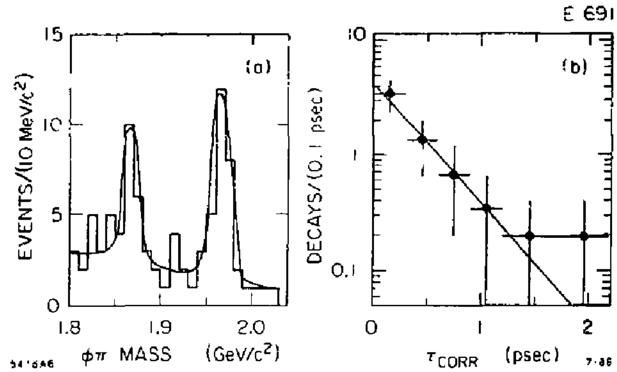

Fig 5. E-691: Effective mass and decay time distribution for the decay $F^+ \to \phi\pi^+$.

2.4 e^+e^- Experiments

Experiments at the storage rings PEP, PETRA, and CESR have increased 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, a major limitation on the lifetime measurements is due to the fact that the production vertex is not observed, but is located anywhere 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 advantage of these experiments is the fact that in e^+e^- annihilation 45% of the 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[20] 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 $151.7 \pm 42.5\mu m$ 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[31] recently completed a measurement of the D^0 and D^+ lifetimes, the HRS,[22-24] TASSO,[25,26] and CLEO[27] groups presented preliminary results on D^0, D^+, and F^+ lifetimes at this summer's conferences. Since space is limited and the analyses are similar for these experiments, only the CLEO analysis will be described in some detail. The charged particle tracking in the CLEO detector relies on two cylindrical drift chambers, a 10 layer vertex chamber with a $90\mu m$ resolution and a larger volume chamber with 17 layers and $140\mu m$ resolution. The chambers are operated in a 10 kGauss magnetic field and are instrumented to measure drift time and specific ionisation. The extrapolation error for a single high momentum track is approximately $100\mu m$. 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) $F^+ \to \Phi\pi^+, \Phi \to K^-K^+$. 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 $150\mu m$ (FWHM) in the vertical and $1200\mu m$ (FWHM) in the horizontal plane. The decay lengths are converted to proper flight distances $c\tau$ using the measured momenta.

In Figure 6 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 F^+ 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 $\tau(F^+) = 4.6 \pm 2.1 \pm 0.5 \cdot 10^{-13}$ s. The systematic errors include the uncertainties in the detector resolution, the background subtraction, and the beam position. The lifetime ratios

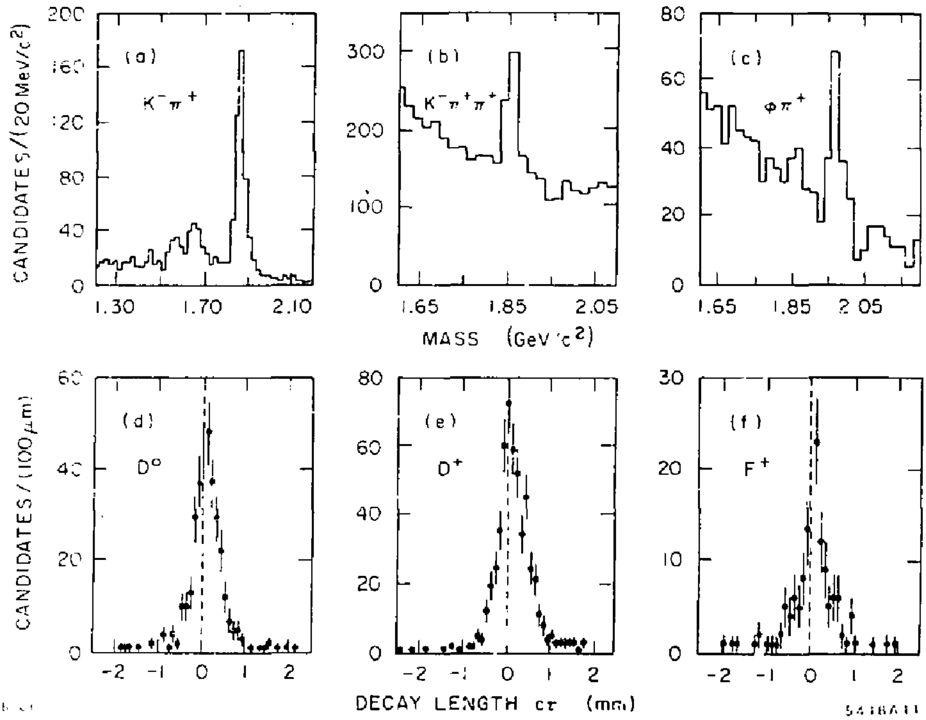

Fig. 6. CLEO: Effective mass and decay length distributions for D^0, D^+ and F^+ decays.

