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Lifetimes of Heavy Flavour Particles

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Abstract

The lifetimes of heavy-flavour hadrons are reviewed. After a brief discussion of the theoretical predictions, the problem of averaging lifetime measurements is discussed. The various experimental measurements are then presented and suitable averages performed. Charmed meson lifetimes are now measured to the few percent level, better than theory can predict, whilst for charmed baryons the lifetime hierarchy has been established for the first time. For beauty hadrons the lifetimes are measured at the 5–10 % level, and are in reasonable agreement with theoretical expectations. Beauty baryon studies are just beginning.

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1 Introduction

The lifetimes of weakly-decaying hadrons containing a heavy quark are important for the following reasons:

1. to gain an understanding of hadron dynamics: including the effects of non-perturbative strong interactions and phenomena such as W-exchange;
2. for the extraction of the CKM matrix element V_{cb};
3. as a tool: knowledge of the lifetimes is essential for calibrating b-tagging algorithms (widely used in Higgs and top-quark searches), and for the study of time-dependent B^0–$\overline{B}^0$ mixing and CP violation in the b system.

'Heavy' in this context means that the quark mass should be large compared to the strong interaction scale ($\Lambda_{\rm QCD} \sim 200\,$MeV). This is perhaps marginal for the charm quark ($m_c \sim 1.5\,$GeV), but should be a good approximation for the b quark ($m_b \sim 5\,$GeV). It is also manifestly true for the top quark ($m_t \sim 174\,$GeV); however, top is heavy enough to decay to a b quark and real W, and the relevant CKM matrix element is close to unity, so the predicted top-quark lifetime is of order $10^{-24}\,$s. In other words $\Gamma_t \gg \Lambda_{\rm QCD}$ and the top quark will decay before hadronising; it will not be considered further here.

In the spectator model, the decay of a heavy quark Q is considered to be independent of the other light quark in the meson (or diquark in a baryon). For semileptonic decays there is then a close analogy to muon decay (see Figure 1), for which the decay width is well known:

$$\Gamma(\mu \to e\nu_e\overline{\nu}_\mu) = \frac{G_F^2\, m_\mu^5}{192\,\pi^3} \sim 5 \times 10^5\,{\rm s}^{-1}\ . \tag{1}$$

Similarly:

$$\Gamma_Q^{s\ell} \equiv \Gamma(Q \to q\ell\nu) = \frac{G_F^2}{192\,\pi^3}\, m_Q^5\, f\, |V_{Qq}|^2\ , \tag{2}$$

where f is a phase-space factor and V_{Qq} is the CKM matrix element that quantifies the weak coupling between the heavy quark Q and its decay product. For charm, $V_{cs} \sim 1$, $f \sim 0.5$ and thus $\Gamma_c^{s\ell} \sim 1.3 \times 10^{11}\,{\rm s}^{-1}$. Naively the total decay width $\Gamma_c = 5\,\Gamma_c^{s\ell}$ since the virtual W couples to $e\nu$, $\mu\nu$ or $u\overline{d}$ (with a factor 3 from colour for the hadronic decay). Thus in this simple picture the lifetime of charmed hadrons $\tau_c = 1/\Gamma_c \sim 10^{-12}\,$s, which is in reasonable agreement with experiment. For beauty, since $\tau \sim 1/m_Q^5$ one might expect $\tau_b \ll \tau_c$, but this is counteracted by the small coupling $V_{cb} \sim 0.04$. There are also extra final states open to the W: as well as $e\nu$, $\mu\nu$ or $u\overline{d}$ with phase space factor $f \sim 0.45$, there are also $\tau\nu$ and $c\overline{s}$ (again with a factor 3 from colour), both with phase space factors $f \sim 0.12$. Thus $\Gamma_b \sim 6\,\Gamma_b^{s\ell}$, and $\tau_b \approx \tau_c \sim 10^{-12}\,$s.

Figure 1: Diagrams for (a) muon decay, (b) semileptonic decay of a heavy-quark hadron.

Figure 2: Diagrams for hadronic spectator decay of a charmed particle: (a) colour allowed, (b) colour suppressed.

Of course, in the naive spectator model, all hadrons with a particular heavy quark are predicted to have equal lifetime. Experimentally $\tau(D^+) \sim 2.5 \times \tau(D^0)$, so at least for the charm system this is not a very good approximation. However, when the effects of the strong interaction are included, hadronic decays proceed via two diagrams as shown in Figure 2: the second of the two is known as 'colour suppressed', as the hadron containing the spectator quark also takes a quark from the W, which would naively lead to a suppression factor as the colour of the two quarks must be matched. For the D^+ both diagrams lead to the same final state, and thus interference can occur. The interference is destructive and thus decreases the hadronic partial width: $\Gamma^{had}(D^+) \sim \frac{1}{3}\Gamma^{had}(D^0)$, increasing the D^+ lifetime.

