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LIFETIME OF HEAVY FLAVOUR PARTICLES*

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ABSTRACT

Recent measurements of the lifetimes of the τ leptons and charm and beauty hadrons are reviewed and their significance for the couplings of the charged weak current, flavour mixing, and models relating quark to hadron decay are discussed.

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1. INTRODUCTION

In the past few years, the decay of heavy flavour hadrons and heavy leptons has become a fashionable topic, for theorists and experimentalists alike. The interest in the lifetimes of weakly decaying particles clearly is based on the conceptual simplicity of these decay processes. In the framework of the standard electro-weak theory, the flavour-changing transitions among quarks and among leptons are described by their coupling to the charged weak bosons, $W^{\pm}$. The parton diagrams for heavy leptons or quarks are identical to the muon decay, and thus apart from differences in the couplings of the $W^{\pm}$ to the various partons, decays rates of heavy quarks Q and leptons L are calculable and closely related to muon decay time τ_{μ}, namely

$$\tau_L = 192\,\pi^3/G_F^2 m_L^5\, BR(L^- \to e^- \bar{\nu}_e \nu_L) = \tau_{\mu}(m_{\mu}/m_L)^5\, BR(L^- \to e^- \bar{\nu}_e \nu_L) \qquad (1)$$

$$\tau_Q = \tau_{\mu}(m_{\mu}/m_Q)^5\, BR(Q \to e\nu_e q) / \sum_q |V_{qQ}|^2 \qquad (2)$$

where G_F is the Fermi constant and BR represents the leptonic or semileptonic branching ratios, that can be calculated and that have been measured. This simple relation only holds for free quarks, and in the absence of flavour-mixing and final state corrections due to the light quarks and gluons participating in hadron decay. The differences in the quark couplings to the $W^{\pm}$ are described by the Cabibbo-Kobayashi-Maskawa matrix elements V_{qQ} [1]. In the absence of K-M suppression, the above naive assumptions would result in $\tau_C \approx 8 \cdot 10^{-13}$sec for charm and $\tau_B \approx 2 \cdot 10^{-15}$sec for beauty particles. Precise measurements of lifetimes and branching ratios of heavy leptons, mesons and baryons serve as a test of these simple assumptions and will continue to help in the formulation of theoretical models of weak decay.

In this review, lifetime measurements for the τ lepton, the charm mesons D^0, D^+, and F^+, the charm baryons Λ_c^+, Ξ_c^+, Ω_c^0, and beauty hadrons, presumably B^0 and B^-, are reviewed. Here, and in the following, reference to a particular particle includes its antiparticle, unless explicitly stated, i.e. D^+ stands for D^+ and D^-. For the charm baryons the naming convention suggested by the Particle Data Group[2] has been adopted. The report will begin with an overview over the experimental techniques used.

2. EXPERIMENTAL TECHNIQUES

Clean 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 relatively large transverse momenta of the decay secondaries, and small (and unfortunately mostly not well-known) branching ratios. The weak coupling causes long lifetimes (of order 10^{-13}sec), the emission of leptons $e^{\pm}$, $\mu^{\pm}$, and neutrinos, with large transverse momenta, and strange particle production due to Cabibbo enhancement. The difficulty in detecting these characteristic features is due to the small production rates of heavy flavour particles and to the large multiplicity of the final state at beam energies above 100 GeV. For example in hadroproduction, the cross-section is $\sigma_{CHARM} = 0.001\ \sigma_{INELASTIC}$; more favourable relative rates are observed in photoproduction and high energy ν interactions with $\sigma^{\gamma}_{CHARM} = 0.01\ \sigma^{\gamma}_{HADRON}$ and $\sigma^{\nu}_{CHARM} = 0.1\ \sigma^{\nu}_{HADRON}$, and in particular in e^+e^- annihilation, where 45% of the hadronic final states contain heavy flavour particles.

There are two different methods commonly used to determine lifetimes of short-lived particles. The standard methods is based on a measurement of the decay path and the particle momentum, and thus requires an accurate determination of the production and decay vertices. This method has been used primarily for charm particle lifetimes and has been limited to decay modes that can be fully reconstructed (except for some neutral pions) to allow for the determination of the momentum. The second method relies on the measurement of the so-called impact parameter[3)] which is defined as the distance of closest approach of a decay track to the production vertex. The impact parameter ρ is proportional to the product of the decay length and the decay angle, and thus at sufficiently high energies becomes insensitive to the momentum of the decaying particle. The clear advantage of this technique is that it does not require a fully reconstructed decay or estimate of momentum, and consequently can use individual tracks from hadronic decays or leptons from semileptonic decays, thus avoiding unacceptable losses due to small branching ratios and limited detector acceptance. Monte Carlo methods need to be applied to relate the average impact parameter to the particle lifetime; this can be done to an accuracy of 10% or better.

In the past few years, measuring particle lifetimes has become a fashionable activity. In addition to a large-acceptance spectrometer with excellent momentum resolution and good particle identification, preferentially both for hadrons and leptons, a vertex detector is required with excellent resolution and granularity. In Table 1, the most recent experiments are listed; they have been grouped according to their method of vertex detection. Many of these experiments have been described in recent reviews[4,5,6)] and therefore here only a brief discussion will follow.

Table I

List of Lifetime Experiments.

The quoted resolution corresponds to the residuals obtained in a track fit. In addition, for bubble chambers, the bubble diameter and for e^+e^- experiments the error on the impact parameter (including the contribution from the beam size) is given.

Experiment	Resolution (μm)	t_{min} (10^{-13}s)	Beam (GeV)	Charged Hadron Identification	Lepton, γ Detection
Emulsions					
WA-75 [7]	0.5	0.05	350 π^-	None	$\mu^\pm$
WA-58 [8]	1	0.05	50 γ	Cerenkov	Pb glass
E-531 [9]	1	0.05	100 ν	TOF	$\mu^\pm$, Pb glass
Bubble Chambers					
NA-18 [10]	2;30	2	340 π^-	None	None
NA-16/27 [11]	2;17	1	360 π^-p 400 p	dE/dx, Cerenkov	Pb glass
SHF [12]	-;40	3	20 γ	Cerenkov	Pb glass
Si-Detectors					
NA-1 [13]		2	100 γ	2 Cerenkovs	Pb glass, Pb scintillator
NA-11 [14]	5	2	100 π^- 200 π^-K^-p	3 Cerenkovs	Pb scintillator Cerenkov
Wire Chambers					
WA-62 [15]	350		350 Σ^-	2 Cerenkovs	None
DELCO [16]	140;400		e^+e^- 29	Cerenkov	Pb-scintillator
HRS [17]	100;350		e^+e^- 29	TOF	Pb-scintillator
MAC [18]	200;530		e^+e^- 29	TOF	$\mu^\pm$, Pb gas
MARK II [19]	95;200		e^+e^- 29	TOF	$\mu^\pm$, Li-Argon-Pb
JADE [20]	170;570		e^+e^- 35	TOF, dE/dx	Pb glass
TASSO [21]	90;380		e^+e^- 44	TOF, 3 Cerenkovs	$\mu^\pm$, Li-Argon-Pb

The emulsion technique has by far the best spatial resolution and granularity, and with the help of computer-aided scanning machines, experimenters have overcome its notoriously low analysing power. In the LEBC bubble chamber of NA-27, the resolution on the impact parameter of a single track has been pushed to 7 µm, by the introduction of high resolution laser optics and improved operating conditions, small bubble diameter (17 µm) combined with high density. At present, holography is being tested in the Fermilab 15 foot chamber, exposed to a TEVATRON ν beam. In spite of these remarkable improvements, and impressive results in recent years, these visual devices will remain limited by their long memory time, lack of trigger and laborious scanning and measuring procedures. Their advantage is that within a given fiducial volume, tracks can be accurately measured and clearly associated with the production and decay vertices.

