Charm Lifetimes and Mixing

Harry W. K. Cheung

Fermilab, P.O. Box 500, Batavia, IL 60510-0500

Abstract. A review of the latest results on charm lifetimes and $D$-mixing is presented. The $e^+ e^-$ collider experiments are now able to measure charm lifetimes quite precisely, however comparisons with the latest results from fixed-target experiments show that possible systematic effects could be evident. The new $D$-mixing results from the $B$-factories have changed the picture that is emerging. Although the new world averaged value of $\gamma_{CP}$ is now consistent with zero, there is still a very interesting and favoured scenario if the strong phase difference between the Doubly-Cabibbo-suppressed and the Cabibbo-flavoured $D^0 \to K\pi$ decay is large.

MOTIVATION FOR THE STUDY OF CHARM LIFETIMES

The study of charm lifetimes is essentially a study of strong interactions [1], and in particular provide a test of the theoretically challenged part of the Standard Model, namely non-perturbative QCD. It is hoped that experimental results in charm lifetimes (possibly combined with other charm results), can give some guidance as to what is needed to theoretically describe strong interactions at all energy scales. This is important not only to improve our theoretical understanding of strong interactions, but also because the theoretical tools used to calculate lifetimes are the same or similar to those used in other areas, for example to extract $V_{cs}$ and $V_{cd}$ in charm decays; to calculate the $b$-particle lifetimes; and to extract other Standard Model parameters or decay constants in heavy flavor physics.

The other motivation is more mundane. Theoretical calculations are used to calculate decay rates whereas experimentally one measures branching fractions. One needs precise particle lifetimes to convert measured branching ratios to decay rates so one can compare to theory and to extract Standard Model parameters. Lifetimes are also important as an experimental tool since the correctness of the measured lifetime will test techniques or probe systematic effects in other areas where lifetimes and lifetime resolution is important. For example in $D$ and $B_s \Delta m$ mixing measurements or in $\Delta \Gamma$ measurements for $D$ and $B$ mesons.

Table 1 shows a comparison of the experiments for which new results in charm lifetimes and mixing have been presented recently. These include both fixed-target experiments and experiments at \( e^+ e^- \) colliders. This is significant as the two types of experiments are quite different and will thus have different systematics. Therefore a comparison of the results between the two types of experiments will be an important check of any systematic effects.

Typically fixed-target experiments have excellent vertex and proper time resolutions in 3-dimensions but large (non-charm) backgrounds. These backgrounds are eliminated by selecting decay vertices that are well separated from the production vertex, \( L > N \sigma_L \) (see Fig.1), and optionally also outside of target material. This means that short-lived decays are preferentially eliminated and the proper time distribution would look like that given in Fig.2(a) requiring large non-uniform acceptance corrections as illustrated in Fig.2(b). This problem is avoided by using the reduced proper time, \( t' = (L - N \sigma_L)/\beta \gamma c \), which starts the clock at the minimum allowed proper time. The lifetime follows the same exponential wherever one chooses to start, so the reduced proper time distribution will follow an exponential with the true lifetime. This is illustrated in Figures 1(c) and (d). The acceptance correction obtained using Monte Carlo simulations can be checked with data by using \( K_s^0 \) decays reconstructed with the vertex detector as these have a well measured lifetime. Absorption corrections are typically small and can similarly be checked in data.

In fixed-target experiments there is usually a compromise between systematics due to backgrounds and systematics due to the acceptance correction. The latter can become larger if one uses other types of vertexing cuts to eliminate more background at the expense of introducing a (larger) lifetime dependence in the acceptance.
FIGURE 2. (a) Proper time distribution for a MC sample when a vertex separation requirement is made to reduce backgrounds; (b) resulting acceptance correction function; (c) reduced proper time distribution showing an exponential where the offset line shows the slope of the true generated lifetime; (d) acceptance as a function of reduced proper time.