There are also non-spectator decays, illustrated in Figure 3. The D_s^+ can decay leptonically via annihilation of its c and $\overline{s}$ quarks, as shown in Figure 3 (a). This process is helicity suppressed, however, since a spin-zero state cannot decay to a massless fermion-antifermion pair; although the charged lepton mass is non-zero, it is still small, and the partial width satisfies $\Gamma(D_s^+ \to \ell\nu) \propto f_{D_s}^2 m_\ell^2$, where f_{D_s} is the D_s^+ decay constant (characterizing the probability that the annihilation occurs) and m_ℓ is the lepton mass. For hadronic decays, the non-spectator contributions take the form of either annihilation or W-exchange diagrams as shown in Figures 3 (b) and (c). Here the helicity suppression may be reduced by gluon exchange, but the contribution is still expected to be small. For baryons, on the other hand, the extra spectator quark removes the helicity suppression and the W-exchange contribution, shown in Figure 3 (d), is expected to be more significant. (There is, of course, no annihilation diagram for the baryons.)

These considerations lead to the qualitative expectation for the charm lifetime hierarchy of: $\tau(D^+) > \tau(D^0) \approx \tau(D_s^+) > \tau(\Lambda_c^+)$. For beauty the spectator model is expected to be a better approximation; a similar hierarchy is predicted: $\tau(B^+) > \tau(B^0) \approx \tau(B_s^0) > \tau(\Lambda_b^0)$, but the magnitude of the differences scale with $1/m_Q^2$ and thus should be $\lesssim 10\,\%$. A comprehensive analysis within the framework of Heavy Quark Effective Theory gives (to a few percent

Figure 3: Diagrams for non-spectator decays of charmed particles: (a) leptonic decay, (b) hadronic annihilation, (c) mesonic W-exchange, (d) baryonic W-exchange.

accuracy) [1]:

$$\begin{aligned} \tau(B^+)/\tau(B^0) &= 1.0 + 0.05 \left(\frac{f_B}{200\,\mathrm{MeV}} \right)^2 , \\ \tau(B_s^0)/\tau(B^0) &= 1.0 , \\ \tau(\Lambda_b^0)/\tau(B^0) &\approx 0.9 . \end{aligned} \tag{3}$$

For the neutral mesons there is a further effect due to particle-antiparticle mixing, which results in a lifetime difference between the weak eigenstates. For the B^0 this is expected to be small, $\Delta\Gamma(B^0)/\Gamma < 1\,\%$, but for the B_s^0 [1]:

$$\frac{\Delta\Gamma(B_s^0)}{\Gamma} \sim 0.18 \left(\frac{f_{B_s}}{200\,\mathrm{MeV}} \right)^2 , \tag{4}$$

which could thus be the largest lifetime difference in the b system! Such an effect is difficult to measure, but could be seen as a difference in the lifetime measured for the B_s^0 when it decays to a CP eigenstate such as $J/\psi\phi$, compared to that measured with semileptonic decays:

$$\tau^{-1}(B_s^0 \to J/\psi\phi) - \tau^{-1}(B_s^0 \to \ell X) \simeq \left| \frac{\Delta\Gamma(B_s^0)}{2} \right| . \tag{5}$$

2 Averaging lifetime measurements

Various schemes have previously been used to average lifetime measurements from different experiments. The naive approach is simply to weight the measurements according to their error: thus for a measurement $\tau_i \pm \sigma_i$ the weight is taken as $1/\sigma_i^2$. But lifetime measurements have an underlying exponential distribution, so $\sigma_i \propto \tau_i$; if a measurement fluctuates low then its weight in the average will increase, leading to a bias towards low values. An alternative method, to avoid this bias, is to calculate the weight using the *relative* error σ_i/τ_i. That this

Figure 4: Weighted mean of many samples, each of N events: (a) weighting with the absolute error σ_i, (b) weighting with the relative error σ_i/τ_i.

is not just an academic question can be illustrated using the world averages quoted for the B_s^0 at the Winter Conferences this year:

$$\begin{aligned} \tau(B_s^0) &= (1.38 \pm 0.17)\,\mathrm{ps} \quad \text{(la Thuile [2])}\ , \\ \tau(B_s^0) &= (1.66 \pm 0.22)\,\mathrm{ps} \quad \text{(Moriond [3])}\ , \end{aligned} \tag{6}$$

even though both averages were performed using essentially the same data! In the first case the absolute error was used in the weight, whilst in the second case the relative error was used.

This issue can be clarified using a simple Monte Carlo: a sample of N events is generated according to an exponential distribution (with $\tau = 1$), smeared by a Gaussian resolution function (with r.m.s width w). The mean τ_i and variance σ_i^2 of the events is then calculated, simulating a single lifetime measurement. This is then repeated for many samples, and their weighted mean calculated. See Figure 4. Weighting with the absolute error, as shown in Figure 4 (a), a bias to low values is seen, as expected. For perfect resolution ($w = 0$) the bias is about 10 % when the sample size is 20 events, decreasing for higher sample sizes; the effect of finite resolution is to reduce the bias. If instead the samples are weighted according to their relative error, as shown in Figure 4 (b), then for perfect resolution there is no bias. However, as the resolution is degraded a bias appears towards *higher* values. For a resolution typical of the experiments measuring heavy flavour lifetimes with microvertex detectors, $w \lesssim \tau/10$, the bias is a few percent or less; nevertheless it seems worthwhile to try to avoid it.