The use of silicon as active target and as a high resolution tracking device was pioneered by two groups at CERN. The NA-1 group uses a target made of 40 silicon wafers, 300 µm thick and spaced by 100 µm to detect multiple vertices in an event that has been reconstructed in the spectrometer. Since there are in general two charm decays per event, the association of the decay lengths in the target and the decay reconstructed in the spectrometer remains ambiguous. The NA-11 group was the first to use silicon microstrips to reconstruct secondary vertices and to demonstrate 99% efficiency and a single track resolution of 5 µm per plane. A system of fast online processors is used to trigger on prompt electrons or more than one kaon, detected by the calorimeter and the Cerenkov counters downstream. Attempts to use the signals from the silicon counters to detect secondary vertices at the trigger level have so far not produced satisfactory results.

Among e^+e^- experiments, the Mark II group has promoted the lifetime measurements by the installation of a high precision drift chamber mounted on the outside of a thin-walled vacuum chamber, and several other groups have followed this example since. At present a major limitation on the accuracy of pathlength or impact parameter measurement is due to the fact that the production vertex is not observed but approximated by the centre of the beam-beam interaction region, and consequently uncertain by the beam size (50 µm horizontal, 400 µm vertical).

3. τ LIFETIME MEASUREMENTS

If we assume, as in the Standard Model, that the τ lepton couples to the charged weak current with the same strength as the muon, and if the τ neutrino is massless, then in the framework of V-A interactions the τ lifetime can be calculated to be (Equation I) $\tau_\tau = (2.82\pm0.18)\cdot10^{-13}$ sec. The uncertainty quoted is due to experimental error on the branching ratio $BR(\tau^- \to e^-\bar{\nu}_e\nu_\tau) = 0.176\pm0.011$[22]. Given that these assumptions are very fundamental, any deviation from this prediction has important consequences.

Though we have been presented evidence for the decay of Z^0 and $W^\pm$ into $\tau^\pm$ leptons by the UA-1 experiment at the SPS collider[23], measurement of branching ratios and lifetimes of the heavy leptons are an unchallenged domain of e^+e^- experiments, which profit from the copious $\tau^+\tau^-$ pair production resulting in an absolutely clean topolological signature. The most precise measurements of the τ lifetime have been reported from two experiments at the e^+e^- storage ring PEP at 29 GeV c.m. energy.

The MAC collaboration[24] has derived the τ lifetime from a measurement of the mean impact parameter δ of the charged τ decay products. Although the expected average impact parameter is small compared to the resolution of an individual track (~ 900 μm), the huge statistics available allows for considerable precision. The data, presented in Figure 1, show a small excess of events at positive values of ρ. The mean value of 43.6±5.0 μm translates to an average τ lifetime of $(3.15\pm0.36\pm0.40)\cdot10^{-13}$s. The systematic error r[illegible] uncertainty in the factor α that relates impact parameter and lifetime; α is determined by Monte Carlo simulation.

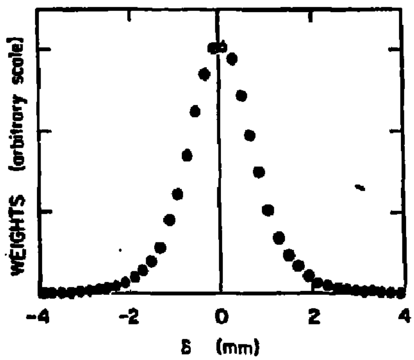

Fig. 1 Impact parameter distribution for a sample of 23,584 tracks from τ decay, measured by the MAC collaboration.

The Mark II[27,6] collaboration has significantly improved the accuracy of charged particle track reconstruction by the installation of a high precision drift chamber around the beam vacuum pipe. The decay length is measured as the distance between the centre of the e^+e^- collision region and the vertex formed by the three charged tracks from the decay $\tau^- \to \pi^+\pi^-\pi^-\nu$. The average resolution in the decay length is 1000 μm, comparable to the mean decay length of 635±36 μm. The data are shown in Figure 2. A maximum likelihood method is applied to determine the average decay length and a factor that scales with the estimated resolution. The fit result translates to an average lifetime of $(2.86\pm0.16\pm0.25)\cdot10^{-13}$sec.

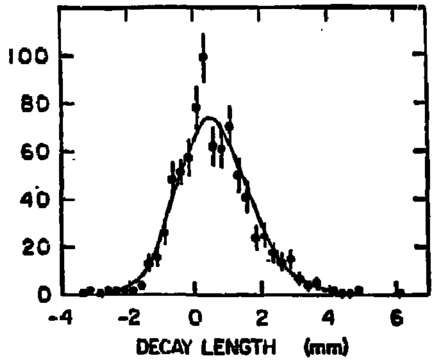

Fig. 2 Decay lengths of 807 τ leptons measured by the Mark II collaboration, the curve represents maximum likelihood fit to the data.

A compilation of these and other τ lifetime measurements is given in Table 2. A large number of these measurements can be viewed as a calibration for the impact parameter technique used in various detectors to measure lifetimes of heavy flavour particles. All experiments are in good agreement with each other and in excellent agreement with the theoretical prediction. The measurement have been used to test the basic assumptions that enter into the calculation of the theoretical prediction. For instance, the Mark II result alone confirms μ–τ universality to a precision of 5%. More sensitive tests on the τ coupling and the possibility of mixing of the ν_τ with other generations, will require not only higher accuracy in the τ lifetime measurement, but comparable improvements in the measurements of the leptonic branching ratio and the τ neutrino mass[30].

4. LIFETIME MEASUREMENTS FOR CHARM MESONS

The WA-58 group has exposed a thin emulsion target in the Ω spectrometer to a photon beam at CERN. The present measurement is based on 43 D^0 and 20 $D^\pm$ decays[31], roughly twice the sample previously published[32]. Due to the superb resolution in the emulsion, more than 80% of the decays are observed in events with two decay vertices. This greatly enhances the purity of selected charm decays, few of which have constrained kinematic fits or unique kaon identification. The experimenters are concerned that a contamination from short-lived $F^\pm$ and Λ_c^+ particles may decrease the apparent lifetime. This concern is shared by many groups, in particular for decays with undetected neutrals and poor mass resolution. Furthermore, the limited thickness of this emulsion stack (0.6 mm set at a grazing angle of 5° to the beam) leads to substantial detection losses at proper times above $3 \cdot 10^{-13}$ sec and results in a large systematic uncertainty in the $D^\pm$ lifetime.

Table 2

Recent Measurements of the τ Lifetime

Experiment		$\tau_\tau(10^{-13}s)$
JADE	26)	3.5 ± 1.1
DELCO	27)	2.9 ± 0.8
HRS	28)	$2.9 \pm 0.4 \pm 0.50$
TASSO	29)	$3.18 \pm ^{0.59}_{0.75} \pm 0.56$
MAC	24)	$3.15 \pm 0.36 \pm 0.40$
MARK II	25,6)	$2.86 \pm 0.16 \pm 0.25$
Average		2.97 ± 0.23

The Fermilab E-531 experiment employs a nuclear emulsion in a ν beam. The data analysis is still in progress, the last update on the published results[33] was given two years ago[5] at this conference in Como. In addition to 56 D^0 and 11 $D^\pm$ decays, the group presented 8 $F^\pm$ decays. In order to separate F^+ from $D^\pm$ meson on an event by event basis, the reconstructed mass for the F candidates was required to exceed 2.0 GeV/c^2 in the first and 1.94 GeV/c in the second data set. It has been verified that all F candidates are consistent with a three-constraint fit to an F decay mode, and kinematically incompatible with any Cabibbo-favoured decay mode of D^+ or Λ_c^+. (The F mass was fixed to 2.03 GeV/c for the earlier data and to 1.97 GeV/c for the more recent data.)

