A High Statistics Measurement of the Λ_c^+ Lifetime

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A high statistics measurement of the Λ_c^+ lifetime from the Fermilab fixed-target FOCUS photoproduction experiment is presented. We describe the analysis technique with particular attention to the determination of the systematic uncertainty. The measured value of 204.6 ± 3.4 (stat) ± 2.5 (syst) fs from 8034 ± 122 $\Lambda_c^+ \to pK^-\pi^+$ decays represents a significant improvement over the present world average.

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Experimental measurements of charm particle lifetimes have been used in the study of strong interaction physics. The measurements provide some guidance for theoretical calculations of nonperturbative strong interaction processes. The steady improvement in the precision of the measurements has not only helped to improve our theoretical understanding of strong interactions but also has helped to stimulate the development of better theoretical tools. These have progressed from the spectator model to various quark models and currently to heavy quark expansion methods [1]. These calculational tools are the same or similar to those used in other areas, for example, to determine the size of the V_{ub} Cabibbo-Kobayashi-Maskawa element through inclusive semileptonic B decays [2]. More precise measurements of all of the charm particle lifetimes will help continue this process of improvement and extension of applicability.

Precise charm lifetime measurements are now beginning to emerge from e^+e^- collider experiments [3,4]. The effects of lifetime and vertex resolution are also important in mixing and CP violation measurements [5,6]. It is crucial to have accurate lifetime measurements from fixed-target experiments to act as a standard to evaluate any relative systematic differences. The Λ_c^+ lifetime presented in this Letter represents the most accurate measurement of this quantity to date and is a significant improvement over the present world average.

The data used were collected by the FOCUS Collaboration in the 1997 fixed-target run at Fermi National Accelerator Laboratory. The FOCUS spectrometer is an upgrade of the spectrometer used in the E687 photoproduction experiment [7]. The vertex region consists of four BeO targets and 16 planes of silicon strip detectors (SSD). Two of the SSD planes were placed immediately downstream of the second target, and two immediately downstream of the fourth (most downstream) target. Momentum analysis was made possible by the use of five multiwire proportional chambers and two magnets with opposite polarities. Hadronic particle identification was achieved using three multicell threshold Čerenkov counters [8]. The data for this measurement were taken using a photon beam with average energy of ~180 GeV for triggered events.

The $\Lambda_c^+ \to pK^-\pi^+$ [9] candidates are reconstructed using a candidate driven algorithm which is highly efficient for all decays including short-lived ones. All $pK^-\pi^+$ candidates are tested to see if they form a vertex with a confidence level greater than 1%. The candidate Λ_c^+ momentum vector is then used to search for a production vertex with one or more tracks. As many tracks as possible are included in the production vertex so long as the vertex confidence level is larger than 1%. The production vertex is required to be within one of the four targets. The separation L between the production and decay vertices is required to be larger than $6\sigma_L$ where σ_L is the error on L calculated on a candidate-by-candidate basis. In addition, each track in the $pK^-\pi^+$ candidate combination must also satisfy the appropriate Čerenkov particle identification criteria.

The $pK^-\pi^+$ invariant mass plot for data is shown in Fig. 1. The fit shown uses a Gaussian signal and a quadratic background function which yields 8034 ± 122 reconstructed Λ_c^+ decays. The lifetime analysis uses

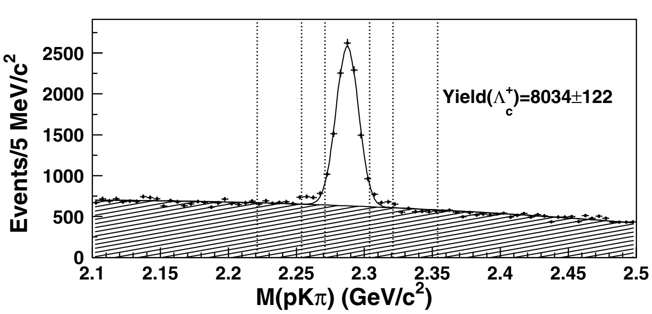

FIG. 1. $pK^-\pi^+$ invariant mass plot for data (points) fitted with a Gaussian signal and quadratic background (solid line). The shaded area indicates the fitted level of background. The vertical dotted lines indicate the signal and sideband regions (see text) used in the lifetime analysis.