In contrast, the $e^+e^-$ experiments operating near $B$ threshold have much less background but have poorer vertex resolutions and hence poorer proper time resolutions. The average interaction point is normally used for constraining the location of the production point but its position is usually only known well in 2-dimensions or even only 1-dimension. The proper time resolution can be large compared to the charm particle lifetime under study. Due to proper time smearing from the poor resolution one has to take into account this smearing on an event-by-event basis. This necessarily requires a more complicated event-by-event likelihood analysis where one has to parameterize the time and mass resolutions as well as background lifetime distributions. These resolutions can be known well as they can be obtained from data but they are not usually parameterizable by a simple function. The resolution can sometimes be improved by using additional constraints like forcing the reconstructed decay secondaries to come from a single point or using the average IP position. However this can also lead to fit biases and subsequent corrections. An example of this is illustrated in Fig.3(a) where constraining a decay track to come from point $B$ instead of $A$ will decrease the opening angle and hence also the reconstructed mass, it would also decrease the lifetime. This produces a correlation between the reconstructed mass and lifetime as seen in CLEO for $\Sigma^+_c \rightarrow \Xi^- \pi^+ \pi^+$ decays in both data, Fig.3(b), and MC Fig.3(c) [2]. Systematic concerns are therefore usually related to the fit method, resolutions and fit biases.
RESULTS ON LIFETIMES

Both BaBar and BELLE would like to demonstrate that they have excellent understanding of their vertexing and lifetime resolutions by measuring the lifetimes of the charm particles. In fact they already have enough data to get charm lifetimes with a precision comparable to the current world averages. BELLE has led the way with preliminary lifetime measurements for the $D_0$, $D^+$ and $D_s^+$ mesons [3]. A summary of the most recent charm lifetime results are given in Fig.4. Together with the published results [4, 5, 6] I have included the preliminary results shown in the figure in my new world averages given in Table 2. For the $D_s^+$ FOCUS preliminary result [7] which does not yet include a systematic uncertainty I have taken the total uncertainty to be $\sqrt{2}$ times the statistical error. The fixed-target and $e^+e^-$ averages are also separately shown and agree fairly well suggesting no additional unaccounted-for systematics. The $e^+e^-$ averages are currently dominated by the preliminary BELLE measurements.

The ratio $\tau(D_s^+)/\tau(D^0)$ continues to be of interest in determining the importance of the suppression of W-exchange and W-annihilation contributions in $D$-meson decays. There are now three direct measurements of this ratio giving an average of $1.171 \pm 0.018$ which agrees well with just taking the ratio of the two world average lifetimes: $1.190 \pm 0.014$. The ratio is much larger than 1.07 which is the maximum expected size for no W-exchange/W-annihilation contributions [8]. An accurately measured value for this ratio can be used to determine phenomenologically the relative size of W-exchange/W-annihilation contributions [9].

There are new preliminary FOCUS lifetime results for the $\Lambda_c^+$, $\Xi_c^+$ and $\Xi_c^0$ baryons [10, 11] and a CLEO preliminary lifetime result for $\Xi_c^+$ [2]. These are shown together with published results in Fig.5. As previously, for the preliminary FOCUS lifetime result for $\Xi_c^0$ which does not include a systematic uncertainty I have taken the total uncertainty

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**TABLE 2.** World averaged lifetimes including also preliminary results.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>World Average</th>
<th>Quantity</th>
<th>World Average</th>
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</thead>
<tbody>
<tr>
<td>$\tau(D^+) (\text{fs})$</td>
<td>$1044.1 \pm 9.1$</td>
<td>$\tau(\Lambda_c^+) (\text{fs})$</td>
<td>$200.2 \pm 3.2$</td>
</tr>
<tr>
<td>$\tau(D_0^0) (\text{fs})$</td>
<td>$413.3 \pm 1.7$</td>
<td>$\tau(\Xi_c^+) (\text{fs})$</td>
<td>$433 \pm 19$</td>
</tr>
<tr>
<td>$\tau(D_s^+) (\text{fs})$</td>
<td>$492.0 \pm 5.3$</td>
<td>$\tau(\Xi_c^0) (\text{fs})$</td>
<td>$106.0^{+9}_{-8}$</td>
</tr>
</tbody>
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to be $\sqrt{2}$ times the statistical error in determining the world average.

