Review of Charm and Beauty Lifetimes

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Review of Charm and Beauty Lifetimes

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Abstract. A review of the latest experimental results on charm and beauty particle lifetimes is presented together with a brief summary of measurement methods used for beauty particle lifetime measurements. There have been significant updates to the $D^{+}_s/D^0$, $B^+_d/B^0_d$, and $\Lambda^0_b/B^0_b$ lifetime ratios which have some theoretical implications. However more precise measurements are still needed before one can make conclusive statements about the theory used to calculate the particle lifetimes.

INTRODUCTION

Motivation

The study of the charm and beauty particle lifetimes is broadly motivated by two main goals. The first is to convert relative branching fractions to partial decay rates and the second is to learn about the strong interaction.

Experimental data on decays are normally obtained by measuring decay fractions, e.g., $\Gamma(D^0 \rightarrow K^-\pi^+)/\Gamma(D^0 \rightarrow X)$, whereas theory calculates the partial decay rate, e.g., $\Gamma(D^0 \rightarrow K^-\pi^+)$. The lifetime of the particle, $\tau = \hbar/\Gamma(D^0 \rightarrow X)$, is needed in order to convert the experimentally measured decay fractions into decay rates. Not only does this allow tests of theoretical predictions but it also enables the extraction of Standard Model parameters if the theoretical calculations are reliable, e.g., a comparison of $B$ semileptonic decay rates may allow the extraction of $|V_{cb}|$ and $|V_{ub}|$.

The second motivation for the study of lifetimes is that they are interesting in their own right. They allow us to learn more about the “Theoretically-Challenged” part of the Standard Model, i.e., non-perturbative QCD. This is one of the few areas of the Standard Model where experimental data and theoretical ideas closely interact. Although this has been touted as an area of the Standard Model not worth pursuing since a lot more theoretical understanding is needed before tests of the Standard Model can be made, it is also one area that is intellectually interesting.

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For example, even though we have some models, we have little idea about exactly how quarks turn into hadrons. In my view this is new physics since it is beyond what the Standard Model can do right now. Calculations using Lattice QCD are only just now being used to study the dynamics of decays and may start producing reliable results \[1\].

## Decay Diagrams

The lifetime of a particle is given by the following expression:

\[
\tau = \frac{\hbar}{\Gamma_{SL} + \Gamma_{NL} + \Gamma_{PL}}
\]

(1)

where \(\Gamma_{SL}\) is the semileptonic decay rate, \((e.g., \Gamma(D^+ \to \ell^+ \nu \ell X))\), \(\Gamma_{NL}\) is the non-leptonic or hadronic decay rate, \((e.g., \Gamma(D^+ \to \text{hadrons}))\), and \(\Gamma_{PL}\) is the purely leptonic decay rate, \((e.g., \Gamma(D^+ \to \ell^+ \nu \ell))\). Compared to the total rate, the purely leptonic decay rate is normally very small due to helicity suppression.\(^2\) In addition, current data for \(D\) meson decays indicates that the semileptonic rate for \(D^+\) and \(D^0\) are equal within at least about 10\% if not better.\(^3\) This means that the large difference between the observed \(D^+\) and \(D^0\) lifetimes \((\tau(D^+)/\tau(D^0) = 2.55 \pm 0.04)\) is due to a large difference in the hadronic decay rates for the \(D^+\) and the \(D^0\). Thus in contrast to the spectator model \([4]\) which has only the free charm quark decay diagram and predicts equal \(D^+\) and \(D^0\) lifetimes, we need to take into account spectator quark effects. This entails taking into account other decay diagrams like those in Figure 1 and any interferences between them.

The conventional wisdom used to explain the smaller hadronic width of the \(D^+\) relative to the \(D^0\) is that in the \(D^+\) Cabibbo allowed decays \((c \bar{d} \to s(u \bar{d}) \bar{d})\), there

\(^2\) The \(B\) and \(D\) mesons both have spin 0 so that in the decay, the resulting lepton (anti-lepton) and anti-neutrino (neutrino) must both be either left-handed or both right-handed in order to conserve angular momentum. However the \(V - A\) nature of the weak interaction requires left-handed particles and right-handed anti-particles \([2]\).