$pK^-\pi^+$ candidates within the signal and symmetric sideband regions as shown in the figure. All three regions are $4\sigma_m$ wide (i.e., $\pm 2\sigma_m$) and the centers of the sidebands are located $\pm 6\sigma_m$ from the mean of the fitted Gaussian, where $\sigma_m = 8.2\ \mathrm{MeV}/c^2$ is the width of the fitted Gaussian.

For the lifetime analysis we use the reduced proper time, $t' = (L - 6\sigma_L)/\beta\gamma c$ [10], where $\beta\gamma = p_{\Lambda_c}/m_{\Lambda_c}$ and require it to be less than 1 ps to reduce long-lived backgrounds. This requirement was already made for the data shown in Fig. 1. The use of the reduced proper time ensures that only a small acceptance correction to the lifetime is needed. The average proper time resolution for this decay sample (42 fs) is small enough compared to the lifetime to use a binned likelihood method [11].

The t' distributions for the decays in the signal and sideband regions are binned into two separate histograms from 0–1 ps in 20 fs bins. The observed number of decays in the ith t' bin is s_i for the signal region and b_i for the sideband region. The t' distribution of the sideband region is used as a measure of the lifetime distribution of background events in the signal region. Thus the expected number of decays in the ith t' bin of the signal region is given by

$$\text{expected events} = n_i = S\,\frac{f(t_i')e^{-t_i'/\tau}}{\sum_i f(t_i')e^{-t_i'/\tau}} + B\,\frac{b_i}{\sum_i b_i}. \tag{1}$$

The likelihood that is maximized in the fit is given by

$$\text{likelihood} = \prod_i \frac{n_i^{s_i}e^{-n_i}}{s_i!} \times \frac{(\alpha B)^{N_b}e^{-\alpha B}}{N_b!}, \tag{2}$$

where S is the total number of signal events and B is the total number of background events in the signal region and $S + B = \Sigma s_i$. The total number of events in the sideband region is $N_b = \Sigma_i b_i$, and α is the ratio of the number of events in the sideband region to the number of background events in the signal region. The value of α is obtained from the fit to the invariant mass distribution and is very close to 2. B and τ are the fit parameters.

The effects of geometrical acceptance, detector and reconstruction efficiencies, and absorption of the Λ_c^+ and decay daughters are given by the $f(t')$ correction function. The $f(t')$ is determined using a detailed Monte Carlo (MC) simulation of the experiment where the production (using PYTHIA [12]) was tuned so that the production distributions for data and MC matched. Note that only the shape of the $f(t')$ function is important and it is obtained by dividing the observed MC t' distribution by a pure exponential with the MC generated lifetime. The $f(t')$ distribution is shown in Fig. 2(a).

Using the likelihood function given above we obtained a fitted lifetime of 204.6 ± 3.4 fs. The lifetime distribution of all decays in the signal region is shown in Fig. 2(b) together with the fit and the level of background contained