The ACCMOR collaboration has completed the analysis of the NA-11 data[34] that were recorded with a prompt electron trigger and with high resolution silicon strip detectors. The decay selection is restricted to three fully reconstructable modes, $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$ and $D^+ \to K^-\pi^+\pi^+$ with identified K-mesons. The charged decay tracks form a distinct vertex. The final sample consists of 33 $D^\pm$ and 29 D^0 decays, including 5±2 and 3±1 background events. To correct for detection losses at short decay times, the measured decay time has been corrected for the smallest detectable decay time, $t_{corr} = t - t_{min}$, compatible with the selection criteria. The background corrected decay time distributions are shown in Figure 3. A maximum likelihood fit yields

$$\tau(D^+) = (10.6 \pm ^{3.6}_{2.4}) \cdot 10^{-13} \mathrm{sec}, \qquad \tau(D^0) = (3.7 \pm ^{1.0}_{0.7}) \cdot 10^{-13} \mathrm{sec},$$

and

$$\tau(D^+)/\tau(D^0) = 2.8 \pm ^{1.1}_{0.8}.$$

The systematic errors are estimated to be a factor of two smaller than the larger of the statistical errors.

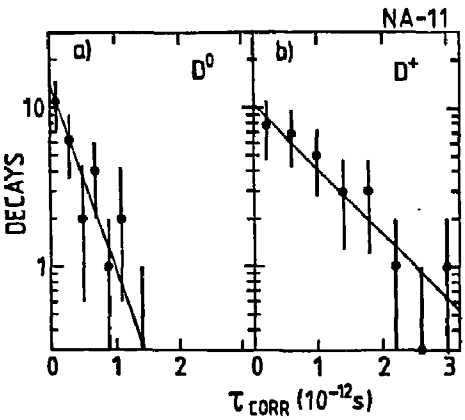

Fig. 3 Corrected decay time distributions for 28 $D^\pm$ and 36 D^0 decays of NA-11. The straight lines represents the result of a maximum likelihood fit to the average lifetimes.

In addition, the ACCMOR group has applied the same analysis to the $K^+K^-\pi^+$ decay, the results[35] are given in Figure 4. There is clear evidence for two enhancements in the effective mass distributions, with 12 events each in the mass intervals 1.95–1.99 GeV/c^2 and 1.85–1.89 GeV/c^2, corresponding to F^+ and D^+ meson decays. The average masses are 1972±2 MeV/c^2 and 1872±2 MeV/c^2. The decay time distributions are distinctly different, the average lifetimes are $(3.1 \pm ^{1.2}_{0.8}) \cdot 10^{-13}$sec for the F^+ candidates and $(9.5 \pm ^{3.5}_{2.4}) \cdot 10^{-13}$sec for the Cabibbo-suppressed decay of the D^+ (fully compatible with the value quoted above). Due to ambiguities in the kaon and proton identification, three of the F^+ and two of the D^+ decays are not distinguishable from Λ_c^+ decays.

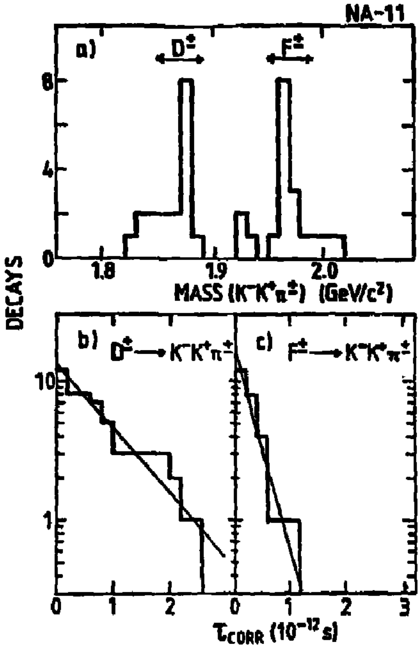

Fig. 4 Measurement of the lifetime of the $F^\pm$ meson by NA-11. a) Effective mass of $K^-K^+\pi^-$ for particles forming a secondary vertex; and integral decay time distributions for b) the 12 $D^\pm$ candidates and c) the 12 $F^\pm$ candidates.

The European Hybrid Spectrometer group has employed LEBC, a small bubble chamber, to study charm particle production in hydrogen by π^- and protons at 360 and 400 GeV/c. Major improvements in the operation of the chamber, the optics, and the use of HPD measuring machines allow for the detection of impact parameters down to 7 μm on the film. At this time, the analysis of the NA-27 π^- data sample is complete[36] and preliminary results based on one third of the proton data are available[37]. The new measurements are restricted to decays that are selected by unique, highly-constrained kinematic fits. There are 34 charged and 29 neutral D meson decay in the total sample. The lifetime distributions are given in Figure 5, together with the result of a maximum likelihood fit, resulting in average lifetimes of

$$\tau(D^+) = (11.6\pm^{3.1}_{2.3})\cdot 10^{-13}\,\text{sec}, \qquad \tau(D^0) = (3.9\pm^{0.9}_{0.7})\cdot 10^{-13}\,\text{sec},$$

and

$$\tau(D^+)/\tau(D^0) = 2.9\pm^{1.2}_{0.7}.$$

These results have been confirmed by an impact parameter measurement that is independent of kinematic fits but depends on individual branching ratios and momentum estimates.

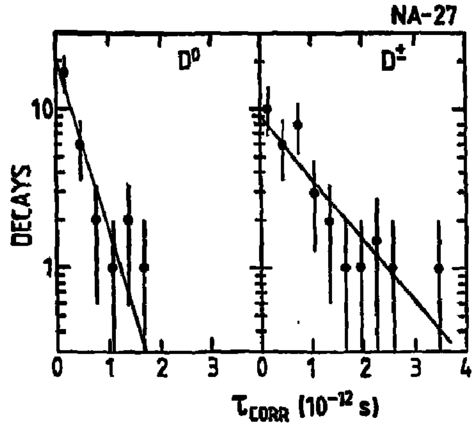

Fig. 5 Corrected decay time distributions for the combined π^- and proton data of NA-27, containing a) 29 D^o and b) 34 $D^{\pm}$ decays.

The SLAC Hybrid Facility group has now completed the analysis[12)] of several exposures in the 20 GeV back-scattered laser beam. To obtain high and uniform detection efficiency, $(97^{+2}_{-4})\%$, and reduce topological ambiguities, a minimum path length of 0.6 mm and one decay track with an impact parameter of at least 100 μm plus a second with 40 μm were required. After some additional cuts to remove photon conversions and strange particle decays, 100 charm particle decays remain, 50 D^o, 48 $D^{\pm}$ and two ambiguous. No direct evidence for $F^{\pm}$ or Λ_c^+ decay was found. Because of unmeasured neutral particles, π^0 and ν, only one-third of the decays are fully constrained. The momentum of the D was derived by scaling from the visible momentum p_{vis} and mass m_{vis}, namely $p_D = p_{vis}(m_D/m_{vis})$. The corrected lifetime distributions are shown in Figure 6; they lead to the results

$$\tau(D^{\pm}) = (8.6 \pm 1.3 ^{+0.7}_{-0.3}) \cdot 10^{-13} \text{sec}, \qquad \tau(D^o) = (6.1 \pm 0.9 \pm 0.3) \cdot 10^{-13} \text{sec},$$

and

$$\tau(D^+)/\tau(D^o) = 1.4 \pm 0.3 ^{+0.2}_{-0.1}.$$

The quoted systematic error on the $D^{\pm}$ lifetime includes the uncertainty in the contribution from Λ_c^+ or $F^{\pm}$ decays. In both the D^o and $D^{\pm}$ sample there is one event with a rather long decay time. In particular, the neutral decay with $\tau = 55 \cdot 10^{-13}$ sec is a fully-constrained, well measured decay with a very low probability (less than 1 in $6 \cdot 10^7$ experiments of this size) of being background. Even though the statistical probability for the observation of such an event is low ($6 \cdot 10^{-4}$ for a lifetime of $4.4 \cdot 10^{-13}$ sec) the authors stressed the fact that the data sample is fully consistent with an exponential decay distribution.