are

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

2.5 Summary on Charm Particle Lifetimes

A compilation of lifetime measurements of charm particles is given in Table I. There are now 16 experiments contributing 1546 D^0, 1361 D^+, 170 F^+, and 39 Λ_c^+ decays, substantially more than a year ago. Major contributions are the high statistics, high resolution results from fixed target experiments at CERN and FNAL, in particular E-691. 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,

$$\tau(D^0) = 4.43\pm^{0.19}_{0.17}, \qquad \tau(D^+) = 10.29\pm^{0.54}_{0.43}, \qquad \tau(F^+) = 3.85\pm^{0.65}_{0.48} .$$

The lifetime for the charged and neutral D mesons are clearly different, the average of the ratio measured by individual experiments is

$$\tau(D^+)/\tau(D^0) = 2.25\pm^{0.15}_{0.14} .$$

This average is strongly affected by the very low ratio of $1.4 \pm 0.3\pm^{0.2}_{0.1}$ from the photoproduction experiment using the SLAC Hybrid Facility. If we exclude this measurement – though there is no good reason – the average of this ratio increases to $2.45\pm^{0.17}_{0.16}$. This means, however, that the remaining eight measurements agree much better than expected from the errors quoted (χ^2/dof=0.15!). The D^+/D^0 lifetime ratio can also be inferred from the semi-leptonic branching ratios. The Mark III group[28] 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.

Measurements of the F^+ 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 F^+ 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.[29] Four 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[30] has presented 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

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

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 $\Omega_c^0 \to \Xi^- K^- \pi^+ \pi^+$ 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.[31]

3. Lifetimes of Beauty Particles

It has been three years since the MAC[32] and Mark II[33] 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.

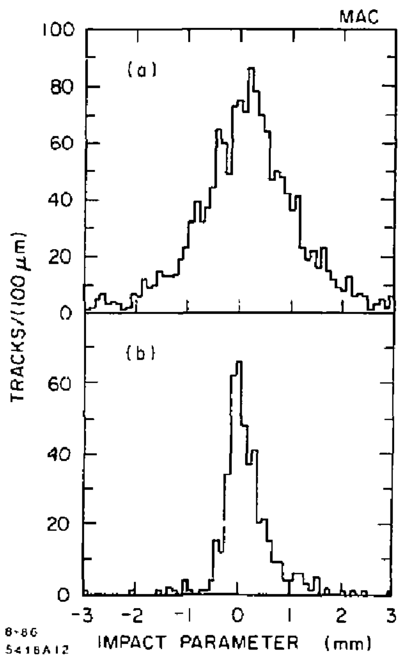

Fig. 7. MAC: Impact Parameter distributions for selected $b\bar{b}$ events recorded a) without and b) with the vertex chamber.

The MAC collaboration[34] 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 50μm. The error on the impact parameter was improved from 350μm for data recorded without the vertex chamber to 90μm for the data with the vertex chamber. Multiple scattering contributes 360μm/p(GeV) and 65μm/p(GeV), respectively, to these errors. Hadronic events containing beauty particles were tagged by a muon or electron with a transverse momentum, with respect to the thrust axis, of more than 1.5 GeV/c. 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 measurement relative to the beam centre. The impact parameter distributions for the selected B samples are shown in Figure 7. 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 $154 \pm 20\mu$m for the early data and $129 \pm 14\mu$m for the vertex chamber data. B lifetimes were obtained by adjusting its value in the Monte Carlo simulation to reproduce the trimmed means in the data. The results are $\tau(B) = 1.14 \pm 0.20$ ps and $\tau(B) = 1.20 \pm 0.24$ ps, for the two subsamples, and for the total sample the lifetime is

$$\tau(B) = \{1.16 \pm 0.16(stat) \pm 0.07(syst)\} \cdot (1.00 \pm 0.15)\ ps.$$

The complete electron sample yields 0.97±0.29 ps, while the muons yield 1.25±0.19 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 ±7%. The uncertainty in the determination of the B production point adds ±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[35] 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±49μm (Figure 8). 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

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

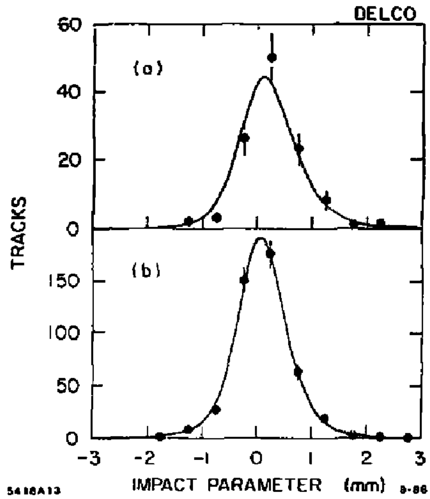

Fig. 8. DELCO: Impact parameter distribution for electrons of a) the $b\bar{b}$ and b) the $c\bar{c}$ sample. The solid curve represents the maximum likelihood fit to the data.