There are two items of note in the new results. The first is that the CLEO published lifetime for $\Lambda_c^+$ appears to disagree with the fixed-target average value when the new FO-
CUS preliminary number is included. This could point to a systematic problem starting to appear which might be related to the short-lived nature of the $\Lambda_c^+$ decay. An example of a possible effect is the mass-lifetime correlation seen in CLEO which introduces very large MC correlations to the lifetime. It is known that the size and type of the resonance sub-structure of a decay like $\Lambda_c^+ \rightarrow pK^-\pi^+$ can be important to the acceptance corrections, and may also be important in the mass-lifetime correlations since the resonance sub-structure alters the angular distributions of the daughter tracks. Uncertainties related to the resonance sub-structure can thus introduce additional systematic studies. Any systematic problems between the fixed-target and $e^+e^-$ results should be kept in mind as the BaBar and BELLE lifetime and mixing results become more precise.

The other interesting feature of the new results is that the ratio $\tau(\Xi_c^+)/\tau(\Lambda_c^+)$ is now $2.16\pm0.11$ compared to the PDG2000 value of $1.60^{+0.31}_{-0.22}$. Many of the calculations favour a value of 1.2–1.6 though with large uncertainties [12]. It would be interesting to see if one can feed back into the calculations this new information and others like the $\tau(D_s^+)/\tau(D^0)$ ratio to get a better understanding, and to see if it affects the prediction for other related quantities like the ratio $\tau(\Lambda_b^+)/\tau(B^0)$. Both the mentioned results suggest that the W-exchange contribution is much more important than have so far been assumed in the calculations.

**D-MIXING REVIEW**

The parameters we use to describe D-mixing can best be defined by the relevant equations relating the states with definite mass and lifetimes: $|D_H(t)\rangle = e^{-i\mu t} e^{-\Gamma_H t/2} |D_H\rangle$, and $|D_L(t)\rangle = e^{-i\mu t} e^{-\Gamma_L t/2} |D_L\rangle$ to the observed $|D^0\rangle$ and $|\bar{D^0}\rangle$ states: $|D_H\rangle = p|D^0\rangle + q|\bar{D^0}\rangle$ and $|D_L\rangle = p|D^0\rangle - q|\bar{D^0}\rangle$. So for example the doubly-
Cabibbo-suppressed (DCS) decay rate $\Gamma(D^0 \rightarrow K^+\pi^-) = |\langle K^+\pi^- | T |D^0(t)\rangle |^2$. We will assume CP conservation in charm decays and use the following approximations for charm: $|q/p| = 1$ and $|x|, |y|, R_{DCS} \ll 1$. Where $x = \Delta m/\Gamma$, $\Delta m = m_H - m_L$, $\Gamma = (\Gamma_H + \Gamma_L)/2$, $y = \Delta\Gamma/2\Gamma = (\Gamma_{CP}\text{even} - \Gamma_{CP\text{odd}}) / (\Gamma_{CP}\text{even} + \Gamma_{CP\text{odd}}) = y_{CP}$. and
My average $\gamma_{CP} = 1.11 \pm 0.87\%$

$R_{DCS} = \frac{\langle K^+ \pi^- | T | D^0 \rangle}{\langle K^+ \pi^- | T | \overline{D^0} \rangle}$. The ratio of the “wrong-sign” $D^0 \to K^+ \pi^-$ to “right-sign” $D^0 \to K^- \pi^+$ decays is given by

$$R_{WS}(t) = R_{DCS} + (ycos\delta - xsin\delta) t \sqrt{R_{DCS}} + \frac{(x^2 + y^2)}{4} t^2 e^{-t}$$

where $y' \equiv ycos\delta - xsin\delta$ and $x' \equiv xcos\delta + ysin\delta$ and $\delta$ is the strong phase difference between the Cabibbo-favoured and the DCS decay.

Information on the charm mixing parameters can be obtained in several ways:

1. Measure the lifetime difference between CP-even, CP-odd and flavour specific states to give $\gamma_{CP}$.
2. Measure wrong-sign semileptonic decays which do not require good lifetime resolution but only give information on $(x^2 + y^2)$ and cannot separate $x$ and $y$.
3. Measure wrong-sign hadronic decays like $D^0 \to K^+ \pi^-$ which require a lifetime study and high S/B and can give information on both $x^2$ and $y$ separately. However there is an additional complication of an unknown strong phase difference, e.g. $\delta_{KK}$ between $D^0 \to K^+ \pi^-$ and $D^0 \to K^- \pi^+$ contributions.