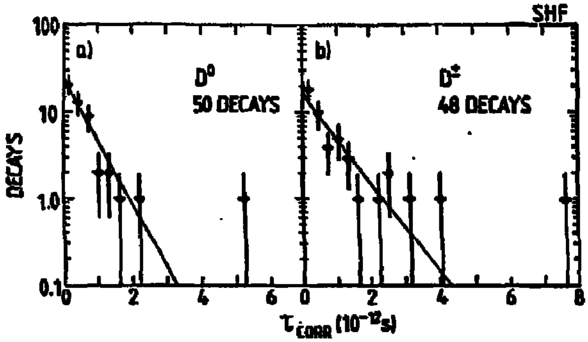

Fig. 6 Corrected decay time distributions for the SHF data.

While the direct observation of decay vertices in an emulsion or bubble chamber is a very clean signature for heavy flavour decay, in e^+e^- experiments, the more favourable production rates permit the selection of charm particle decays on the basis of kinematics alone, thus avoiding corrections for losses at small lifetimes. The Mark II collaboration has recently completed the measurement of of D^o and D^+ lifetimes[38]. Based on the observation that a large fraction of charm mesons are produced as the vector mesons D^{*+} and D^{*o}, the experimenters have used the small difference in mass between the D^{*+} and the scalar mesons D^o and D^+ to isolate D meson decays from a large combinatorial background. This is illustrated in Figure 7 for three different decay modes, namely $D^{*+} \to D^o\pi^+$ with $D^o \to K^-\pi^+$ and $D^o \to K^-\pi^+\pi^o$ and $D^{*+} \to D^+\pi^o$ with $D^+ \to K^-\pi^+\pi^+$. For the D^+ production, the π^o is almost at rest in the D^{*+} frame and thus its laboratory energy is strongly correlated with that of the D^{*+}; this has been used to further enhance the D^+ signal. The proper time distributions for 74 D^o and 23 $D^\pm$ decays are shown in Figure 8; they include 8 and 7 background events, respectively. Although the measurement of the decay distances is limited by the detector resolution and the beam size, a displacement of the nearly Gaussian distribution to positive values is apparent. By contrast, the distribution of background is centred on zero. A maximum likelihood fit to the data, taking into account the measurement error for each decay, gives mean values of

$$\tau(D^\pm) = (8.9\pm^{3.0}_{2.7}\pm1.3)\cdot10^{-13}\,\text{sec}, \qquad \tau(D^o) = (4.7\pm^{0.9}_{0.8}\pm0.5)\cdot10^{-13}\,\text{sec},$$

and

$$\tau(D^+)/\tau(D^o) = 1.9\pm^{0.9}_{0.7}\pm0.3.$$

The systematic error includes the uncertainty in the detector resolution, and effects due to background and D mesons originating from B decay. No experimental bias against events with extremely long or short lifetimes has been detected.

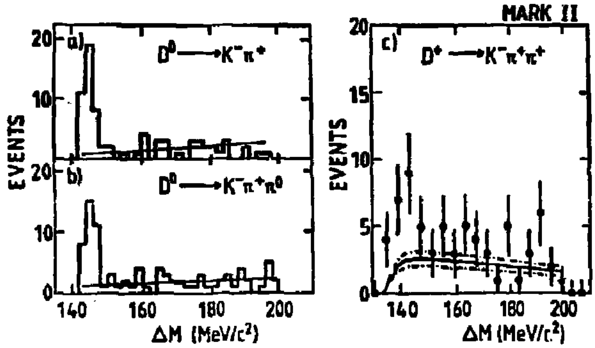

Fig. 7 The mass difference $\Delta M = M(D^{*+}) - M(D)$ for the three decay channels measured by the Mark II collaboration.

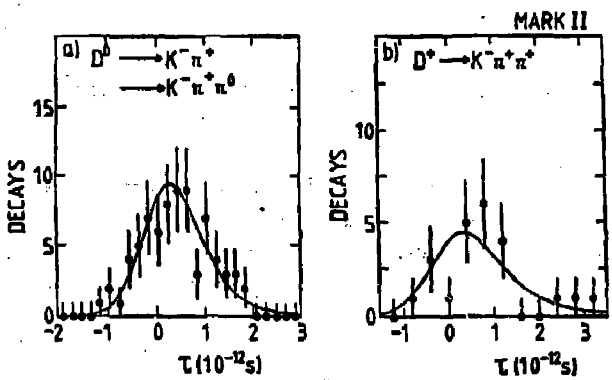

Fig. 8 Lifetime distributions of Mark II for decays a) $D^0 \to K^-\pi^+$ and $D^0 \to K^-\pi^+\pi^0$ and b) $D^+ \to K^-\pi^+\pi^+$. The curves are results of a maximum likelihood fit.

Three other e^+e^- experiments have recently presented D^0 lifetime measurements. The HRS[39] and TASSO[40] collaborations demonstrate the use of their newly installed vertex detectors using the same method as Mark II to select 31 and 8 decays $D^0 \to K^-\pi^+$. The DELCO group[41] at PEP has measured the impact parameter of the K^- and π^+ relative to the beam centre which 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 decays of the modes $D^0 \to K^-\pi^+$ + neutrals. The result is presented in Figure 9. The data are fitted by a maximum likelihood method taking into account a Gaussian error function and a flat background with a specific width and probability for each individual decay. The average impact parameter of 151.7±42.3 μm translates to a lifetime $\tau(D^0) = (4.6\pm1.5\pm^{0.7}_{0.8})\cdot10^{-13}$ sec. Detailed systematic studies show that the measurement is largely bias free and insensitive to effects like nuclear interactions in the beam pipe, small misalignments of the drift chambers, etc.

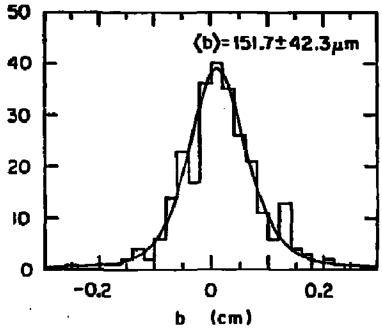

Fig. 9 Impact parameter measurement for the K^- and π^+ from D^0 decays measured by DELCO.

A compilation of lifetime measurements for charm mesons is given in Table 3. The overall picture has not changed dramatically; there are now twelve experiments contributing 384 $D^{\pm}$, 342 D^0 and 20 $F^{\pm}$ decays. While the uncertainties in the individual measurements remain large, the agreement is satisfactory. A major improvement will require one or two experiments with a selective trigger and a vertex detector with a resolution of a few μm. In attempting to combine the available information, averages and combined errors have been calculated. The individual measurements 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, 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 a more appropriate weight.) Using the combined statistical and systematic errors quoted, the best estimate for the lifetime of the charged D mesons is

$$\tau(D^+) = (9.25 \pm ^{1.11}_{0.77}) \cdot 10^{-13}\,\text{sec.}$$

There is only one experiment that deviates from this average by more than one standard deviation (it used to be more), namely WA-58, which is known to have large detection losses for proper times exceeding $3 \cdot 10^{-13}$ sec.