\(^3\) The semileptonic decay rate is given by the ratio of the semileptonic branching ratio to the lifetime. Using the world average values for these compiled by the Particle Data Group \([3]\), \(\Gamma_{SL}(D^+) = (1.071 \pm 0.119) \times 10^{-12}\) GeV and \(\Gamma_{SL}(D^0) = (1.067 \pm 0.041) \times 10^{-12}\) GeV.
exist identical quarks in the final state unlike for $D^0$, so there are additional (destructive) interference contributions for the $D^+$. Or, if we are talking about exclusive rather than inclusive decays, one can view the interference as that between the external spectator and internal spectator decay diagrams of Figure 1 which can lead to the same exclusive final state. It is relatively easy to show that the additional interference for inclusive hadronic decays for $D^+$ is destructive and can lead to a lifetime ratio of $\tau(D^+)/\tau(D^0) \sim 2.0$. However it is difficult to determine exactly how large a ratio of $\tau(D^+)/\tau(D^0)$ interference effects can accommodate and therefore how large is the additional contribution of Cabibbo allowed W-exchange decays in the $D^0$. Cabibbo allowed $W$-exchange decay is expected to contribute to lowering the $D^0$ lifetime but this contribution is wavefunction and helicity suppressed ($\sim \frac{|V_{cd}|^2 |m_{s}^2}}{m_{c}^2}$) and is difficult to calculate reliably.

Clearly a better understanding of both charm and beauty inclusive decays is necessary. Experimental data on lifetimes from all the charm and beauty particles will allow us to learn more about how they decay and in turn use the data to extract standard model parameters like quark masses and the CKM matrix elements $|V_{cs}|$, $|V_{cd}|$, $|V_{cb}|$ and $|V_{ub}|$.

**Theoretical Overview for Inclusive Decays**

A systematic approach now exists for the treatment of inclusive decays that is based on QCD and consists of an Operator Product Expansion in the Heavy Quark Mass [5]. In this approach the decay rate is given by:

$$\Gamma_{HQ} = \frac{G_F m_Q^5}{192\pi^3} \Sigma f_i |V_{Qq}|^2 \left[ A_1 + \frac{A_2}{\Delta^2} + \frac{A_3}{\Delta^3} + \frac{A_4}{\Delta^4} + \cdots \right]$$

(2)

where the expansion parameter $\Delta$ is often taken as the heavy quark mass and $f_i$ is a phase space factor. $A_1 = 1$ gives the spectator model term and the $A_2$ term produces differences between the baryon and meson lifetimes. The $A_3$ term includes the non-spectator $W$-annihilation and Pauli interference effects. For mesons this term can be related to certain observables whereas for baryons particular quark models or QCD sum rules are needed to determine the parameters fully. Though scaling formally as $1/\Delta^3$, these non-spectator terms actually scale like $f_0^2/M_Q^2$ and thus predict that the lifetime differences for the beauty particles should be about 10% of those seen in charm.

A theoretical review is outside the scope of this article and the reader is referred to other reviews [5].

**REVIEW OF EXPERIMENTAL RESULTS**

There have been new measurements of charm and beauty lifetimes since the 1998 review performed by the PDG [3]. Some are results published in journals while
others were presented at conferences this year. Given the title of this Workshop, it is interesting to note that all the measurements of the $B$ particle lifetimes come from collider experiments whereas all the ones for charm come essentially only from fixed target experiments.

In the past and even today, as well as lifetime measurements of the different species of $B$ particles, measurements are often given for admixtures of $B$ hadrons, either $B^+ / B^0_d$, $B^+ / B^0_s$/$b$-baryon or $b$-baryons. Given how well the lifetimes of the different species of $B$ particles are now measured I think reviewing the measurements of the admixtures no longer makes sense from a physics standpoint. Even the measurement for $b$-baryons is not so much more precise than that for $\Lambda_b^0$, and the $b$-baryons sample contains a large contamination of $\Xi_b$ with unknown lifetime. In the same vein I shall not include lifetime ratios derived from ratios of branching fractions as these involve additional assumptions and also because they do not significantly change the world average values.