The bias arises due to the neglect of the asymmetry of the errors for the individual measurements. In an ideal world each experiment would provide the log-likelihood function that they have calculated for their events, these would be summed and then fitted for the combined lifetime. In practice this would be difficult to organize, and there is the additional question of how to include systematic errors. Instead an attempt has been made to reconstruct the likelihood function of each experiment (in the region of the minimum) from the quoted asymmetric errors. For an experiment with perfect resolution, with an underlying exponential

Figure 5: Illustration of the averaging technique: (a) the $-\log \mathcal{L}$ distributions for three hypothetical measurements (relative to their minima); (b) the sum of those log-likelihoods, which provides the average.

distribution, the form of the likelihood function is maximally asymmetric and can be calculated:

$$\ln \mathcal{L}_{\mathrm{E}}(\tau) = -N \left(\frac{\tau_i}{\tau} + \ln \tau \right) . \tag{7}$$

In the limit of poor resolution the likelihood function is symmetric:

$$\ln \mathcal{L}_{\mathrm{G}}(\tau) = -\frac{1}{2} \left(\frac{\tau_i - \tau}{w} \right)^2 . \tag{8}$$

The approximation is made that the likelihood function for a given experiment is a linear combination of these two forms:

$$\ln \mathcal{L} = a \ln \mathcal{L}_{\mathrm{E}} + b \ln \mathcal{L}_{\mathrm{G}} , \tag{9}$$

and the coefficients a and b are determined from the quoted errors, using (for a value $\tau\ {}^{+\sigma_1}_{-\sigma_2}$) $\ln \mathcal{L}(\tau + \sigma_1) = \ln \mathcal{L}(\tau - \sigma_2) = \ln \mathcal{L}(\tau) - \frac{1}{2}$. The functions $-\ln \mathcal{L}$ are then summed for all of the experiments, and a fit is made for the minimum of their sum, which gives the average. This is illustrated in Figure 5, where three hypothetical measurements are shown, with errors that are respectively maximally asymmetric, symmetric, and somewhere between the two extremes. Their estimated negative log-likelihood functions are shown in Figure 5 (a), and the summed log-likelihood in Figure 5 (b).

A final complexity is the treatment of correlated systematic errors: a second parameter is added to the fit, to allow a common movement of the mean, with a Gaussian constraint applied according to the correlated error. The result of this approach when applied to the B_s^0 data from the Winter Conferences is $\tau(B_s^0) = (1.56\ {}^{+0.20}_{-0.18})$ ps, which lies between the values quoted above in Equation (6). (Those two extremes are reproduced if the likelihood is forced to be symmetric, or maximally asymmetric, respectively.)

3 Charmed particle lifetimes

Charm lifetime measurements are dominated by fixed target experiments with microstrip detectors. Most of the recent results come from E687, a photoproduction experiment with $\langle E_\gamma \rangle \sim 220\,\mathrm{GeV}$ at Fermilab. The experiment has 12 planes of silicon microstrips arranged into a telescope just downstream from a beryllium target, followed by a magnetic spectrometer with three threshold Čerenkov detectors and calorimeters; 510,000,000 events were written to tape. A selection of their beautiful charm signals is shown in Figure 6, where the signal-to-background has been enhanced by cutting on the decay-length significance: $N_\sigma = d/\sigma_d$.

The lifetimes are extracted using a binned maximum-likelihood technique, fitting to the reduced proper time $t' = (d - N_\sigma\,\sigma_d)/\beta\gamma c$, where β and γ are the relativistic velocity and boost of the charmed particle. The number of events predicted in a reduced proper-time bin

$$n_i = N_S \,\frac{f(t_i)\,\mathrm{e}^{-t_i/\tau}}{\Sigma f(t_i)\,\mathrm{e}^{-t_i/\tau}} + N_B\,\frac{b_i}{\Sigma b_i}\ , \tag{10}$$

where N_S and N_B are the number of signal and background events respectively and b_i is the number of background events in bin i, determined using the sidebands; $f(t)$ is an acceptance correction factor that is derived using Monte Carlo simulation, as shown in Figure 7. As can be seen, for the D^0 the acceptance is almost flat with reduced proper time, whilst for the D^+ a loss of acceptance is seen at long proper time due to a fiducial cut which is applied

Figure 6: Charm signals from E687: (a) $D^0 \to K^-\pi^+$ (from $D^{*+} \to D^0\pi^+$) with $N_\sigma > 5$ [4]; (b) $D^+ \to K^-\pi^+\pi^+$ with $N_\sigma > 15$ [4]; (c) $D^+, D_s^+ \to \phi\pi^+$ with $N_\sigma > 3$ [5]; (d) $\Lambda_c^+ \to pK^-\pi^+$ with $N_\sigma > 4$ [6].