The same averaging scheme yields for the neutral D meson lifetime

$$\tau(D^0) = (4.38 \pm ^{0.38}_{0.32}) \cdot 10^{-13}\,\text{sec.}$$

Table 3

Measurements of Lifetimes of Charmed Mesons

Experiment	$D^{\pm}$ Decays	$D^{\pm}$ $\tau(10^{-13}s)$	D^{o} Decays	D^{o} $\tau(10^{-13}s)$	$F^{\pm}$ Decays	$F^{\pm}$ $\tau(10^{-13}s)$
E-531 [5,33]	11	$11.5^{+7.5}_{-3.5}$	57	$3.5^{+0.5}_{-0.4}\pm0.3$	8	$2.5^{+1.2}_{-0.8}\pm0.8$
WA-58 [31,32]	20	$5.4^{+1.9}_{-1.2}\pm0.8$	43	$3.4^{+1.1}_{-0.8}\pm0.3$		
NA-1 [43]	98	$9.5^{+3.1}_{-1.9}$				
NA-11 [34,35]	28	$10.6^{+3.6}_{-2.4}\pm1.6$	26	$3.7^{+1.0}_{-0.7}\pm0.5$	12	$3.1^{+1.2}_{-0.8}$
NA-16 [44]	15	$8.4^{+3.5}_{-2.2}$	16	$4.1^{+1.3}_{-1.0}$		
NA-18 [45]	7	$6.3^{+4.9}_{-2.3}\pm1.5$	9	$4.1^{+2.6}_{-1.3}\pm0.5$		
NA-27 [36]	23	$9.8^{+3.4}_{-2.2}$	11	$3.5^{+1.4}_{-0.9}$		
[37]	11	$14.7^{+7.5}_{-4.2}$	18	$4.1^{+1.2}_{-0.8}$		
SHF [12]	48	$8.6\pm1.3^{+0.7}_{-0.3}$	50	$6.1\pm0.9\pm0.3$		
MARK II [38]	23	$8.9^{+3.8}_{-2.7}\pm1.3$	74	$4.7^{+0.9}_{-0.8}\pm0.5$		
HRS [39]			31	$4.5\pm1.4\pm0.8$		
TASSO [40]			8	$4.6^{+2.9}_{-1.7}{}^{+1.0}_{-1.3}$		
DELCO [41]				$4.6\pm1.5^{+0.7}_{-0.6}$		
Average	284	$9.25^{+1.11}_{-0.77}$	342	$4.38^{+0.38}_{-0.31}$	20	$2.8^{+0.8}_{-0.6}$

Here, the SHF result, among the most precise of all, deviates most. Excluding this measurement - though there is no good reason - reduces the mean by $0.4 \cdot 10^{-13}$ sec. Measurements of the lifetime of the F^+ meson have in the past suffered from the uncertainty in the F^+ mass. The increased sample of 12 events observed by the NA-11 experiment provides the most reliable information, even though at this time the question of possible contamination by Λ_c^+ decays has not been settled. Combined with the earlier E-531 measurement, the best estimate for the F^+ lifetime is

$$\tau(F^{\pm}) = (2.8\pm^{0.8}_{0.6})\cdot 10^{-13}\,\text{sec.}$$

Thus the $F^{\pm}$ lifetime appears to be closer to the D^o than the D^+ lifetime.

In summary, the charm meson lifetimes agree within a factor of two or three with the naive prediction for the charm quark lifetime. The lifetimes for the charged and neutral D mesons are clearly different, the ratio of the averages is

$$\tau(D^+)/\tau(D^o) = 2.1\pm0.3$$

This average is strongly affected by the low value of $1.4\pm0.3\pm^{0.2}_{0.1}$ from the SHF experiment. The lifetime ratio can also be inferred from the semileptonic branching ratios. The Mark III collaboration has reported[42)]

$$BR(D^+ \to e^+X) = 0.170\pm0.019\pm0.007,$$
$$BR(D^o \to e^+X) = 0.075\pm0.011\pm0.004,$$

and

$$BR(D^+ \to e^+X)/BR(D^o \to e^+X) = \tau(D^+)/\tau(D^o) = 2.3\pm^{0.5}_{0.4}\pm0.1,$$

in agreement with the ratio from the direct measurement.

Since the leptonic width of the D mesons is negligible and the semileptonic partial widths of the D^o and D^+ should be nearly equal (unless Cabibbo-suppressed processes in D^+ decay are important), a difference in lifetimes and semileptonic branching ratios implies a difference in the non-leptonic widths of the two states. Numerous theoretical solutions have been proposed either to enhance the D^o or suppress the D^+ hadronic width. It has been noted[43)] that QCD corrections to the weak Hamiltonians are largely equal for D^o and D^+. A difference can arise if the two D^+ amplitudes leading to identical final states[44)] (Figure 10 a,b) interfere destructively. The presence of so-called W exchange processes[45)] (Figure 10 c) would also lead to a difference in hadronic width, since they contribute to D^o and not D^+ decay. Similarly, the W annihilation process is Cabibbo-allowed for F^+ decay, but Cabibbo-suppressed for D^+. However, exchange and annihilation graphs are expected to be suppressed by helicity conservation and by small overlap of the wave functions. Resolution of these questions requires study of specific exclusive decay modes.

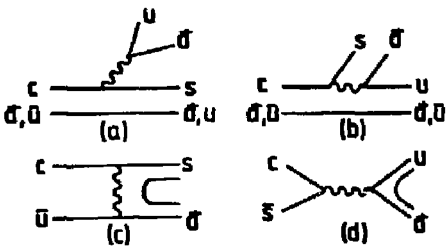

Fig. 10 Quark diagrams representing the hadronic decays of charm mesons (a,b), spectator diagrams common to D^o and D^+, c) W^+ exchange diagram for D^+ and d) annihilation diagram for F^+ decay.

The Mark III collaboration[46)] has derived evidence for destructive interference between two-body D^+ decay amplitudes from a comparison of two Cabibbo-suppressed decay rates,

$$\Gamma(D^+ \to \pi^o\pi^+)/\Gamma(D^+ \to \bar{K}^o\pi^+) < 0.13 \quad 90\%\ \mathrm{C.L.}$$

and

$$\Gamma(D^+ \to \bar{K}^oK^+)/\Gamma(D^+ \to \bar{K}^o\pi^+) = 0.32 \pm 0.10$$

The conclusion is based on the fact that such interference is possible for $D^+ \to \bar{K}^o\pi^+$ and $D^+ \to \pi^o\pi^+$, but not for $D^+ \to \bar{K}^oK^+$.

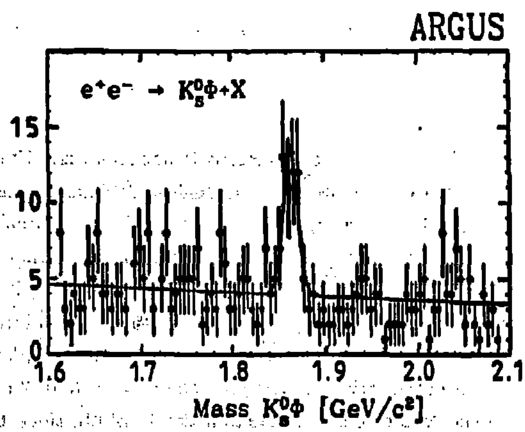

Fig. 11 Evidence for the decay $D^o \to K_s\phi$ from the ARGUS experiment.

