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Measurements of charm lifetimes at Belle II

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We report on absolute lifetime measurements of charmed hadrons using the data collected by the Belle II experiment between 2019 and 2021. The measured lifetimes of D^0, D^+, and Λ_c^+ are the most precise to date and consistent with previous measurements. Our result indicates that Ω_c^0 is not the shortest-lived singly charmed baryon.

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1. Introduction

Predictions of beauty and charm hadron lifetimes are achieved by the heavy quark expansion (HQE) model [1–6]. The charm lifetime predictions are particularly challenging due to the significant higher-order corrections and spectator quark effects. So the charm lifetime measurements allow for HQE validation and refinement that increases the reliability and precision of standard model predictions in flavor dynamics. The best measurements of charm meson lifetimes date back to FOCUS [7] while LHCb recently reported precise measurements of charm baryon lifetimes, relative to D^+ lifetime [8–10].

We report absolute lifetime measurements of the charm hadrons using the data collected by the Belle II detector [11], which is built around the interaction region (IR) of the SuperKEKB [12] asymmetric energy e^+e^- collider. SuperKEKB adopts a nano-beam scheme that squeezes the IR to achieve large instantaneous luminosity. The Belle II detector consists of a tracking system, a particle identification system, and an electromagnetic calorimeter kept inside a 1.5 T superconducting magnet. The outer layer consists of a dedicated muon and K_L^0 detector. The details of the Belle II detector can be found elsewhere [11]. Excellent vertex resolution, precise alignment of the vertex detector, and accurate calibration of particle momenta in Belle II are crucial in the measurements of lifetimes.

2. Lifetime extraction

The proper decay times of charm hadrons are calculated as $t = m(\vec{L} \cdot \hat{p})/p$, where m is the known mass of hadrons, $\vec{L}$ is the flight length between the production and decay vertices, and p is the momentum of hadrons. Lifetimes are extracted by using unbinned maximum-likelihood fits to the t and its uncertainty, σ_t, of the candidates populating the signal regions of data. The signal probability-density function (PDF) is the convolution of an exponential function in t with a resolution function that depends on σ_t, multiplied by the PDF of σ_t. The time constant of the exponential function will return the lifetime. The σ_t PDF is a histogram template derived directly from the signal region of the data. In all cases but D^0, the template is obtained from the candidates in the signal region after having subtracted the distribution of the sideband data. Simulation demonstrates that for D^+, Λ_c^+, and Ω_c^0, a single Gaussian function is sufficient, whereas for D^0, a double Gaussian function with a common mean is required.

3. D^0 and D^+ lifetimes

We measured D^0 and D^+ lifetimes using 72 fb^{-1} of Belle II data in the decays of $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$, respectively. 171×10^3 signal candidates are reconstructed for $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ decays in the signal region: $1.851 < m(K^-\pi^+) < 1.878$ GeV/c^2. In the D^0 case, the per-mille-level fraction of background candidates in the signal region is neglected, and a systematic uncertainty is assigned for this. 59×10^3 signal candidates are reconstructed for $D^{*+} \to D^+(\to K^-\pi^+\pi^+)\pi^0$ decays in the signal region: $1.855 < m(K^-\pi^+\pi^+) < 1.883$ GeV/c^2. For the D^+ case, a sizable background contamination in the signal region is accounted for using the data sideband: $1.758 < m(K^-\pi^+\pi^+) < 1.814$ GeV/c^2, $1.936 < m(K^-\pi^+\pi^+) < 1.992$ GeV/c^2.

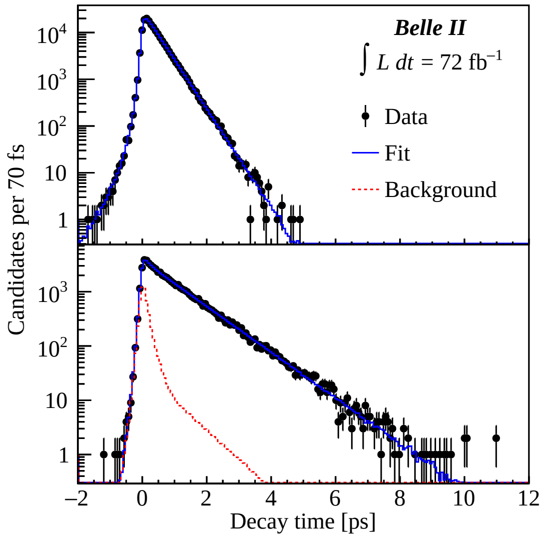

Figure 1: Decay-time distributions of (top) $D^0 \to K^-\pi^+$ and (bottom) $D^+ \to K^-\pi^+\pi^+$ candidates in their respective signal regions with fit projections overlaid.

