Charm lifetime measurements at Belle II

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Abstract

We report precision measurements of lifetimes of charmed mesons and baryons performed by the Belle II experiment. Specifically, we measure \(D_s^+, D^+, D^0, \Lambda_c^+,\) and \(\Omega_c^0\) lifetimes. Our results for \(\tau(D_s^+), \tau(D^+), \tau(D^0),\) and \(\tau(\Lambda_c^+)\) are the world’s most precise; our result for \(\tau(\Omega_c^0)\) confirms that the \(\Omega_c^0\) lifetime is longer than that of the \(\Lambda_c^+\) and the \(\Xi_c^0\).

1 Introduction

The lifetime of a particle, like its mass, is one of its fundamental properties. The lifetime is the reciprocal of the sum of all partial widths, and thus all final states contribute to it. In this manner, the lifetime can provide information about final states that are difficult to measure or calculate.

Charm lifetimes are calculated within the framework of the Heavy Quark Expansion (HQE) \([1]\). Using the optical theorem, the expansion takes the form (for a \(D\) meson) \([2]\):

\[
\Gamma(D) = \frac{1}{2m_D} \sum_X \int \frac{(2\pi)^4 \delta^4(p_D - p_X)}{p_S} |\langle X(p_X)|H_{\text{eff}}|D(p_D)\rangle|^2
\]

\[
\to \Gamma_3 + \Gamma_5 \frac{\langle O_5 \rangle}{m_c^2} + \Gamma_6 \frac{\langle O_6 \rangle}{m_c^3} + \ldots + 16\pi^2 \left( \frac{\Gamma_6 \langle \tilde{O}_6 \rangle}{m_c^3} + \frac{\Gamma_7 \langle \tilde{O}_7 \rangle}{m_c^4} + \ldots \right),
\]

where the summation in Eq. (1.1) is over all final states, and the \(\Gamma_n\) terms in Eq. (1.2) are Wilson coefficients that are expanded in powers of \(\alpha_s\) and calculated perturbatively. The \(\langle O_n \rangle\) and \(\langle \tilde{O}_n \rangle\) terms are matrix elements of dimension-\(n\) local operators and must be calculated using non-perturbative methods.\(^1\) Comparing HQE calculations with experimental measurements tests our understanding of QCD. Here we present several lifetime measurements of charmed hadrons performed by the Belle II experiment \([3]\).

Belle II runs at the SuperKEKB \(e^+e^-\) collider \([4]\) based at the KEK laboratory in Tsukuba, Japan. The experiment studies weak decays of \(B\) and \(D\) mesons, and \(\tau\)

\(^1\)No tilde denotes a two-quark operator; a tilde denotes a four-quark operator \([2]\).
leptons, with the goal of uncovering new physics. The Belle II detector is described in Ref. [5]. The measurements reported here were performed with early data sets, before the second layer of the silicon pixel detector was fully installed. The lifetime is determined from a fit to the decay time distribution. For a particle of mass $m$ and momentum $\vec{p}$, the decay time is calculated as $t = m(\vec{d} \cdot \vec{p})/|\vec{p}|$, where $\vec{d}$ is the displacement vector from the $e^+e^-$ interaction point (IP), where the particle is produced, to its decay vertex position. The IP in Belle II is measured every 30 minutes using $e^+e^- \rightarrow \mu^+\mu^-$ events. All charm lifetime analyses impose a momentum requirement on the decaying meson or baryon to eliminate those originating from $B$ decays, which are displaced from the IP and would corrupt the lifetime measurement.

The uncertainty on $t$, denoted $\sigma_t$, is calculated event-by-event by propagating the uncertainties on $\vec{d}$ and $\vec{p}$, taking into account their correlations. The decay time resolution $\langle \sigma_t \rangle$ is approximately twice as precise as that achieved at Belle and Babar: 80–90 fs versus $\sim$200 fs. For the analyses presented here, the uncertainty $\sigma_t$ multiplied by a scaling factor is taken as the width of a Gaussian resolution function used to fit the decay time distributions.

## 2 $D_s^+$ lifetime

The most recent measurement is that of the $D_s^+$ lifetime, which used 207 fb$^{-1}$ of data [6]. The Cabibbo-favored (CF) decay $D_s^+ \rightarrow \phi(\rightarrow K^+K^-)\pi^+$ is reconstructed, and candidates with an invariant mass satisfying $M(\phi\pi^+) \in [1.960, 1.976]$ GeV/$c^2$ are used to measure the lifetime. Fitting the $M(\phi\pi^+)$ distribution, we obtain a signal yield in this range of $116 \times 10^3$ events with a purity of 92%.