Figure 7: Reduced proper-time acceptance from the Monte Carlo simulation of E687 (a) for the D^0, (b) for the D^+.

Figure 8: Reduced proper-time distributions from E687 (a) for the D^0, (b) for the D^+; the dashed histograms show the background distribution.

before the first microstrip plane. The resulting proper time distributions are shown in Figure 8, demonstrating a clear exponential character. A detailed study of systematic biases has been performed, checking that there is no significant variation of the result as various parameters such as the decay-length significance cut are varied. The lifetime measurements give

$$\frac{\tau(D^+)}{\tau(D^0)} = 2.54 \pm 0.04 \ , \qquad (11)$$

$$\frac{\tau(D_s^+)}{\tau(D^0)} = 1.15 \pm 0.05 \ .$$

These values are in good agreement with the previous world averages, as shown in Figure 9, and are of a comparable precision; the new averages are shown in the figure. The precision on the charmed-meson lifetime measurements is currently greater than the ability to calculate them, and the focus now moves to charmed baryons.

Only singly-charmed baryons have been discovered so far, and of these only four are weakly decaying: the Λ_c^+, Ξ_c^+, Ξ_c^0 and Ω_c^0. As mentioned in Section 1, for the baryons W-exchange is not helicity suppressed and is large if the baryon contains a d quark (which is the case for the Λ_c^+ and Ξ_c^0). The presence of a u spectator quark leads to destructive interference (for the Λ_c^+ and Ξ_c^+) whilst the presence of an s spectator quark leads to *constructive* interference (for

Figure 9: Comparison of the E687 charm lifetime measurements with the previous world averages. In this and subsequent summary plots, the $\pm 1\sigma$ error of the new average is displayed as a shaded band.

the Ξ_c^+, Ξ_c^0 and Ω_c^0). Taking these considerations into account, different authors have predicted different lifetime hierarchies for the charmed baryons:

$$\begin{aligned} \tau(\Omega_c^0) \approx \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+) \;\; [7] \; , \\ \tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) \approx \tau(\Xi_c^+) \;\; [8] \; , \\ \tau(\Lambda_c^+) \approx \tau(\Xi_c^0) < \tau(\Omega_c^0) < \tau(\Xi_c^+) \;\; [9] \; . \end{aligned} \qquad (12)$$

For the Ξ_c^+ there is data from the WA89 experiment at CERN that uses a 330 GeV hyperon (Σ^-) beam and has recorded 300,000,000 events. They see a signal for $\Xi_c^+ \to \Lambda K^- \pi^+ \pi^+$, shown in Figure 10 (a). Experiment E687 have a signal for $\Xi_c^+ \to \Xi^- \pi^+ \pi^+$, and also for $\Xi_c^0 \to \Xi^- \pi^+$, shown in Figure 10 (b), which gives only the second measurement of this particle's lifetime. For the Ω_c^0 the first observation was made by WA62 in 1985, with only three events seen in the channel $\Omega_c^0 \to \Xi^- K^- \pi^+ \pi^+$ [13]. No lifetime measurement was quoted, but an average of the proper times of the events gave a rather large value of (0.79 ± 0.34) ps, in contrast to the theoretical expectations. Now there are strong signals from E687 for $\Omega_c^0 \to \Sigma^+ K^- K^- \pi^+$ and $\Omega_c^0 \to \Sigma^+ K^- K_S^0$, where no N_σ cut is applied, bearing in mind the short expected lifetime. See Figures 10 (c) and (d). They do not quote a final lifetime yet, but their measured value appears

Figure 10: Charmed baryon signals: (a) $\Xi_c^+ \to \Lambda K^- \pi^+ \pi^+$ from WA89 [10]; (b) $\Xi_c^0 \to \Xi^- \pi^+$ from E687 [11]; (c) $\Omega_c^0 \to \Sigma^+ K^- K^- \pi^+$ from E687 [12]; (d) $\Omega_c^0 \to \Sigma^+ K^- K_S^0$ from E687 [12].

to be similar to their resolution ~ 0.04 ps [12]. The charmed baryon lifetime measurements are summarised in Figure 11, and support the prediction of Guberina *et al.* [7].

4 Inclusive b lifetime

Beauty lifetime measurements are dominated by colliding beam machines: LEP and the Tevatron. At LEP each of the four experiments has almost 2,000,000 $Z \to q\overline{q}$ events of which $\sim 22\,\%$ are $b\overline{b}$. CDF at the Tevatron has taken ~ 21 pb of integrated luminosity with a single-lepton or dilepton trigger, corresponding to 250,000 $b \to \ell\nu X$ and 25,000 $b \to J/\psi X$. All of these experiments are instrumented with cylindrical silicon vertex detectors (the L3 silicon detector was only recently installed so they feature less strongly in the current results).