**Measurements of Beauty Particle Lifetimes**

Methods used for the measurement of lifetimes of the $B$ mesons can be broadly divided into three classes. The $B$ meson can be completely reconstructed ("Exclusive"); the $B$ meson decay vertex is reconstructed but its momentum is only partially reconstructed ("Inclusive 1"); and neither the $B$ meson vertex nor its momentum is completely reconstructed ("Inclusive 2"). It is interesting to separate the measurements into these three different classes as they have different systematic uncertainties and any differences may reflect effects which are not sufficiently understood.

**Measurements of $B^+$ and $B^0_d$ Lifetimes**

Exclusive reconstruction is performed by the CDF and ALEPH collaborations. CDF uses $B$ meson decays to $J/\psi K$, $J/\psi K^*$, $\psi K$ and $\psi K^*$ [6], whereas ALEPH looks for $B$ decays to $J/\psi K$, $J/\psi K^*$ and $D, D^*$ plus charged pions, (either direct pions or pions from the decay of the $\rho$ or $\omega$) [7]. Measurements are still very much statistics limited since the $B$ meson is completely reconstructed. The dominant systematics in the measurements are from non-Gaussian tails, possibly from mis-reconstruction, and uncertainties in the background lifetime distribution.

The Inclusive 1 reconstruction involves reconstruction of semileptonic decays $B^0_d \rightarrow D^{\ast+}\ell^-X$, $B^0_d \rightarrow D^{\ast0}\ell^-X$ and $B^+ \rightarrow D^0\ell^-X$, where the $D^0$ is explicitly tested to make sure it is not compatible with being from $D^{\ast+} \rightarrow D^0\pi^+$. However there is still contamination or dilution of the $B^+$ sample from $B^0_d$ decays and vice-versa. For example, the $D^{(\ast)+}\ell^-X$ sample can contain 10–25% $B^+$ decays, due to $B^+ \rightarrow D^{(\ast)0}$, $D^{(\ast)0} \rightarrow D^{(\ast)+}\pi^-$. The $B^+$ and $B^0_d$ lifetimes are obtained by a simultaneous fit to the $D^{(\ast)+}\ell^-X$ and $D^{\ast}\ell^-X$ samples. Since the lifetimes of the $B^+$ and $B^0_d$ are so close together the $B$ compositions of the samples are constrained
FIGURE 2. Lifetime measurements for $B^+$ and $B^0_d$ split into the three measurement method classes described in the text.

to be within the uncertainties of measurements for the various branching fractions needed in the calculation of the compositions. In addition, although the $B$ vertex is obtained from the intersection of the $D$ momentum vector and the lepton, the $B$ momentum is not completely determined because of the unobserved neutrino in the $B$ semileptonic decay. A Monte Carlo simulation is used to correct for this effect. The dominant systematic uncertainties for this type of measurement are the uncertainties in the composition and the corrections for the $B$ momentum as well as uncertainties in the background. Measurements using this method have been done by the DELPHI [8] and OPAL [9] collaborations including using the $D^+ \ell ^-X$ sample, whereas the CDF [10] and ALEPH [7] collaborations use only the $D^{*-}\ell^-X$ and $D^0\ell^-X$ samples. L3 only uses their $D^{*-}\ell^-X$ sample in a (single) fit to obtain the $B^0_d$ lifetime [11].

In the "Inclusive" method the $B$ meson decay vertex is not fully reconstructed. This includes a topological/vertex-charge method as well as methods based on the correlations of the $B$ and subsequent charm decay products. The SLD [12], DELPHI [13] and L3 [14] collaborations use a topological method where a well separated (smeared $B$) secondary vertex is reconstructed from charged tracks to help select out a $B$ particle decay and the vertex charge is used to tag whether the decay is from the $B^+$ or from the $B^0_d$. The SLD group also includes an event sample where a lepton is part of the secondary vertex to help further discriminate between $B$ particle decays and background. Of the $B$ particle decays the vertex charge selects out only about 55-77% of the correct $B$ meson type. The fit for the $B^0_d$ and $B^+$ lifetimes are obtained by simultaneously fitting the charged and neutral vertex samples and with the help of Monte Carlo simulations. Since the composition has to be modeled as well as the smearing for both the $B$ decay length and momentum, the measurement of the $B$ lifetimes are already systematics limited for the measurements with the smallest statistical errors [12]. However the measurement of the $B^+/B^0_d$ lifetime ratio is not yet systematics limited. The other measurements
TABLE 1. Summary of $B$ lifetime measurements split by experiment