The lifetime is determined from an unbinned maximum likelihood fit to the decay time ($t$) distribution. As the uncertainty $\sigma_t$ is used in the resolution function, and its distribution differs for signal and background events, we include probability density functions (PDFs) for $\sigma_t$ in the likelihood function to avoid biasing the fit results [7]. The likelihood function for event $i$ is given by

$$L(t_i^i, \sigma_t^i) = f_{\text{sig}} P_{\text{sig}}(t_i^i|\tau, \sigma_t^i) P_{\text{sig}}(\sigma_t^i) + (1 - f_{\text{sig}}) P_{\text{bkg}}(t_i^i|\sigma_t^i) P_{\text{bkg}}(\sigma_t^i),$$

(2.1)

where $f_{\text{sig}}$ is the fraction of events that are signal decays, and $P_{\text{sig}}(t_i^i|\tau, \sigma_t^i)$ is the signal PDF for measuring $t_i$ given a lifetime $\tau$ and an uncertainty $\sigma_t^i$. The background PDF $P_{\text{bkg}}(t_i^i|\sigma_t^i)$ is an exponential function determined from events in the sideband $M(\phi\pi^+) \in [1.990, 2.020]$ GeV/$c^2$. The PDF $P_{\text{bkg}}(\sigma_t^i)$ is a histogram also determined from the $M(\phi\pi^+)$ sideband, and $P_{\text{sig}}(\sigma_t^i)$ is a histogram determined from events in the $M(\phi\pi^+)$ signal region after subtracting off the $P_{\text{bkg}}(\sigma_t^i)$ contribution. The fraction $f_{\text{sig}}$ is determined from the fit to the $M(\phi\pi^+)$ distribution.

The PDF for signal decays is

$$P_{\text{sig}}(t_i^i|\tau, \sigma_t^i) = \frac{1}{\tau} \int e^{-t'/\tau} R(t' - t_i^i; \mu, s, \sigma_t^i) dt',$$

(2.2)

where $R$ is a Gaussian function with mean $\mu$ and a per-candidate standard deviation $s \cdot \sigma_t^i$, with $s$ being a scaling factor. The lifetime $\tau$ is determined by maximizing the total likelihood $\Sigma_i L_i$, where the summation runs over all signal candidates. The floated parameters are $\tau$, $\mu$, and $s$. The result of the fit is $\tau(D_s^+) = (499.5 \pm 1.7 \pm 0.9)$ fs,
where the first uncertainty is statistical and the second is systematic. The projection of the fit result is shown in Fig. 1. The sources of systematic uncertainty are listed in Table 1.

![Figure 1](image-url)

**Table 1**: Systematic uncertainties for the $D_{s}^{+}$ lifetime measurement [6].

| Source                              | Uncertainty (fs) |
|-------------------------------------|------------------|
| Resolution function                 | +0.43            |
| Background ($t, \sigma_{t}$) distribution | ±0.40          |
| Binning of $\sigma_{t}$ histogram PDF | ±0.10            |
| Imperfect detector alignment        | ±0.56            |
| Sample purity                       | ±0.09            |
| Momentum scale factor               | ±0.28            |
| $D_{s}^{+}$ mass                    | ±0.02            |
| **Total**                           | ±0.87            |

### 3 $D^{+}$ and $D^{0}$ lifetimes

The measurements of the $D^{0}$ and $D^{+}$ lifetimes [8] are similar to that for the $D_{s}^{+}$ but use a smaller data set: 78 fb$^{-1}$. To reduce backgrounds, $D^{0}$ and $D^{+}$ candidates are required to originate from either $D^{*+} \rightarrow D^{0}\pi_{s}^{+}$ or $D^{*+} \rightarrow D^{+}\pi_{s}^{0}$ decays. The pion daughter in these decays has very low momentum in the laboratory frame and thus is labeled the “slow” pion ($\pi_{s}$). The $D^{0}$ and $D^{+}$ are reconstructed in the CF final states $K^{-}\pi^{+}$ and $K^{-}\pi^{+}\pi^{+}$, respectively. To eliminate signal candidates originating from $B \rightarrow DX$, we require that the $D^{*}$ momentum in the $e^{+}e^{-}$ center-of-mass (CM) frame be greater than 2.5 GeV/c for $D^{0}$ candidates and >2.6 GeV/c for $D^{+}$ candidates. For the lifetime fits, we select $D^{0}$ candidates satisfying $M(K^{-}\pi^{+}) \in [1.851, 1.878]$ GeV/c$^{2}$ and $M(K^{-}\pi^{+}\pi_{s}^{+}) - M(K^{-}\pi^{+}) \in [144.94, 145.90]$ MeV/c$^{2}$, and $D^{+}$ candidates satisfying $M(K^{-}\pi^{+}\pi_{s}^{+}) \in [1.855, 1.883]$ GeV/c$^{2}$ and $M(K^{-}\pi^{+}\pi_{s}^{0}) - M(K^{-}\pi^{+}\pi_{s}^{+}) \in$...
These samples contain $171 \times 10^3 D^0 \to K^-\pi^+$ candidates (99.8% purity) and $59 \times 10^3 D^0 \to K^-\pi^+\pi^+$ candidates (91% purity).