Early b lifetime results from the PEP and PETRA machines were inclusive, using the lepton impact parameter technique: studying the distance of closest approach of leptons (from semileptonic b decay) to their production point, typically determined from the beam spot position. Similar analyses have been performed at LEP with greater precision, due to the

Figure 11: Summary of charmed baryon lifetime measurements. The values given for the Ω_c^0 are not official: that from WA62 is an average of the proper times of their three events, whilst that from E687 is a first estimate. In this and subsequent summary plots, the full error bar shows the sum in quadrature of statistical and systematic errors, whilst the small ticks indicate the statistical error alone.

higher statistics and improved resolution. Leptons are selected with high momentum (due to the hard b fragmentation) and with high transverse momentum (due to the large b mass), providing a $\sim 90\,\%$ pure b-decay sample. The lepton three-dimensional impact parameter can then be studied, as shown in Figure 12 (a). An alternative is to determine the decay length in hadronic events using inclusive vertexing as shown in Figure 12 (b). By comparing the measured distributions to Monte Carlo simulation the inclusive lifetime can be extracted; this is limited by systematic uncertainties, particularly in the modelling of the b decay. Another technique uses reconstructed J/ψ's, which at LEP are almost entirely from b decays. The apparent decay length d of the J/ψ is measured, with typical resolution $\sim 200\,\mu$m, and this is converted to proper time $t = d\, m_b/p_b$, using for example a nucleated-jet technique to determine the b-hadron momentum starting with the momentum of the J/ψ, with a relative precision of typically $\sim 20\,\%$. See Figures 12 (c) and (d).

The measurements of the inclusive b lifetime are summarized in Figure 13. Their average

Figure 12: Inclusive b lifetime measurements: (a) the three-dimensional impact parameter distribution for leptons from ALEPH [19]; (b) the decay-length distribution in hadronic events from DELPHI [20]; (c) invariant mass for $\mu^+\mu^-$ and e^+e^- from ALEPH, showing signals for J/ψ and ψ' [21]; (d) proper-time distributions for the signal regions in (c) and for the background.

gives $\langle\tau_b\rangle = (1.524 \pm 0.027)\,\mathrm{ps}$.[1] This is substantially higher than the 1992 world average of $(1.29 \pm 0.05)\,\mathrm{ps}$, continuing the general trend of the measured average to increase over the last few years; it has at least been relatively stable since last year. One might worry about the effect of a lifetime difference between different b-hadron species on the average: this would tend to *increase* the value measured using leptons, as the semileptonic branching ratios would be proportional to the species' lifetimes; it is however a second order effect, and should be less than a percent or so—there is no evidence of such an effect in the data.

The inclusive b lifetime, along with the semileptonic branching ratio, can be used to

[1] This result differs from the value of $(1.55 \pm 0.06)\,\mathrm{ps}$ quoted by Roudeau at the Glasgow conference the following month: he selected the four most precise measurements (plus a new result from SLD), and chose to inflate the error.

Figure 13: Summary of inclusive b-hadron lifetime measurements. The top value (from the 1992 world average) is included for comparison only—it is not used in the new average.

extract the CKM element V_{cb}. From Equation (2) (with the addition of $b \to u$ transitions):

$$f_c |V_{cb}|^2 + f_u |V_{ub}|^2 = \frac{192\,\pi^3}{G_F^2\, m_b^5} \, \frac{\mathrm{B}(b \to \ell \nu X)}{\langle \tau_b \rangle} \;, \tag{13}$$

where the coefficients $f_q(m_q/m_b, \alpha_S)$ have been calculated [28]; they correct for phase space and QCD effects, and are anticorrelated with m_b. Taking $m_b = (5.0 \pm 0.3)\,\mathrm{GeV}$, $m_b - m_c = (3.3 \pm 0.1)\,\mathrm{GeV}$ [29] and $\mathrm{B}(b \to \ell\nu X) = (11.0 \pm 0.5)\,\%$ [30], the resulting constraint on the (V_{cb}, V_{ub}) plane is labelled 'inclusive lepton' in Figure 14. The $\Upsilon(4S)$ experiments give $|V_{ub}/V_{cb}| = 0.08 \pm 0.02$ [30], which provides the second band in the figure, and from the region allowed by both constraints:

$$|V_{cb}| = 0.041 \pm 0.002 \; {}^{+0.004}_{-0.003} \;. \tag{14}$$

The first error is from the uncertainties in $\mathrm{B}(b \to \ell\nu X)$ and $\langle \tau_b \rangle$, whilst the second error is dominated by the uncertainty on m_b: even though the error on $\langle \tau_b \rangle \sim 2\,\%$, the error on $V_{cb} \sim 10\,\%$ due to the m_b^5 dependence.

Figure 14: Extracting V_{cb} from the inclusive b lifetime measurement.