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\tau(B^+)$ ps</th>
<th>$\tau(B^0_d)$ ps</th>
<th>$\tau(B^+)/\tau(B^0_d)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF$^a$</td>
<td>1.661 ± 0.052</td>
<td>1.513 ± 0.053</td>
<td>1.091 ± 0.050</td>
</tr>
<tr>
<td>SLD$^a$</td>
<td>1.675 ± 0.046</td>
<td>1.586 ± 0.057</td>
<td>1.059 ± 0.039</td>
</tr>
<tr>
<td>L3$^a$</td>
<td>1.662 ± 0.061</td>
<td>1.571 ± 0.058</td>
<td>1.090 ± 0.076</td>
</tr>
<tr>
<td>ALEPH</td>
<td>1.580 ± 0.095</td>
<td>1.550 ± 0.067</td>
<td>1.030 ± 0.082</td>
</tr>
<tr>
<td>DELPHI</td>
<td>1.700 ± 0.090</td>
<td>1.548 ± 0.051</td>
<td>1.050 ± 0.100</td>
</tr>
<tr>
<td>OPAL</td>
<td>1.520 ± 0.166</td>
<td>1.530 ± 0.144</td>
<td>0.990 ± 0.147</td>
</tr>
<tr>
<td><strong>World Average</strong></td>
<td><strong>1.660 ± 0.027</strong></td>
<td><strong>1.551 ± 0.025</strong></td>
<td><strong>1.065 ± 0.026</strong></td>
</tr>
</tbody>
</table>

$^a$ Updated since PDG98

included in this class are from ALEPH [7] and DELPHI [13]. ALEPH used $\pi^-\pi^+_D$ correlations in $\overline{B}^0_d \rightarrow \pi^-\pi^+_D D^{*+}$ ($D^{*+} \rightarrow D^0\pi^+_D$), and DELPHI used $\pi^+_D\ell^-\nu$ correlations in $\overline{B}^0_d \rightarrow D^{*+}\ell^-\nu X$ ($D^{*+} \rightarrow D^0\pi^+_D$) to select out a signal and to fit for the $B^0_d$ lifetime.

The measurements for $\tau(B^+)$, $\tau(B^0_d)$ and $\tau(B^+)/\tau(B^0_d)$ split into the three measurement method classes are shown in Figure 2. One can conclude that no systematic differences between the measurement methods exist to within the current uncertainties. The measurements split by collaboration are summarized in Table 1. Note that each collaboration already did an excellent job of calculating their own averages taking into account the correlations of their measurements using different methods. The LEP B Lifetime Working Group also calculates a world average as well as a LEP average. Using almost the same measurements as input they obtain the following world averages: $\tau(B^+) = 1.67 \pm 0.03$ ps, $\tau(B^0_d) = 1.57 \pm 0.03$ ps and $\tau(B^+)/\tau(B^0_d) = 1.07 \pm 0.03$ [15].

The lifetime for the $B^+$ is now measured to be 2.6$\sigma$ higher than for the $B^0_d$, which is becoming more significant.

Measurements of the $B^0_s$, $\Lambda^0_b$ and $B^+_c$ Lifetimes

Just as for the $B^+$ and $B^0_d$ lifetime measurements, the methods for measuring the $B^0_s$ lifetime can be split into the three measurement method classes described previously. Only CDF uses a fully reconstructed mode, $B^0_s \rightarrow J/\psi\phi^0$ [6]. For the Inclusive 1 method, OPAL [16], ALEPH [17], CDF [18] and DELPHI [19] uses $\overline{B}^0_s \rightarrow D_s^{*+}\ell^-\nu X$ and ALEPH [20] and DELPHI [19] also use $\overline{B}^0_s \rightarrow D_s^{*+}\phi\ell^-\nu X$ where $h$ is one (or more) hadrons. For the Inclusive 2 where the $B^0_s$ vertex is not reconstructed we have measurements from OPAL [21] and DELPHI [19] using $\overline{B}^0_s \rightarrow D_s^{*+}\ell^-\nu X$ and DELPHI includes $\overline{B}^0_s \rightarrow \phi\ell^-\nu X$. These measurements are shown in Figure 3(a) and summarized in table 2.