As in the $D^+_s$ analysis, the lifetimes are determined from unbinned maximum likelihood fits to the decay time, and the per-candidate uncertainty $\sigma_t$ multiplied by a scaling factor is used as the width(s) of a double Gaussian ($D^0$) or single Gaussian ($D^+$) resolution function. The decay time PDF for $D^+$ background is obtained from the sideband $M(K^-\pi^+\pi^+) \in [1.758, 1.814] \cup [1.936, 1.992]$ GeV/$c^2$, whereas $D^0$ background is negligible. The results of the fits are $\tau(D^0) = (410.5 \pm 1.1 \pm 0.8)$ fs and $\tau(D^+) = (1030.4 \pm 4.7 \pm 3.1)$ fs, where the first uncertainty is statistical and the second is systematic. The decay time distributions are shown in Fig. 2 along with projections of the fit result. The sources of systematic uncertainty are listed in Table 2.

![Figure 2: Decay time distribution with the fit result superimposed for $D^0 \to K^-\pi^+$ (top) and $D^+ \to K^-\pi^+\pi^+$ (bottom) [8].](image)

Table 2: Systematic uncertainties for the $D^0$ and $D^+$ lifetime measurements [8].

| Source                | $\tau(D^0)$ (fs) | $\tau(D^+)$ (fs) |
|-----------------------|------------------|------------------|
| Resolution model      | 0.16             | 0.39             |
| Backgrounds           | 0.24             | 2.52             |
| Detector alignment    | 0.72             | 1.70             |
| Momentum scale        | 0.19             | 0.48             |
| Total                 | 0.80             | 3.10             |
4 $\Lambda_c^+$ lifetime

Measurement of the $\Lambda_c^+$ lifetime [9] is similar to that for the $D_{(s)}^+$ and $D^0$ lifetimes. The reconstructed decay is $\Lambda_c^+ \to pK^-\pi^+$. However, some $\Lambda_c^+$ candidates originate from $\Xi_c^0 \to \Lambda_c^+\pi^-$ and $\Xi_c^+ \to \Lambda_c^+\pi^0$ decays; since $\tau(\Xi_c^+) = 152$ fs and $\tau(\Xi_c^0) = 453$ fs [10], such $\Lambda_c^+$ candidates corrupt the $\tau(\Lambda_c^+)$ measurement. Fortunately, they can be identified from the displacement of the $\Lambda_c^+$ decay vertex from the IP in the plane transverse to the beam line: $\Lambda_c^+$ candidates from $\Xi_c^0$ decays typically have larger values. Fitting this distribution yields $374 \pm 88 \Xi_c^0 \to \Lambda_c^+X$ decays in the entire $\Lambda_c^+$ sample. These events are reduced by 40% by combining the $\Lambda_c^+$ candidate with a $\pi^-$ or $\pi^0$ candidate and vetoing those that satisfy $M(pK^-\pi^-) - M(pK^-\pi^+) \in [183.4, 186.4]$ MeV/$c^2$ or $M(pK^-\pi^+\pi^0) - M(pK^-\pi^+) \in [175.3, 187.3]$ MeV/$c^2$. The effect of the remaining $\Lambda_c^+$ candidates is evaluated using MC simulation; the resulting bias of $+0.34$ fs is subtracted from the fitted $\tau(\Lambda_c^+)$ and included as a systematic uncertainty (see Table 3). The final fitted sample consists of $116 \times 10^3$ events with 92.5% purity. The fit result after the bias correction is $\tau(\Lambda_c^+) = (203.20 \pm 0.89 \pm 0.77)$ fs.

| Source                  | Uncertainty [fs] |
|-------------------------|------------------|
| Resolution model        | 0.46             |
| $\Xi_c$ contamination   | 0.34             |
| Non-$\Xi_c$ background  | 0.20             |
| Detector alignment      | 0.46             |
| Momentum scale          | 0.09             |
| Total                   | 0.77             |