The ARGUS collaboration has recently[47] presented evidence for the decay $D^0 \to K^0\phi$, a process that should occur predominantly via W exchange. The observation is based on 51.9±12.6 decays $D^0 \to K_s K^+ K^-$ of which 25.7±5.8 are attributed to $D^0 \to K_s\phi$. The data are presented in Figure 11. Comparison with the decay $D^0 \to K_s\pi^+\pi^-$, using relative efficiencies and the most recent branching ratios[48], yields relatively large branching ratios

$$BR(D^0 \to \bar{K}^0\phi) = (1.41 \pm 0.46)\%$$

and

$$BR(D^0 \to \bar{K}^0 K^+ K^-) = (1.40 \pm 0.49)\%$$

The analysis is not fully supported by the Mark III group[48] who observes 28 decays $D^0 \to K_s K^+ K^-$ above a background of 4.7±1.7 events. From a detailed study of the Dalitz plot the authors conclude that only 5±3.3 events can be attributed to the decay $D^0 \to K_s\phi$. This translates to a branching ratio of $BR(D^0 \to K_s\phi) = 0.7 \pm 0.5 \pm 0.2\%$ or an upper limit at 90% C.L. $BR(D^0 \to K_s\phi) < 2.5\%$, compatible with the ARGUS result. No evidence for any other W exchange process decay was found; present limits are[48]

$$BR(D^0 \to \bar{K}^0 K^0) < 5.6 \cdot 10^{-3}$$
$$BR(D^0 \to \bar{K}^{*0} K^0) < 7.1 \cdot 10^{-3}$$

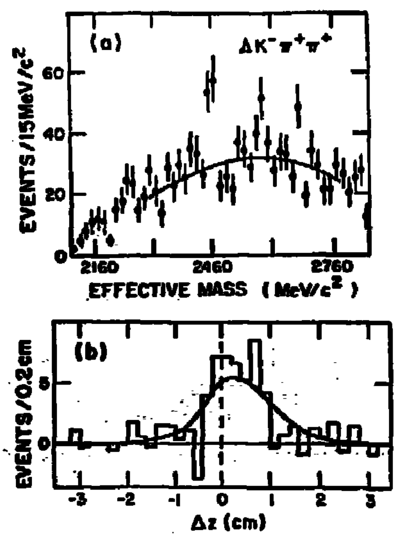

Fig. 12 Measurement of the lifetime of the Ξ_c^+ baryon by the WA-62 experiment; a) effective mass $\Lambda K^-\pi^+\pi^+$ for selected events and b) background-subtracted decay length distribution for the Ξ_c^+ signal.

5. LIFETIME MEASUREMENTS OF CHARM BARYONS

Among the ten $J^P = \frac{1}{2}^+$ charm baryon states predicted by standard SU_4 theory, only the lowest mass state, Λ_c^+ (cud), is well established at a mass of 2285.6±1.8 MeV/c² [49]. Hints of the Σ_c^{++} (cuu) have been observed in a number of experiments[50] at a mass of 2452±3 MeV/c². More recently the WA-62 experiment in the CERN hyperon beam has presented evidence for a strange charm baryon, the Ξ_c^+ (csu) at a mass of 2460±15 MeV/c² [51]. The trigger of this experiment was designed to select final states of strangeness s = −2 and s = −3 by requiring a K^- and a proton in the Cerenkov counters and a V^0 decay in the spectrometer. The effective mass for the $\Lambda K^-\pi^+\pi^-$ combinations is shown in Figure 12 a; there are 53 events in the narrow peak above a background of 59 events. The lifetime is extracted from a simultaneous fit to the pathlength distributions of the candidate events in the peak region and suitably normalized background events. The difference of these distributions shows a clear shift to positive decay lengths (Figure 12 b). The fit yields

$$\tau(\Xi_c^+) = (4.8 \pm^{2.1}_{1.0} \pm^{1.0}_{1.0}) \cdot 10^{-13}\,\text{sec.}$$

The systematic error includes the uncertainties in the background and resolution estimates and a possible effect of charm mesons produced in association with the Ξ_c^+.

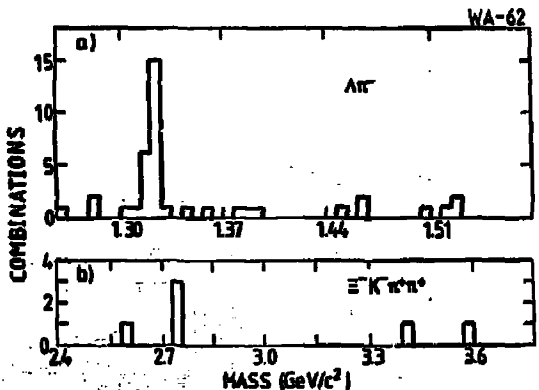

Fig. 13 Evidence for the decay $\Omega_c^0 \to \Xi^- K^-\pi^+\pi^+$ with $\Xi^- \to \Lambda^0\pi^-$ obtained by the WA-62 experiment.

The same experiment has also searched for evidence for the production of the Ω_c^0 (css) baryon[52], a state that decays weakly to final states of strangeness s = −3, like $\Xi^- K^-\pi^+\pi^+$. The data are presented in Figure 13. There are 20 decays $\Xi^- \to \Lambda\pi^-$ of which six have two additional tracks that are consistent with the decay $K^{0*}(896) \to K^-\pi^+$. Three of these six events cluster in a $\Xi^- K^-\pi^+\pi^+$ mass bin of 30 MeV/c². If one accepts these combinations as evidence for a Cabibbo-favoured decay of the charm baryon Ω_c^0. Its mass is (2740±20)MeV/c^2, and the mass difference $M(\Omega_c^0)-M(\Xi_c^+)$ = 280±10 MeV/c^2. From the reconstructed momentum and decay lengths for these candidates, one obtains the proper times 10.2±4.2, 3.3±5.6, and 8.5±5.3$\cdot10^{-13}$sec. The average is

$$\tau(\Omega_c^0) = (7.9\pm2.8\pm2.0)\cdot10^{-13}\text{sec.}$$

Four experiments with a total of 32 decays have contributed measurements of the Λ_c^+ lifetime. A summary is given in Table 4. The selection criteria and kinematic fitting procedures vary widely among these experiments, and so does the possible contamination of the sample by D^+ and F^+ decays. If one restricts the sample to fully reconstructed three-prong decays with at most one associated Λ^0 or K_s decay, giving a unique fit to a Cabibbo-favoured decay of the Λ_c, there remain 9 events, 3 from E-531 and 6 from NA-27, with an average lifetimes of

$$\tau(\Lambda_c^+) = (1.1\pm^{0.5}_{0.3})\cdot10^{-13}\text{sec.}$$

This value is a factor of two smaller than tha average given a year ago; it is strongly influenced by the new and still preliminary results from the NA-27 experiment. This smaller value may also explain why no Λ_c decays have been observed by the SHF and NA-11 experiments.

Table 4

Measurement of Lifetimes of Charm Baryon Λ_c

Experiment	Decays	$\tau(10^{-13}s)$
E-531 [33)]	8	$2.3\pm^{1.0}_{0.6}\pm0.2$
WA-58 [31)]	10	$2.1\pm^{1.2}_{0.6}\pm0.6$
NA-16 [53)]	4	$1.9\pm^{1.4}_{0.7}$
NA-27 [54)]	10	$1.14\pm^{0.45}_{0.30}$
Average	32	$1.45\pm^{0.37}_{0.24}$

Theoretically, one would expect the Λ_c^+ lifetime to be shorter than the lifetime of the Ξ_c^+ and Ω_c^0, because the Λ_c^+ decay can occur via the W^+ exchange diagrams, whereas for the Cabibbo-allowed decays of the strange charm baryons only the so-called spectator processes are possible. Estimates for the ratio of the Ξ_c^+ to Λ_c^+ lifetime vary between two and four[55]. Within the large errors, the data support these estimates.