The $\Lambda^0_b$ lifetime has been measured using $\overline{B}^0_s \rightarrow \Lambda^+_c\ell^-\nu X$ where the $\Lambda^+_c$ decay is fully reconstructed via various decay modes. The sample typically contains 70-90$\%$ $\Lambda^0_b$ with a 1$\%$ contamination from $\Xi_b$. There has only been one minor update


Average $\tau(B_c^0) = 1.489 \pm 0.058$ psec
$\tau(B_c^0)/\tau(B_b^+) = 0.957 \pm 0.041$
$\tau(\Lambda_b^0)/\tau(B_b^+) = 0.804 \pm 0.055$
$\tau(\Lambda_b^0)/\tau(B_b^+) = 0.795 \pm 0.052$

![Lifetime measurements for $B_c^0$ and $\Lambda_b^0$ mesons](image)

**FIGURE 3.** Lifetime measurements for (a) $B_c^0$ split by experiment methods as described in the text; and (b) $\Lambda_b^0/B_c^0$ split by experiment.

**TABLE 2.** Summary of $B_c^0$ and $\Lambda_b^0$ lifetime measurements split by experiment

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\tau(B_c^0)$ ps</th>
<th>$\tau(\Lambda_b^0)$ ps</th>
<th>$\tau(\Lambda_b^0)/\tau(B_c^0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF$^a$</td>
<td>$1.356 \pm 0.094$</td>
<td>$1.320 \pm 0.166$</td>
<td>$0.872 \pm 0.114$</td>
</tr>
<tr>
<td>OPAL</td>
<td>$1.570 \pm 0.140$</td>
<td>$1.290 \pm 0.238$</td>
<td>$0.843 \pm 0.175$</td>
</tr>
<tr>
<td>ALEPH</td>
<td>$1.510 \pm 0.110$</td>
<td>$1.210 \pm 0.110$</td>
<td>$0.781 \pm 0.079$</td>
</tr>
<tr>
<td>DELPHI$^b$</td>
<td>$1.670 \pm 0.140$</td>
<td>$1.170 \pm 0.195$</td>
<td>$0.756 \pm 0.128$</td>
</tr>
<tr>
<td>World Average</td>
<td>$1.489 \pm 0.058$</td>
<td>$1.237 \pm 0.078$</td>
<td>$0.804 \pm 0.055$</td>
</tr>
</tbody>
</table>

$^a$ Updated since PDG98 for $\tau(B_c^0)$

$^b$ Updated since PDG98 for $\tau(\Lambda_b^0)$

$^c$ 0.795 \pm 0.052 including other measurements for $\tau(B_c^0)$.

from DELPHI [22] since PDG98. The results are summarized in Table 2 and the results for $\tau(\Lambda_b^0)/\tau(B_c^0)$ are shown in Figure 3(b) compared to the theoretical limit. Although $\tau(\Lambda_b^0)/\tau(B_c^0)$ is small compared to theory it is still within 2\sigma of the theoretical limit.

CDF has observed the $B_c^+$ meson with a lifetime of $0.46^{+0.18}_{-0.16} \pm 0.03$ ps [23].

**Measurements of Charm Particle Lifetimes**

The World average lifetimes for the weakly decaying charm particles are dominated by measurements from Fermilab E687 published in 1993-1995. However there have been a few updates this year. The Fermilab E687 collaboration has published an new value for the lifetime of $\Xi_c^+ = 0.34^{+0.07}_{-0.05} \pm 0.02$ ps using an additional decay mode [24]. This supercedes their earlier published result. Direct measurements of charm particle lifetimes using the CLEO 2.5 experiment has been reported at conferences this year: $\tau(D^+) = 1.034 \pm 0.033^{+0.033}_{-0.088}$ ps [25], $\tau(D_s^+) =$
$0.475 \pm 0.024 \pm 0.025$ ps [25] and a more updated $\tau(D^0) = 0.410 \pm 0.006 \pm 0.005$ ps [26]. Although their new silicon tracker enables them to measure lifetimes to a precision rivaling the fixed target E687 results, the next generation fixed target experiment FOCUS will be overwhelming with a huge sample of fully reconstructed charm decays [27]. Results have also been presented by Fermilab E791 for $\tau(D^0) = 0.413 \pm 0.003$ (stat) ps [28] and $\tau(D_s^+) = 0.518 \pm 0.014 \pm 0.007$ ps [29].