The published results are summarized in Fig.7(a) which include the $\gamma_{CP}$ measurement from FOCUS [15], the limits on $(x', y')$ from CLEO allowing and not allowing for CP violation [14], and the E791 limits from semileptonic decays [13].

The preliminary measurements from CLEO [16], BELLE [3] and BaBar [17] for $\gamma_{CP}$ are given in Fig.6. Including these produces a world average of $1.11 \pm 0.87\%$ which is quite consistent with zero$^2$. However the situation is still interesting due to in part to a preliminary result from FOCUS for the allowed region in $x'$ and $y'$ [19]. The 95% confidence level allowed regions for the FOCUS and CLEO measurements are given in Fig.7(b) in the $(x, y)$ space assuming the strong phase difference $\delta_{KK} = 0$. The slightly

$^2$ At “press time” the $\gamma_{CP}$ value of $+0.5 \pm 1.0^{+0.8}_{-0.9}$ shown by BELLE at the conference was superceded by a new value of $-0.5 \pm 1.0^{+0.7}_{-0.7}$ contained in their new preprint [18]. The same data sample was used but the analysis contained updated MC corrections. This moves the world average value down to $0.63 \pm 0.85$. 

FIGURE 6. Summary of recent $\gamma_{CP}$ measurements.
larger (lighter) region for CLEO is when CP-conservation is not assumed. Also shown are the allowed region in $y$ from the combined lifetime difference measurements assuming no CP-violation, and the circular allowed region from wrong-sign semileptonic decay limits from E791 [13]. The smaller circular line gives the expected size of the allowed region from FOCUS wrong-sign semileptonic decays [20].

Even though I do not have the likelihood contour of the CLEO allowed region in order to combine the FOCUS and CLEO results, it can be seen that the combined allowed region is beginning to exclude zero, especially if no CP-violation is assumed. The other point is that the combined FOCUS and CLEO $K\pi$ result for the allowed region does not agree well with the world average allowed $\chi_{CP}$ range when one assumes $\delta_{K\pi} = 0$. This could indicate one of three things: it is just a statistical fluctuation; the systematic uncertainties are underestimated; or the most interesting is that $\delta_{K\pi}$ is large and non-zero. Knowing the value of $\delta_{K\pi}$ is crucially important. For example in the absence of a theoretically favoured value, the experimentally preferred value is about 110° as shown in Fig.7(c). This would be a really interesting situation since the favoured scenario is with $y$ near zero and a large value of $x$ of $\approx 3\%$. This is the most likely expected signature of new physics beyond the Standard Model since these can produce sizable non-zero values in $\Delta m$ but not usually in $\Delta \Gamma$.

**CONCLUSIONS**

Charm lifetime measurements continue to be an interesting way to study non-perturbative strong interaction physics and evaluate possible systematic problems

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3 Note that the new lower world average value of $\chi_{CP}$ does not significantly change these favoured values.
for measurements that require good lifetime resolutions. The larger than expected values of $\tau(D^{+}_{s})/\tau(D^{0})$ and $\tau(\Xi^{+}_{c})/\tau(\Lambda^{+}_{c})$ indicates that W-exchange is much more important than normally thought which could have implications on other theoretical predictions, like $\tau(\Lambda^{+}_{c})/\tau(B^{0})$.

The D-mixing situation is still very interesting as the data now favour a $y$ value near zero and a large value of $x$ of $\approx 3\%$. This could be a signature of new physics beyond the Standard Model. However its requires the strong phase difference $\delta_{K\pi} \approx 110^\circ$ which is unexpected theoretically. The possibility that this is a statistical fluctuation or a systematic underestimation can be greatly clarified by new precise D-mixing results from BaBar and BELLE and we look forward eagerly for these results in the future.

ACKNOWLEDGMENTS

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REFERENCES

3. J. Tanaka, these proceedings; and K. Abe et al., “Precise Measurements of Charm Meson Lifetimes and the Search for $D^{0} - \overline{D^{0}}$ Mixing at Belle”, BELLE-CONF-0131 (2001).