6. MEASUREMENTS OF LIFETIMES OF BEAUTY PARTICLES

There is now direct evidence for hadro-production of beauty particles from the WA-75 hybrid-emulsion experiment at CERN[7]. Two stacks of emulsion were exposed, one perpendicular (18.5 mm thick) and one parallel (40 mm long) to the beam, to record $1.5 \cdot 10^6$ interactions triggered by a muon of at least 1 GeV/c transverse momentum. The interaction vertex was predicted from tracks reconstructed in the beam and vertex microstrip detectors with an accuracy of 70 μm transverse and 500 μm longitudinal, thus allowing for a very restricted scan volume in the emulsion. At present roughly 10% out of a sample of 10^4 events have been fully analysed, and one beautiful event with four decay vertices was found. This event, displayed in Figure 14, is interpreted as the production of a $B^-\bar{B}^0$ pair. The B^- decays at vertex 1 into a negative muon of 1.9 GeV/c transverse momentum and a neutral particle, presumably a D^0 meson, which itself decays at vertex 2 into four charged particles. The $\bar{B}^0$ decays at vertex 3 into a positively charged hadron and a negative particle, presumably a D^-, which decays to a negative muon of 0.45 GeV/c transverse momentum at vertex 4. The mass of the supposed B^- and $\bar{B}^0$ must be high because of the transverse momenta of the decay particles, 1.9 GeV/c and 1.2 GeV/c for the μ^- and D^- respectively. Alternate explanations for the observed topology are estimated to be extremely unlikely.

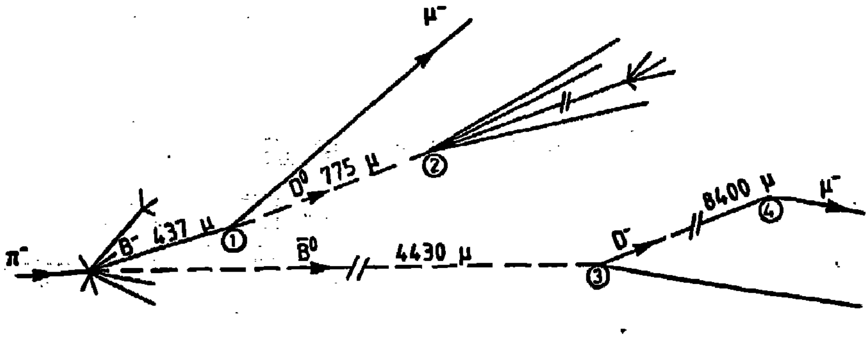

Fig. 14 Configuration of the $B^-\bar{B}^0$ event found in the emulsion of WA-75.

Since, apart from the muons, the particle identities and energies are unknown, the proper times of flight of the two beauty particles can only be estimated. Two methods have been tried, one uses the measured impact parameters[3], the other is based on kinematics of "plausible decay schemes". The two methods render consistent results for the proper times, $\tau(B^-) = (0.8\pm0.1)\cdot10^{-12}$ sec and $\tau(\bar{B}^0) = (5^{+2}_{-1})\cdot10^{-12}$ sec.

It has been almost two years since the MAC[56] and Mark II[58] collaborations first reported lifetimes of the beauty hadrons 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 the earlier results with additional data, improved detectors and some refinements in analysis are available. Two different techniques have been used to determine the B lifetime, one based on the measurement of the impact parameters for leptons or hadrons, and the other on the determination of the decay path from the vertex of the B jet.

Four groups, MAC[57], Mark II[6], JADE[26] and DELCO[60], have reported updates of their B lifetime results, based on the procedure used in the original measurements. The production of beauty hadrons is tagged by a lepton with a high transverse momentum relative to the thrust axis of the event. The impact parameter of the lepton is then taken as a measure of the B lifetime. The four experiments differ in the purity of their selected sample due to differences in lepton identification and kinematic cuts. The data are presented in Figure 15. All experiments observe a mean impact parameter that is significantly positive. The observed distributions are fitted by maximum likelihood methods to the sum of background, charm, and bottom contributions. The relative normalization of these contributions has been obtained in studies of inclusive lepton production; the shape of the background distribution is measured directly, the distribution of charm and beauty events (as a function of lifetime) are determined by Monte Carlo simulation. As a cross check, all four experiments have measured impact parameters for high transverse momentum hadrons, and find results consistent with the Monte Carlo generated distributions. All experiments have applied the impact parameter technique to τ leptons and find good agreement with the published lifetime measurements. The Mark II and DELCO experiments have extracted the average charm particle lifetime using low transverse momentum leptons; the results are consistent with other measurements.

The MAC group has increased the sample by 40% and has now 505 lepton tagged beauty events, containing 29% background. The new result[57] differs by two standard deviations from the earlier one[58], mainly due to a significant (and not fully understood) shift in the electron distribution towards shorter lifetimes. The MAC group expects to improve this measurement with new data recorded with a recently installed precision vertex chamber. This device is built around a vacuum pipe of 3.5 cm radius, and consists of

6 layers of thin-walled tube chambers operated at a pressure of 4 atmospheres. It is hoped that a resolution of 40-50 µm can be maintained, thus allowing for a determination of the interaction vertex on an event by event basis.

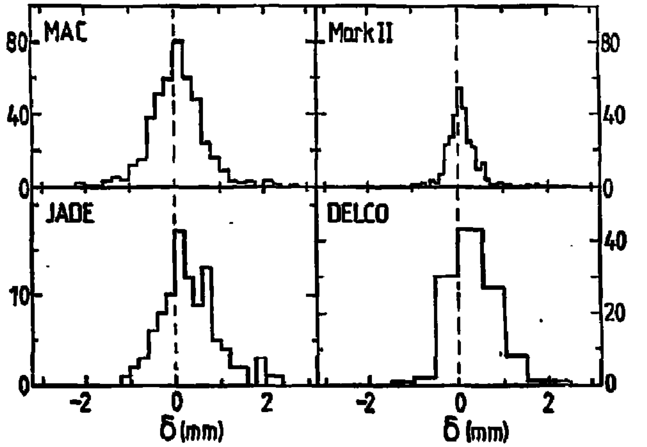

Fig. 15 Measurements of the average B-lifetime. Distributions of the lepton impact parameter from a) MAC, b) Mark II, c) JADE, and d) DELCO experiments.

The Mark II group[6] has tripled the sample compared to the original publication[58]; the 282 leptons used in the analysis have an error on the impact parameter of less than 310 µm. This superior resolution gives the measurement the best statistical accuracy. A publication with refinements of analysis is in preparation.

The excellent electron identification of the DELCO experiment leads to a very clean $b\bar{b}$ sample, and allows for a looser cut on the electron momentum. As a result the average impact parameter is larger than for the MAC and Mark II sample. The new result[60] is roughly one standard deviation above the previously published measurement that was based on one half the present statistics.

The JADE experiment combines dE/dx information from the drift-chamber with the lead glass signals to obtain good electron identification. In addition, the group eliminates three jet events to reduce the contamination of the lepton sample by high $p_\perp$ hadrons and to assure a correct determination of the thrust axis. The selected $b\bar{b}$ sample contains less than 20% background. The measured lifetime remains unchanged since last summer[26].