Table 1: Systematic uncertainties for D^0 and D^+ lifetimes.

Source	$\tau(D^0 \to K^-\pi^+)$ [fs]	$\tau(D^+ \to K^-\pi^+\pi^+)$ [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

The background PDF consists of a zero-lifetime component and two exponential components, all convolved with the resolution function. The decay-time distributions of the data, with fit projections overlaid, are shown in Fig. 1. The D^0 and D^+ lifetimes are measured to be $410.5 \pm 1.1 \pm 0.8$ fs and $1030.4 \pm 4.7 \pm 3.1$ fs, respectively [13]. The errors are statistical and systematic (all relevant effects are studied as summarized in Table 1), respectively. The results are consistent with their respective world average values [14].

4. Λ_c^+ lifetime

The most precise measurement of the Λ_c^+ lifetime is reported by the LHCb experiment [8]. We report a preliminary result on the absolute measurement of the Λ_c^+ lifetime in $\Lambda_c^+ \to pK^-\pi^+$ decays reconstructed using 207 fb^{-1} of the Belle II data. We reconstruct 116×10^3 candidates for the decay $\Lambda_c^+ \to pK^-\pi^+$ in the signal region: $2.283 < m(pK^-\pi^+) < 2.290$ GeV$/c^2$, with a background contamination of 7.5%. The Λ_c^+ lifetime is extracted in the same way as the D^+ lifetime. Background events in the signal region are constrained using data sideband ($2.249 < m(pK^-\pi^+) < 2.264$ GeV$/c^2$, $2.309 < m(pK^-\pi^+) < 2.324$ GeV$/c^2$).

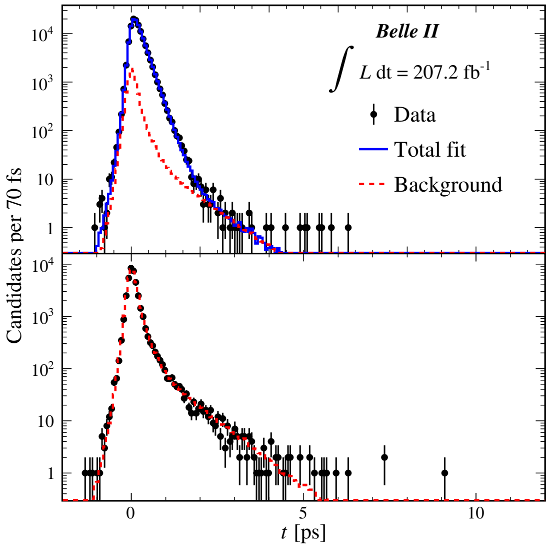

Figure 2: Decay-time distributions of $\Lambda_c^+ \to pK^-\pi^+$ candidates in their (top) signal and (bottom) sideband regions with fit projections overlaid.

Table 2: Systematic uncertainties for Λ_c^+ lifetime.

Source	Uncertainty (fs)
Ξ_c contamination	0.34
Resolution model	0.46
Non-Ξ_c background model	0.20
Detector alignment	0.46
Momentum scale	0.09
Total	0.77

Decays of $\Xi_c^0 \to \pi^-\Lambda_c^+$ and $\Xi_c^+ \to \pi^0\Lambda_c^+$ may bias the measurement of the Λ_c^+ lifetime, since the Ξ_c^0 and Ξ_c^+ have non-zero lifetimes and may shift the production vertex of the Λ_c^+ away from the IR. A veto is applied to suppress such candidates, and a systematic uncertainty is assigned for the remaining contamination (details can be found at [15]). We measure the Λ_c^+ lifetime to be $203.20 \pm 0.89 \pm 0.77$ fs, where the uncertainties are statistical and systematic (summarized in the Table 2), respectively [15]. Our result is consistent with the current world average [14].