The Mark II group[36] has tripled the data sample since its first publication. They measure an average impact parameter of $80 \pm 17\mu m$ for 282 selected leptons. The analysis is very similar to that of the DELCO group, and a final publication is in preparation.

The Jade Experiment JADE,[37] 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[37] also inserted a precision drift chamber and has recently presented an update on their B lifetime measurement based on twice the number of events previously published.[39] 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 $91 \pm 17 \mu m$ with the Monte Carlo predictions for different $\tau(B)$. The result is listed in Table III. 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. Figure 9a shows this distribution for 3106 vertices, the mean is $141 \pm 16 \mu m$. 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 $328 \pm 28 \mu m$ (Figure 9b). The lifetime is estimated to be $\tau(B) = 1.62 \pm^{0.33}_{0.29} \pm 0.25$ ps.

A compilation of the five recent measurements of the average lifetime of B hadrons produced in e^+e^- annihilation is given in Table III. 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

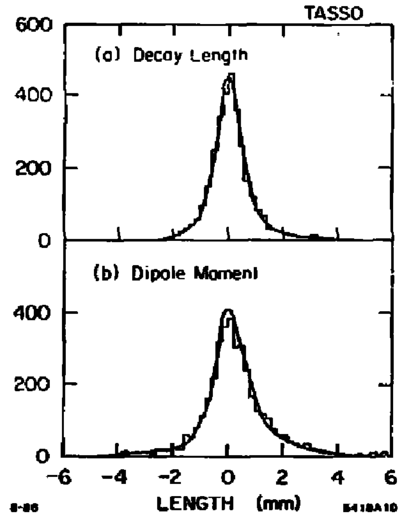

Fig. 9. TASSO: Distribution of a) the "decay length" and b) the "dipole moment". The solid curve shows the result of a Monte Carlo simulation with the B lifetime and fragmentation adjusted to fit the data.

Table III: Measurements of the Average Lifetimes of Beauty Particles

Experiment	Ref.	Decays	Beauty Fraction	Lifetimes ($10^{-12}s$)
JADE	37	99	0.82	$1.80\pm^{0.51}_{0.30}\pm0.40$
Mark II	36	272	0.64	$0.85\pm0.17\pm0.21$
TASSO	38	406	0.30	$1.57\pm0.32\pm^{0.37}_{0.34}$
DELCO	35	113	0.79	$1.17\pm^{0.27}_{0.22}\pm^{0.17}_{0.16}$
MAC	34	562	0.70	$1.16\pm0.16\pm0.17$
Total		1452		$1.13\pm^{0.14}_{0.13}$

analysis, leading to errors that are not totally independent. The weighted average of the measurements is

$$\tau(B) = 1.13 \pm^{0.14}_{0.13} \cdot 10^{-12}\ s.$$

The only information on the lifetimes of individual B mesons has been obtained by the CLEO collaboration.[40] 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 current, in particular,

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

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 $B = 1.18$.[41] Using the average of the semi-leptonic branching ratios of B mesons of $(11.8 \pm 0.3 \pm 0.6)\%$[42] one obtains

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

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, ARGUS and Crystal Ball groups, we obtain

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

With this additional input and the unitarity condition, the absolute values of all elements of the Cabibbo-Kobayashi-Maskawa matrix 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.[43] 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 summarised 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 $D^0 \to K_s\Phi$ supports contributions from W exchange, while the relatively large branching ratios for $D^0 \to \overline{K}^0\pi^0$ and $D^+ \to \Phi\pi^+$ suggest the absence of colour suppression. The large rate of $D^+ \to \overline{K}^0 K^+$ relative to $\overline{K}^0\pi^+$ could be explained by interference in D^+ decay and may be contributing to its reduced hadronic width.

- Five measurements at e^+e^- storage rings agree on an average lifetime of the B hadrons produced of $(1.13\pm^{0.14}_{0.13})$ ps. There is still only one directly observed, hadro-produced $B^-\overline{B}^0$ event.[44]

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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