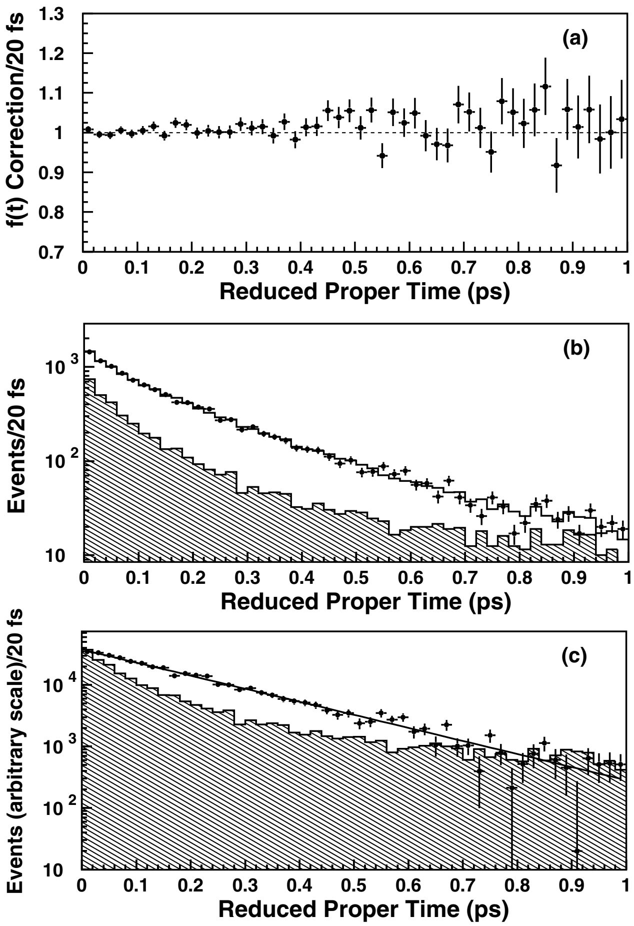

FIG. 2. (a) The $f(t')$ correction function. Deviation from a flat line indicates the correction from a pure exponential. (b) The lifetime distribution for all decays in the data signal region (points) and the fit (histogram). The shaded distribution shows the lifetime distribution of the background component in the signal region. (c) The lifetime distribution for Λ_c decays (points), i.e., the sideband subtracted and $f(t')$ corrected yield. The line is a pure exponential with the fitted lifetime. The background distribution (shaded region) is overlaid for comparison. An arbitrary yield scale is used because of the particular normalization of $f(t')$.

in the signal region. The fit probability is 4% (χ^2/d.o.f. = 66/48).

Detailed studies were performed to determine the systematic uncertainty in this measurement [13].

The uncertainty in the absolute time scale was investigated by studying the absolute length and momentum scales in the experiment. For the length scale, comparisons were made between measurements of the distances between silicon planes in the target region. The values obtained using vertex positions in the data with the standard vertexing code agree well with those obtained using precision instruments. The absolute momentum and mass scales were checked by comparing the reconstructed masses of charm and strange mesons and hyperons with established values. Our studies showed no evidence of any scale offset, but due to the limited statistical precision of these comparisons we assign an uncertainty of $\pm 0.11\%$ to the absolute time scale.

The backgrounds are composed of a noncharm and a charm component; these two background components are approximately equal in our sample and fairly evenly distributed across the signal and sideband mass regions. The level and lifetime distribution of the background in the signal mass region is assumed to be well represented by symmetric mass sidebands close to the signal region. The uncertainties that arise because of these assumptions were determined by a large number of studies.

The contamination from $D^+ \to K^-\pi^+\pi^+$, $D^+ \to K^-K^+\pi^+$, and $D_s^+ \to K^-K^+\pi^+$ decays misidentified as $pK^-\pi^+$ decays were determined in our sample. We loosened the Čerenkov requirements on the data and used the MC efficiencies to extrapolate to tighter particle identification criteria. From this we found the above three decays contribute, respectively, 0.5%, 1.3%, and 2.7% of the total background in the signal region. The small contribution of these reflection backgrounds and the fact that they are distributed fairly uniformly across the signal and sideband mass regions mean they give rise to insignificant uncertainties. This was verified in a test by explicitly eliminating them by cutting out the appropriate mass regions. Using variations in particle identification and vertexing selection to significantly change the signal/background ratio also showed no significant uncertainties.