5. Ω_c^0 lifetime

The Ω_c^0 was believed to be the shortest-lived singly charmed baryon that decays weakly. In 2018, LHCb measured a large value of Ω_c^0 lifetime [9], and this observation inverted the lifetime hierarchy of singly charmed baryons. LHCb confirmed their result in 2022 using a different data sample [10]. We performed the first independent measurement of Ω_c^0 lifetime using 207 fb^{-1} of data collected at Belle II. We reconstructed 90 signal candidates in the signal region $(2.68 < m(\Omega^-\pi^+) < 2.71\ \text{GeV}/c^2)$ for the decay $\Omega_c^0 \to \Omega^-\pi^+$, where $\Omega^- \to \Lambda^0(\to p\pi^-)K^-$. It is a complex decay chain with two extra decay vertices in addition to the Ω_c^0 decay vertex.

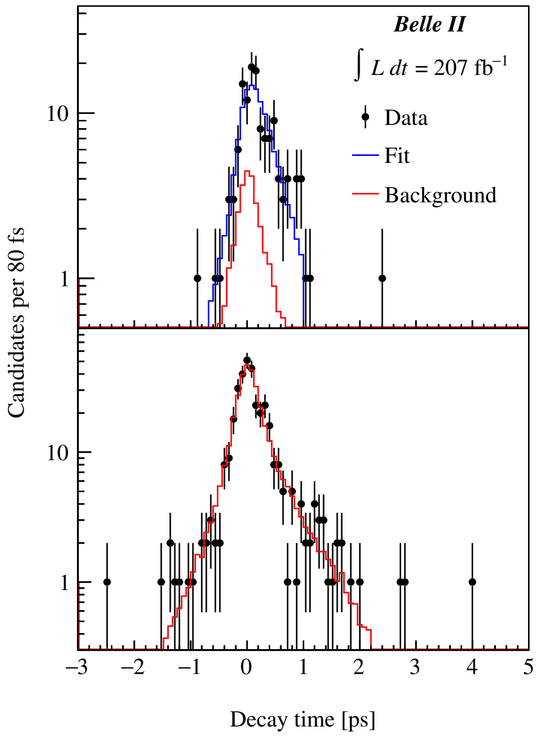

Figure 3: Decay-time distributions of $\Omega_c^0 \to \Omega^- \pi^+$ candidates in their (top) signal and (bottom) sideband regions with fit projections overlaid.

Table 3: Systematic uncertainties for Ω_c^0 lifetime.

Source	Uncertainty (fs)
Fit bias	3.4
Resolution model	6.2
Background model	8.3
Detector alignment	1.6
Momentum scale	0.2
Input Ω_c^0 mass	0.2
Total	11.0

The lifetime is extracted by fitting the signal and sideband regions simultaneously. The signal region has a background contamination of 33% and is constrained the using events in the sideband ($2.55 < m(\Omega^-\pi^+) < 2.65\,\mathrm{GeV}/c^2, 2.75 < m(\Omega^-\pi^+) < 2.85\,\mathrm{GeV}/c^2$). The Ω_c^0 lifetime is measured to be $243 \pm 48 \pm 11$ fs, where the uncertainties are statistical and systematic (summarized in Table 3), respectively [16]. The result is consistent with LHCb measurements and inconsistent with previous measurements at 3.4 standard deviations.

6. Conclusions

In conclusion, D^0, D^+, Λ_c^+, and Ω_c^0 lifetimes are measured using the data collected by the Belle II experiment. The results on D^0, D^+, and Λ_c^+ lifetimes are the most precise to date and are consistent with previous measurements. Our result on Ω_c^0 lifetime is consistent with the LHCb results [9, 10], and inconsistent at 3.4 standard deviations with the pre-LHCb world average [17]. The Belle II result, therefore, confirms that the Ω_c^0 is not the shortest-lived weakly decaying charmed baryon.

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