5 Exclusive b lifetimes

The B^+ and B^0 are produced copiously at the $\Upsilon(4S)$, but almost at rest. However:

$$\begin{aligned} \frac{\tau(B^+)}{\tau(B^0)} &= \frac{\Gamma(B^0)}{\Gamma(B^+)} = \frac{\Gamma(B^0)}{\Gamma_{s\ell}} \frac{\Gamma_{s\ell}}{\Gamma(B^+)} \\ &= \frac{\mathrm{B}(B^+ \to X\ell^+\nu)}{\mathrm{B}(B^0 \to X\ell^+\nu)} \, , \end{aligned} \tag{15}$$

assuming that the semileptonic widths $\Gamma_{s\ell}(B^+) = \Gamma_{s\ell}(B^0)$, since the spectator model should hold for semileptonic decays. The B^+ and B^0 can be identified using $D^{(*)}\ell$ correlations, since:

$$\begin{aligned} B^+ &\to \overline{D}^0 \ell^+ \nu \\ B^0 &\to D^{*-} \ell^+ \nu \, . \end{aligned} \tag{16}$$

This assignment is confused by the subsequent decay $D^{*-} \to \overline{D}^0 \pi^-$, but this occurs with a known branching ratio. More troublesome is the contribution from higher excited charm states, referred to generically as D^{**}, which lead to decays such as $B \to D^{**}\ell\nu \to D\,\pi\ell\nu$; such decays are believed to account for 20–30 % of the semileptonic B decays, but are rather poorly known at present. Finally the assumption is made that the production rates of B^+ and B^0 at the $\Upsilon(4S)$ are equal.

To avoid these uncertainties, CLEO [31] has fully reconstructed B decays, using an impressive selection of channels: $B^+, B^0 \to D^{(*)}\pi^-$, $D^{(*)}\rho^-$, $D^{(*)}a_1^-$, $J/\psi K^{(*)}$, with:

$$\begin{aligned} D^{*+} &\to D^0\pi^+,\ D^+\pi^0 \\ D^{*0} &\to D^0\pi^0 \\ D^0 &\to K^-\pi^+,\ K^-\pi^+\pi^0,\ K^-\pi^+\pi^+\pi^-,\ K_S^0\pi^0,\ K_S^0\pi^+\pi^- \\ D^+ &\to K^-\pi^+\pi^+,\ K_S^0\pi^+ \\ J/\psi &\to e^+e^-,\ \mu^+\mu^- \, . \end{aligned} \tag{17}$$

They find a signal of 834 ± 42 B^+ decays, shown in Figure 15. Similarly they find 515 fully-reconstructed B^0 decays, which they supplement with partially-reconstructed decays using $\ell\pi$

Figure 15: Invariant mass plot of fully reconstructed B^+ candidates from CLEO [31]: (a) the full sample; (b) requiring a lepton to be present.

correlations from $B^0 \to D^{*-}\ell^+\nu \to \overline{D}^0\pi^-\ell^+\nu$ and $\pi\pi$ correlations from $B^0 \to D^{*-}\pi^+ \to \overline{D}^0\pi^-\pi^+$. They then measure the fraction of B events with an identified lepton, leading to:

$$\begin{aligned} \mathrm{B}(B^+ \to X\ell^+\nu) &= (10.1 \pm 1.8 \pm 1.4)\,\% \\ \mathrm{B}(B^0 \to X\ell^+\nu) &= (10.9 \pm 0.7 \pm 1.1)\,\% \ , \end{aligned} \tag{18}$$

and hence $\tau(B^+)/\tau(B^0) = 0.93 \pm 0.18 \pm 0.12$ using Equation (15).

$D^{(*)}\ell$ correlations are also studied at LEP, but there a direct measurement of the decay length is possible, by vertexing the decay products. The decay length is converted into proper time by estimating the B momentum from that of the $D\ell$ combination, with correction for the missing neutrino from Monte Carlo simulation. The resulting proper-time distributions from such an analysis are shown in Figure 16 (a). Relating the measured lifetimes $\tau(D^{(*)}\ell)$ to the B^+ and B^0 lifetimes suffers from the D^{**} uncertainty discussed above.

An alternative technique has been pioneered by DELPHI [23], using topological vertexing to measure the decay time, and determining the B charge by counting the tracks from the decay vertex. Care must be taken to exclude events with tracks that are ambiguous between production and decay vertices, which is achieved by cutting on the χ^2 difference between the various assignments. Requiring at least three tracks from the decay vertex, with an invariant mass of greater than 2.2 GeV, they find 1816 candidates with a b purity $\sim 99\,\%$. The charge is found to be correctly determined in $\sim 70\,\%$ of the cases, by studying multiply-charged vertices. The proper time is measured for each vertex, relative to the point at which the vertex would no longer be resolved: this gives a distribution that is close to exponential, as seen in Figure 16 (b). The resulting lifetimes are:

$$\begin{aligned} \tau(B^+) &= (1.72 \pm 0.08 \pm 0.06)\,\mathrm{ps} \\ \tau(b^0) &= (1.63 \pm 0.11 \pm 0.07)\,\mathrm{ps} \ . \end{aligned} \tag{19}$$

With assumptions on the B_s^0 and Λ_b^0 production fractions and lifetimes, the neutral b lifetime

Figure 16: Measuring the B^+ and B^0 lifetimes: (a) proper-time distributions from OPAL [32] for $D^0\ell$ and $D^*\ell$ events, the dashed curves are show the distribution after background subtraction; (b) proper-time distributions for topologically vertexed events from DELPHI [23] (relative to the point at which the vertex would no longer be resolved) for neutral and charged vertices; (c) invariant mass plot for fully reconstructed B^+ and B^0 decays from ALEPH [21].

can be related to $\tau(B^0)$. This analysis is remarkable for the small systematic errors that are claimed.