The background lifetime uncertainty was further investigated by using symmetric sidebands of different widths (4 to $16\sigma_m$), and located at different separations from the signal region (± 4 to $\pm 16\sigma_m$). The effect of using only the low or only the high mass sideband was also studied. The effect of having the fit parameter B truly free by eliminating the background term in the likelihood [second term in Eq. (2)] was studied and found to be inconsequential. Note that the results of the $pK^-\pi^+$ mass fit are used only in the background term in the likelihood.

Finally, an independent analysis which did not rely on knowledge of the background lifetime distribution was performed. In this analysis the data were split into twenty 50 fs wide reduced proper time bins from 0–1 ps. The number of $\Lambda_c^+ \to pK^-\pi^+$ decays in each bin was determined in a mass fit and the yields fitted to an exponential decay distribution modified by a $f(t')$ correction function. This $f(t')$ function was obtained separately for this analysis from the MC, doing the same split into 20 time bins and fitting the mass distributions for each MC bin. This $f(t')$ correction function agrees well with that obtained in the standard analysis method.

From these studies we assign a background systematic uncertainty of $\pm 0.77\%$.

Uncertainties in the $f(t')$ correction include uncertainties from the geometrical acceptance, the detector and reconstruction efficiencies, the production model, the absorption cross sections, and the decay dynamics.

TABLE I. Contributions to the systematic uncertainty.

Contribution	Systematic (%)
Time scale	± 0.11
Backgrounds	± 0.77
Acceptance	± 0.83
Production	± 0.38
Resolutions	± 0.12
Absorption	± 0.23
Total	± 1.23

With our chosen selection criteria, the $f(t')$ correction reduces the fitted lifetime by 1.19%. A number of studies were performed to study the uncertainty in this correction. Since the correction function is obtained from MC simulations, care was taken to ensure that this simulation correctly reproduces a very large number of data distributions. In particular, the MC reproduces the data Λ_c^+ longitudinal and transverse momenta, the multiplicity of the production vertex, and the decay length and proper time resolutions. A sensitive check of the acceptance and efficiency part of the MC correction was done using high statistics $K_S^0 \to \pi^+\pi^-$ decays. Short-lived K_S^0 decays were reconstructed using the same analysis methods in the same decay region as the Λ_c^+ decays. Since the K_S^0 lifetime is well known we can determine the $f(t')$ correction in data and compare it to that obtained in our MC simulation. The agreement is excellent but was limited by both data and MC statistics to a sensitivity of $\pm 2\%$ of the correction. Using this as the level of the uncertainty in the $f(t')$ correction, we can assign a systematic uncertainty due to this correction of $\pm 0.83\%$. Possible time dependent systematic effects were looked for by splitting the data into different time periods and comparing the fitted lifetimes. We also compared the separate fitted lifetimes for decays originating from each of the four targets. No systematic uncertainties were found in these two comparisons.

Our limited knowledge of the production and decay of the Λ_c^+ could contribute to a systematic uncertainty. This was studied using different MC simulations where the production parameters and the resonance substructure of the decay were varied over reasonable ranges. Production systematics were also studied by splitting the data into different bins of longitudinal and transverse Λ_c^+ momenta, primary vertex multiplicity, and by comparing the fitted lifetimes for particles and antiparticles. We assign a systematic uncertainty of $\pm 0.38\%$ due to our limited knowledge of Λ_c^+ production and decay.

In order to use the reduced proper time we must be able to correctly model our proper time resolution. This was verified by comparing the distributions for data and MC and by studying splits of the data sample that can be sensitive to resolution effects. The data were split into bins of proper time resolution and reconstructed invariant mass. Variations of the proper time bin width from 10 to 100 fs were also studied as was changing the fitted range from 0–0.6 ps to 0–1.4 ps, and from 0–1 ps to 0.2–1 ps. We assign a systematic uncertainty of $\pm 0.12\%$ to the lifetime due to resolution uncertainties.

TABLE II. Comparison of recent Λ_c^+ lifetime measurements.