5 $\Omega_c^0$ lifetime

Measurement of the $\Omega_c^0$ lifetime [11] follows the same procedure as described above for the $\Lambda_c^+, D_{(s)}^+$, and $D^0$ lifetimes. The reconstructed decay is $\Omega_c^0 \to \Omega^-\pi^+$ followed by $\Omega^- \to \Lambda(p\pi^-)K^-$. To eliminate $\Omega_c^0$ candidates originating from $B \to \Omega_c^0X$, we require $p_{\Omega_c^0}/p_{\text{max}} > 0.60$, where $p_{\text{max}} = \sqrt{(E_{\text{beam}})^2 - m(\Omega^-\pi^+)^2}$, and the momentum $p_{\Omega_c^0}$ and beam energy $E_{\text{beam}}$ are evaluated in the $e^+e^-$ CM frame. The final candidate sample is much smaller than those of the other lifetime measurements: 132 signal candidates with 67% purity – see Fig. 3 (left). The final result is $\tau(\Omega_c^0) = (243 \pm 48 \pm 11)$ fs, where the first uncertainty is statistical and the second is systematic. The systematic uncertainty is dominated by the resolution function ($\pm 6.2$ fs) and background modeling ($\pm 8.3$ fs). The fitted decay time distribution is shown in Fig. 3 (right) along with projections of the fit result. The measured lifetime is significantly longer than the lifetime measured by Fermilab E687 [12], CERN WA89 [13], and FOCUS [14], but it agrees with more recent measurements by LHCb [15]. This lifetime is unexpectedly longer than that of lighter charmed baryons, i.e., the hierarchy of charm baryon lifetimes becomes $\tau(\Xi_c^+) > \tau(\Omega_c^0) > \tau(\Lambda_c^+) > \tau(\Xi_c^0)$.
Figure 3: Invariant mass distribution for $\Omega_c^0 \rightarrow \Omega^- (\rightarrow \Lambda K^-)\pi^+$ candidates (left); decay time distribution for $\Omega_c^0$ candidates in the signal region $M(\Omega^-\pi^+) \in [2.68, 2.71]$ GeV/$c^2$ (right top); decay time distribution for $\Omega_c^0$ candidates in the sideband $M(\Omega^-\pi^+) \in [2.55, 2.65] \cup [2.75, 2.85]$ GeV/$c^2$ (right bottom). The latter events are fitted to obtain the decay time PDF used for background in the signal region [11].

6 Summary

Except for the $\Omega_c^0$ charm baryon, the lifetime measurements presented here are the world’s most precise. For the $\Omega_c^0$, the Belle II measurement confirms the unexpectedly long lifetime measured by LHCb [15]. All measurements are compared to theory predictions [2, 16] in Table 4. Currently, the theory uncertainties are large and preclude a precision test of QCD. While all measurements agree with theory predictions within $2\sigma$, the measured values of $\tau(D^0)$, $\tau(D^+)$, and $\tau(\Lambda_c^+)$ differ from the predictions by more than $1\sigma$. Such differences can help discriminate among different calculational approaches and ultimately improve our understanding of QCD.

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Table 4: Comparison between measurements and HQE theory predictions for charm lifetimes. The limits listed correspond to 90% C.L. The HQE calculations for $\tau(D^+_s \to \tau^+\nu)$ do not include the partial width for $D^+_s \to \tau^+\nu$, as $m_\tau > m_c$.

|               | Belle II | King et al. [2] | Gratrex et al. [16] |
|---------------|----------|-----------------|---------------------|
| $\tau(D^0)$  | 410.5 ± 1.1 ± 0.8 [8] | $629^{+296}_{-167}$ | $595^{+344}_{-166}$ |
| $\tau(D^+)$  | 1030.4 ± 4.7 ± 3.1 [8] | > 1193 | > 1690 |
| $\tau(D^+_s)$ | 499.5 ± 1.7 ± 0.9 [6] | $637^{+381}_{-190}$ | $599^{+459}_{-180}$ |
| $\tau(D^+)/\tau(D^0)$ | 2.510 ± 0.016 | $2.80^{+0.86}_{-0.90}$ | $2.89^{+0.78}_{-0.85}$ |
| $\tau(D^+_s)/\tau(D^0)$ | 1.217 ± 0.006 | 1.01 ± 0.15 | 1.00±$^{+0.23}_{-0.24}$ |
| $\tau(\Lambda^+_c)$ | 203.20 ± 0.89 ± 0.77 [9] | | $312^{+128}_{-96}$ |
| $\tau(\Omega^0_c)$ | 243 ± 48 ± 11 [11] | | $237^{+111}_{-75}$ |
| $\tau(\Omega^0_c)/\tau(\Lambda^+_c)$ | 1.20 ± 0.24 | | $0.83^{+0.30}_{-0.28}$ |

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