The full reconstruction of B^+ and B^0 mesons has been pursued by CDF and ALEPH. CDF [33] use their large sample of J/ψ's; they reconstruct 148 ± 16 $B^+ \to J/\psi K^+$, $J/\psi K^{*+}$ and 121 ± 16 $B^0 \to J/\psi K^0_S$, $J/\psi K^{*0}$. ALEPH [21] have studied a large number of channels, similar to those listed in Equation (17), and find 38 B^+ and 44 B^0, shown in Figure 16 (c).[2] The boost reconstruction is, of course, no problem for these events (the resolution is typically a fraction of a percent); the main limitation is statistics. The measurements of the B^+ and B^0

[2] The lifetime measurements using these events were not ready for this conference (they were shown at Glasgow), so earlier results are quoted from about half the statistics.

Figure 17: Summary of B^+ lifetime measurements.

Figure 18: Summary of B^0 lifetime measurements.

Figure 19: Summary of B^+/B^0 lifetime ratio measurements; in the upper part of the plot direct measurements are displayed, whilst in the lower part indirect results from the ratio of branching fractions are given.

lifetimes, and their ratio, are summarized in Figures 17, 18 and 19.

For the B_s^0 lifetime, $D_s^- \ell^+$ correlations can be used, from the semileptonic decay $B_s^0 \to D_s^- \ell^+ X$. The backgrounds from $B \to D_s^{(*)-} X_s \ell^+ \nu$ and $B \to D_s^{(*)-} D$ with $D \to X \ell^+ \nu$ are expected to be small, $< 5\,\%$. The D_s^- invariant mass plot for right-sign $D_s^- \ell^+$ combinations in an analysis from CDF [38] are shown in Figure 20 (a), with a clear signal of 76 ± 8 events. No enhancement is seen in the wrong-sign $D_s^+ \ell^+$ combinations. CDF perform a fit to the 'pseudo-$c\tau$', given by $d\,m(B_s)/p_T(D_s \ell)$, as shown in Figure 20 (b), and extract a lifetime of $\tau(B_s^0) = (1.42 \ ^{+0.27}_{-0.23} \pm 0.11)$ ps. They also have a signal for the fully reconstructed mode $B_s^0 \to J/\psi \phi \to \mu^+ \mu^- K^+ K^-$, shown in Figure 20 (c). With the additional requirement of vertex detector hits they are left with 11 signal events, with $c\tau$ distribution shown in Figure 20 (d); the measured lifetime is $\tau(B_s^0) = (1.74 \ ^{+0.90}_{-0.60} \pm 0.07)$ ps. Using these two results, the width difference of the B_s^0 weak eigenstates can be determined, following Equation (5): $|\Delta\Gamma(B_s^0)/\Gamma| = 0.4 \ ^{+1.0}_{-0.7}$. An increase in statistics is clearly necessary to probe the expected width difference. The measurements of the B_s^0 lifetime are summarized in Figure 21.

For the Λ_b^0 lifetime, $\Lambda \ell^-$ correlations can be used, as illustrated in Figure 22 (a). The wrong-sign $\Lambda \ell$ correlations come from Λ's produced in fragmentation; the *excess* in the right-

Figure 20: Measuring the B_s^0 lifetime: (a) $\phi\pi^+$ invariant mass plot from CDF [38], with an associated opposite-sign lepton; (b) proper-time distribution for the B_s^0 signal in (a), with the combinatoric background contribution shown dashed; (c) $J/\psi\phi$ invariant mass plot from CDF [38]; (d) proper-time distribution for the B_s^0 events with vertex detector hits in (c).

Figure 21: Summary of B_s^0 lifetime measurements.

Figure 22: Measuring the Λ_b^0 lifetime: (a) $p\pi^-$ invariant mass plot from OPAL [41], with an associated lepton, with the wrong-sign combinations shown as the shaded histogram; (b) decay-length distribution for the right-sign $\Lambda\ell^-$ events, with the background contribution shown.

sign plot are expected to be dominantly from $\Lambda_b^0 \to \Lambda_c^+\ell^-\nu X$, with $\Lambda_c^+ \to \Lambda X'$. The lifetime can be determined from the decay length measured to the $\Lambda\ell$ vertex, since the Λ_c^+ lifetime is short; see Figure 22 (b). The Λ_b^0 lifetime measurements are summarized in Figure 23. There is a new result from DELPHI [23] for another b baryon, the Ξ_b, for which they use $\Xi^-\ell^-$ correlations, with $\Xi^- \to \Lambda\pi^-$. These are expected to be dominantly from $\Xi_b^- \to \Xi_c^0\ell^-\overline{\nu}X$ or $\Xi_b^0 \to \Xi_c^+\ell^-\overline{\nu}X$, with $\Xi_c \to \Xi^-X'$. A possible contribution from $\Lambda_b^0 \to \Lambda_c^+\ell^-\overline{\nu}X$ with $\Lambda_c^+ \to \Xi^-K^+\pi^+$ is

Figure 23: Summary of Λ_b^0 lifetime measurements; the χ^2 per degree of freedom of the average is surprisingly small.