Experiment	Type	$\tau(\Lambda_c^+)$ fs
E687 [11]	FT	$215 \pm 16 \pm 8$
SELEX [16]	FT	$198.1 \pm 7.0 \pm 5.6$
CLEO II.5 [4]	e^+e^-	$179.6 \pm 6.9 \pm 4.4$
FOCUS (this result)	FT	$204.6 \pm 3.4 \pm 2.5$

The systematic uncertainty due to absorption of the Λ_c^+ and daughter particles was studied by varying the charm interaction cross section by 100% and the daughter particle interaction cross sections by 50% in the MC [15]. It was also studied by comparing the lifetimes of decays occurring inside and outside of the target, and by comparing the lifetimes for decays where the Λ_c^+ was produced in the upstream half of each target with those produced in the downstream half of the same target. We determined a systematic uncertainty of $\pm 0.23\%$ due to absorption.

Contributions to the systematic uncertainty are summarized in Table I. Taking contributions to be uncorrelated we obtain a total systematic uncertainty of $\pm 1.23\%$ or ± 2.5 fs.

We have measured the Λ_c^+ lifetime to be 204.6 ± 3.4 (stat) $\pm$ 2.5 (syst) fs using 8034 ± 122 $\Lambda_c^+ \to pK^-\pi^+$ decays from the Fermilab FOCUS photoproduction experiment. This measurement represents a significant improvement in accuracy and special care was taken to investigate and properly quantify possible systematic uncertainties. Table II compares our measurement with previous recent published results. The difference between this measurement and the measurement from the CLEO e^+e^- experiment may point to the emergence of possible relative systematic effects [17]. Any such systematic difference would be important to resolve given the number of recent and future mixing and CP-violation measurements that rely on accurate knowledge of lifetime distributions.

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[1] G. Bellini, I. I. Y. Bigi, and P. J. Dornan, Phys. Rep. **289**, 1 (1997).

[2] M. B. Voloshin, Phys. Lett. B **515**, 74 (2001).
[3] G. Bonvicini *et al.,* Phys. Rev. Lett. **82**, 4586 (1999).
[4] A. H. Mahmood *et al.,* Phys. Rev. Lett. **86**, 2232 (2001).
[5] R. Godang *et al.,* Phys. Rev. Lett. **84**, 5038 (2000).
[6] K. Abe *et al.,* hep-ex/0111026.
[7] P. L. Frabetti *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **320**, 519 (1992).
[8] J. M. Link *et al.,* hep-ex/0108011 [Nucl. Instrum. Methods Phys. Res., Sect. A (to be published)].
[9] The charge conjugate mode is implicitly implied unless otherwise stated.
[10] The reduced proper time has the clock started at the minimum allowed time for each decay candidate. In the absence of other corrections, it does not matter where along the decay exponential one starts the clock; hence the reduced proper time also follows a pure exponential.
[11] P. L. Frabetti *et al.,* Phys. Rev. Lett. **70**, 1755 (1993).
[12] T. Sjöstrand *et al.,* Comput. Phys. Commun. **135**, 238 (2001).
[13] The numerical value of the systematic contributions in each study was usually obtained in one of three ways. For variational studies the deviation due to variation of a parameter (e.g., the absorption cross section) is taken as the systematic. For studies involving statistically independent split samples, a method similar to the Particle Data Group S-factor method is used [14]. If $S > 1$ the systematic is taken to be very nearly $\sigma_{\rm tot}\sqrt{S^2 - 1}$, where $\sigma_{\rm tot}$ is the statistical error of the total sample. For studies using variants of essentially the same data sample (e.g., varying the t' bin width) the rms is taken as the systematic.
[14] Particle Data Group, D. E. Groom *et al.,* Eur. Phys. J. C **15**, 1 (2000).
[15] The daughter momentum dependent cross sections are taken from [14], while the Λ_c^+ cross section is taken to be momentum independent at half the value for 20 GeV neutrons.
[16] A. Kushnirenko *et al.,* Phys. Rev. Lett. **86**, 5243 (2001).
[17] H. W. K. Cheung, hep-ex/0111050.