The most significant consequence of these new measurements is that $\tau(D_s^+)$ is conclusively larger than $\tau(D^0)$, since the world average is now $\tau(D_s^+)/\tau(D^0) = 1.193 \pm 0.027$ compared to the earlier PDG98 value of $1.125 \pm 0.042$.

LIFETIMES AND THEORY

$\Lambda_b^0$, $B^+$ and $B_d^0$ Lifetimes

The smallness of the $\Lambda_b^0$ lifetime compared to the $B_d^0$ is often cited as a problem. In fact the measured ratio of $\tau(\Lambda_b^0)/\tau(B_d^0)$ is only 2σ from the theoretical limit of 0.9 given by Bigi [30]. Furthermore it was pointed out recently by Neubert and Sachrajda that if they use the same theoretical approach but without model dependent constraints on the parameters of the mass expansion, they can obtain ratios as low as 0.8 for $\tau(\Lambda_b^0)/\tau(B_d^0)$ and also the sign of $\tau(B^+) - \tau(B_d^0)$ is not determined [31]. Given that the measurements now indicate $\tau(B^+) > \tau(B_d^0)$ their results would point to a larger theoretical limit than 0.8. However more precise lifetime measurements are still needed.

In particular measurements to convincingly show that $\tau(B^+) > \tau(B_d^0)$ is interesting since studies of $B^+$ exclusive decay modes give the same sign for the external and internal spectator diagrams [32] which would suggest constructive interference in $B^+$ decays which could lead to a shorter lifetime than for the $B_d^0$.

Other theoretical approaches have been reported to explain the shortness of the $\Lambda_b^0$ lifetime. Datta, Lipkin and O’Donnell have shown that the $\Lambda_b^0$ lifetime can be shortened by phase space enhancement through isospin conservation [33]. Other authors have used the mass expansion approach but with the hadron mass instead of the heavy quark mass [34], or with the energy release instead of the quark mass as the expansion parameter [35].

$D^0$ and $D_s^+$ Lifetimes

The $D_s^+$ lifetime is now conclusively measured to be above the $D^0$ lifetime. However exactly how much larger is still not measured that precisely. A more accurate measurement is needed and may tell us much more about the nature and size of the W-annihilation contribution to the inclusive decay. Bigi and Uraltsev have used the mass expansion approach to analyze this lifetime difference and have concluded that a difference of $< 7\%$ is possible without WA contributions. Their estimation of the WA contribution puts an upper limit of $\tau(D_s^+)/\tau(D^0) < 1.20$ [36].
CONCLUSIONS

The most significant updates are that the $D^+_s$ lifetime is now conclusively measured to be above the $D^0$ lifetime, $\tau(D^+_s)/\tau(D^0) = 1.193 \pm 0.027$, however more precise measurements are needed to really study the size of weak annihilation effects. The $B^+_s$ meson has been observed with a lifetime of $0.46^{+0.28}_{-0.36} \pm 0.03$. The measured values of $\tau(B^+)/\tau(B^0) = 1.068 \pm 0.026$ and $\tau(\Lambda^0)/\tau(B^0) = 0.795 \pm 0.052$ are becoming more precise but still more accurate measurements are needed for both of these ratios. These ratios taken together, if more precisely measured, can indicate in a model independent fashion whether there is really a contradiction between theory and the measurements.

We can look forward to much more precise charm particle lifetimes from FOCUS [27] within a year and the future for new beauty particle lifetime measurements is also very bright with several new experiments ready soon or within a few years to take data (BELLE, BABAR, HERA-B, CDF and D0).

The study of charm and beauty lifetimes should continue to be an exciting field.

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