Figure 24: Summary of exclusive b lifetime measurements.

suppressed by the small branching ratio of the latter decay ($\sim 0.3\,\%$) measured by CLEO [43]. DELPHI use a dedicated algorithm to track the Ξ^- in their vertex detector, and find a signal of 10 Ξ_b candidates with little background; a simple average of their proper times gives a lifetime estimate of (1.5 ± 0.6) ps.

The exclusive b lifetimes are summarized in Figure 24, where they are compared to the inclusive measurement discussed in the previous section. As can be seen, the meson lifetimes are all consistent with being equal, whilst the Λ_b^0 has a clearly shorter lifetime: it lies $2.7\,\sigma$ lower than the inclusive value. For a reasonable assumption on the production fractions of the different b-hadron species at LEP, the average calculated using the exclusive lifetimes is (1.60 ± 0.10) ps, in agreement with the inclusive value.

6 Prospects

In the charm sector, experiment E687 should soon provide its official measurement of the Ω_c^0 lifetime, and WA89 expects to have strong signals for all of the charmed-strange baryons. Experiment E791 at Fermilab has taken 20,000,000,000 events on tape using a 500 GeV π^- beam. Their data-taking finished early in 1992, and the processing of the events should finish soon! Meanwhile, from 15 % of their data, they already have clean charm signals—including ~ 400 D_s^+ events with a similar signal-to-background ratio as Figure 6 (c); with their full sample the lifetime measurements could be the most precise yet.

In the beauty sector, fixed target experiment WA92 at CERN has taken data with a 350 GeV π^- beam, and expects to reconstruct a few hundred b decays, with fine decay-length resolution provided by their 10 μm pitch decay detector. For the colliders, LEP expects to have a total of about four million hadronic Z decays per experiment by the end of 1994, and perhaps a further two million in 1995 (although the program for 1995 running is not yet finalised). CDF expect to have four times their current data sample by the end of 1995, whilst SLD hope to have accumulated ~ 0.5 million hadronic Z events by then; with their small beam spot and excellent tracking resolution they may be competitive for B^+/B^0 lifetime measurements.

One of the important goals in the beauty sector is to measure the lifetime of the B_c^+: this is the only weakly-decaying heavy-flavour meson that remains to be discovered. Its predicted mass is ~ 6.3 GeV, and predicted production fraction $f(b \to B_c^+) \sim 10^{-3}$. The decay of the B_c^+ is interesting as it has two heavy quarks, which compete in determining the lifetime. Different models give different weight to the b or c quark decay, and the annihilation diagram, leading to lifetime predictions that range from 0.5 ps [44] to 1.4 ps [45]: its measurement would therefore be valuable.

7 Conclusions

The study of heavy flavour particle lifetimes is an extremely active field. It has received great impetus from the high-statistics samples that are now available (from fixed-target experiments for charm, and from colliders for beauty), coupled with the use of high-resolution microstrip vertex detectors. The following conclusions can be drawn:

1. Charmed meson lifetimes are measured to about $\pm 1\,\%$, more precisely than can be calculated, at least for now.

2. The singly-charmed baryon lifetime hierarchy is now on the point of being established. So far no multiply-charmed baryons have been discovered.

3. After a long and chequered history, the inclusive b lifetime appears to be settling down, with the current world average $\langle \tau_b \rangle = (1.524 \pm 0.027)$ ps, little changed since last year.

4. Beauty lifetime predictions should be more solid than those for charm. They are supported by the current data, although $\tau(\Lambda_b^0)$ is rather lower than expected. By the end of 1995 the errors should decrease by roughly a factor of two, as shown in Table 1.

5. Beauty baryon studies are just beginning, with the first measurement of the Ξ_b lifetime.

6. Measurement of the b-hadron lifetimes to $\pm 1\,\%$, necessary for a stringent test of the theory, will wait for B factories or the LHC.

Table 1: b-hadron lifetime ratio measurements

Ratio	Theory	Experiment	1995 ?
$\tau(B^+)/\tau(B^0)$	1.05	1.01 ± 0.09	± 0.04
$\tau(B_s^0)/\tau(B^0)$	1.00	0.98 ± 0.12	± 0.06
$\tau(\Lambda_b^0)/\tau(B^0)$	0.90	0.71 ± 0.10	± 0.05

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