The TASSO collaboration at PETRA has recently upgraded the detector by installing a precision inner drift-chamber, similar in design and performance to the Mark II vertex detector. The group has presented[62] an update of their B lifetime measurement based on twice the number of events previously published[61]. The lifetime is determined from the measured impact parameter of charged decay products of all decay modes of the B hadrons. This increases the sensitivity due to the larger multiplicity of B decays compared to hadrons composed of charm and lighter quarks. A further advantage of using many tracks in an event is that the uncertainties in the beam position and size tend to cancel. The sensitivity of the measurement is increased by an event selection that raises the contents of $b\bar{b}$ events to 33%. This is achieved by a cut on the product of the sphericities of the two jets which tends to be large for $b\bar{b}$ events. This sphericity is measured in a frame that approximates the rest frame of the produced B meson. The impact parameter distribution for the B enriched sample shows a marked excess at positive value of δ compared to the B depleted sample (Figure 16). 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 result is $\tau(B) = (1.36\pm0.42)\cdot10^{-12}$sec. When combined with the less accurate earlier data, the new result is

$$\tau(B) = (1.57\pm0.32\pm^{0.37}_{0.34})\cdot10^{-12}\text{sec.}$$

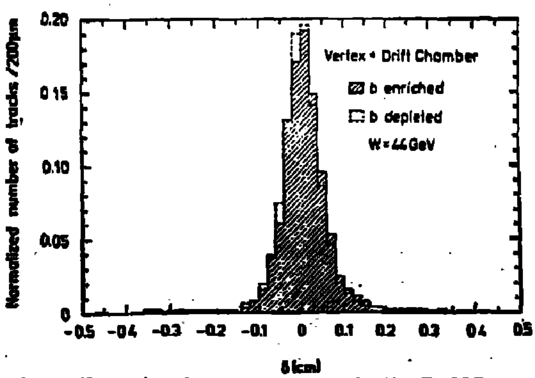

Fig. 16 Distribution of the hadron impact parameter by the TASSO experiments.

The main contributions to the systematic error are from the uncertainties in the Monte Carlo modelling. The authors point out that this is the only measurement that is independent of the semi-leptonic branching ratios of B^0 and B^-, which could be different if the lifetimes were different.

The Mark II group has used another, totally different technique[63], applied to the event sample enriched by the high $p_\perp$ lepton requirement. Each event is cut in two halves by the plane perpendicular to the thrust axis, and a separate vertex is determined from the tracks in each half. At least three well measured tracks are required for a good vertex. The path length is measured as the distance between the vertex and the beam centre. The distribution, shown in Figure 17, has a mean value of 413±43 μm, comparable to the width. The average B lifetime is determined from a maximum likelihood fit to this observed distribution. As in the impact parameter method, the ansatz assumes contributions from $b\bar{b}$, $c\bar{c}$, and background events. While the latter is measured directly, the $b\bar{b}$ and $c\bar{c}$ components have to be Monte Carlo simulated as a function of the particle lifetimes. The fit yields

$$\tau(B) = (1.25 \pm^{0.26}_{0.19} \pm 0.32) \cdot 10^{-12} \text{sec.}$$

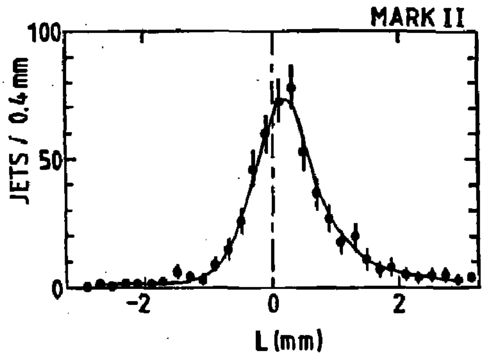

Fig. 17 Distribution of path lengths for lepton enriched $b\bar{b}$ jets by Mark II.

Table 5
Recent Measurements of the Beauty Lifetime

Experiment	Decays	Beauty Fraction	Length (μm)	$\tau(10^{-12}s)$
MAC [56,57]	505	0.53	70±22	0.81±0.28±0.17
Mark II [58]	272	0.64	80±17	0.85±0.17±0.21
DELCO [59,60]	115	0.77	215±81	1.47±0.30±0.29
JADE [26]	99	0.82	330±56	$1.80\pm^{0.5}_{0.3}\pm0.4$
TASSO [61,62]	406	0.30	92±17	$1.57\pm0.32\pm^{0.37}_{0.34}$
Mark II [63]	551	0.64	413±43	$1.25\pm^{0.26}_{0.19}\pm0.40$

A compilation of the six recent measurements of the B lifetime is given in Table 5. The experiments agree reasonably well and confirm that the lifetime is of the order of 1 psec. The systematic errors remain substantial because of uncertainties in the sample purities, resolutions, systematic biases, etc. Certain assumptions in the modelling of the hadronic final states are common among the experiments, leading to errors that are not totally independent. The weighted average of the measurement is

$$\tau(B) = (1.12 \pm 0.16) \cdot 10^{-12} \text{sec.}$$

As pointed out earlier, the B lifetime can be related to the Kobayashi-Maskawa matrix elements V_{cb} and V_{ub} that represent the coupling of the charged current to the b quark. Based on Equation 2, one obtains

$$|V_{cb}|^2 = BR\,(b \to Xe\nu)\, K_{cb}\, R_b/(1+R_b)\, \tau_b$$

$$|V_{ub}|^2 = C_{cb}\, R_b\, |V_{cb}|^2,$$

where the constants C_{cb} and K_{cb} are correction factors due to phase space and QCD. They depend on the quark masses m_u, m_c, m_b and have been determined from a detailed study of the lepton spectra in semileptonic decays of charm and beauty mesons[64], $K_{cb} = 2.353 \pm 0.134$ and $C_{cb} = 0.442 \pm 0.040$. Combining measurements from CUSB[65], CLEO[66] and ARGUS[67], the best limit on the ratio $R_b = \Gamma(b \to u)/\Gamma(b \to c)$ at 90% confidence level is $R_b < 0.03$. Based on measurements at CESR, the semileptonic branching ratio of B mesons is $11.8 \pm 0.36 \pm 0.75$[65,66]. Thus with an average B lifetime of 1.1 ± 0.2 one obtains

$$|V_{cb}| = 0.049 \pm 0.005 \quad \text{and} \quad |V_{ub}| < 0.006.$$

With this additional input and the unitarity condition, the absolute values of all elements of the 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 third generation of quarks. The small value of $|V_{bc}|$ imposes interesting constraints on the top mass[68], the ratio of ϵ'/ϵ in K^0 decay[70] and mixing and CP violation in beauty meson decay[71].

7. CONCLUSIONS

The present situation can be summarized as follows

- Measurements of the lifetime of the τ lepton support the concept of lepton universality.

- Lifetimes of different charm particles differ,

$$\tau(D^+) > \tau(D^o) \geq \tau(\Lambda_c^+)$$

and

$$\tau(\Omega^o_c) \geq \tau(\Xi_c^+) \geq \tau(\Lambda_c^+).$$

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. Fortunately, there is new information on many exclusive channels available from the Mark III and ARGUS experiments. In particular, the observation of $D^o \to K_s\phi$ supports contributions from W exchange, while the relatively large branching ratios for $D^o \to \bar{K}^o\pi^o$ and $D^+ \to \phi\pi^+$ suggest the absence of colour suppression. The large rate of the $D^+ \to \bar{K}^oK^+$ relative to $\bar{K}^o\pi^+$ could be explained by interference effects in D^+ decay, and may be contributing to a reduced hadronic width.

- One spectacular, hadro-produced $B^-\bar{B}^o$ event places the cross-section at roughly 1 nb, and this experiment could give us a few more events to determine the average lifetime. Six measurements at e^+e^- machines give an average B-lifetime of $(1.1\pm0.2)\cdot10^{-12}$sec. This establishes a rather small mixing for quarks of the third and second generation.

In summary, lifetime measurements are very difficult experimentally, and orders of magnitude more data are needed to study lifetime for individual charm and beauty mesons and baryons. Many experiments are presently underway, NA-14 and NA-32 at CERN, E-690, E-653 and E-687 at FNAL, MAC and HRS at SLAC, as well as TASSO and ARGUS at DESY and CLEO at Cornell. It is an enormous effort, but it is fun. It may take a decade or two to perfect measurements of heavy flavour lifetimes and couplings, but remember, it took two millenia to develop "La Haute Cuisine et les Grands Crus de la Bourgogne".

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