Measurement of the Λ_b^0 Lifetime Using $\Lambda_b^0 \to \Lambda_c^+ \ell^- \bar{\nu}$

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(Received 19 April 1996)

The lifetime of Λ_b^0 is measured using the semileptonic decay $\Lambda_b^0 \to \Lambda_c^+ \ell^- \bar{\nu}$, where the Λ_c^+ is reconstructed through its decay $\Lambda_c^+ \to pK^-\pi^+$. The data were collected by the CDF detector at the Tevatron Collider during 1992–1995 and correspond to an integrated luminosity of 110 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. From a fit to the decay length distribution of the Λ_c-lepton system from 197 ± 25 signal events, the lifetime of Λ_b^0 is measured to be $1.32 \pm 0.15 \pm 0.07$ ps. [S0031-9007(96)00942-8]

PACS numbers: 14.20.Mr, 13.30.Ce

The naive spectator model predicts that the lifetimes of weakly decaying hadrons containing the same heavy quark should be identical. Therefore any lifetime difference between hadrons with the same heavy quark reflects contributions from nonspectator diagrams, such as final state quark interference and W exchange, which play important roles in the large lifetime differences between charm hadrons [1,2]. These effects are predicted to be smaller for heavier quark masses; in particular, the lifetime differences among b hadrons are expected to be less than 10% [3]. However, the observed Λ_b^0 lifetime from LEP experiments [4] shows a discrepancy from this picture which more experimental studies and theoretical calculations should clarify. In this Letter, we report a measurement of the Λ_b^0 lifetime using the partially reconstructed semileptonic decay $\Lambda_b^0 \to \Lambda_c^+ \ell^- \bar{\nu}$, where ℓ^- is either an electron or a muon.

The data were collected with the CDF detector at the Fermilab Tevatron Collider at a center-of-mass energy $\sqrt{s} = 1.8$ TeV during the 1992–1995 collider run, and correspond to an integrated luminosity of 110 pb^{-1}. The CDF detector is described in detail elsewhere [5]. We describe here only those detector components most relevant to this analysis. The silicon vertex detector (SVX) and the central tracking chamber (CTC) provide the tracking and momentum measurement of charged particles. The SVX consists of four layers of silicon microstrip detectors and provides spatial measurements in the r-ϕ plane [6] with a resolution of 15 μm [7]. The CTC is a cylindrical drift chamber containing 84 layers grouped into 9 alternating superlayers of axial and stereo wires. Electrons are identified using the tracking system and the central electromagnetic calorimeter (CEM) [8]. The CEM covers the pseudorapidity interval of $|\eta| < 1.1$, where $\eta = -\ln[\tan(\theta/2)]$. Muons are identified using the central muon chambers which cover approximately 53% of the solid angle for $|\eta| < 0.6$ [9]. A charmed particle produced in association with a lepton serves as a signature of b-hadron production. Therefore we search for the semileptonic decays in the b-hadron-rich inclusive lepton samples collected with the CDF trigger system [10]. The inclusive lepton trigger is fully efficient for leptons with transverse momentum above 8 GeV/c.

We search for the decay $\Lambda_b^0 \to \Lambda_c^+ \ell^- \bar{\nu}$ by detecting a $\Lambda_c^+ \ell^-$ (right sign) pair with invariant mass in the kinematically allowed range $m_{\Lambda_c} < m_{\Lambda_c \ell} < m_{\Lambda_b^0}$. Throughout this Letter, charge conjugate modes are always implied. The charmed baryon Λ_c is reconstructed through its decay to $pK^-\pi^+$. Tracks used in the reconstruction are required to be within a cone of $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.8$ centered on the lepton direction. The minimum transverse momentum to the beam line required for the proton, kaon, and pion are 1.5 GeV/c, 0.7 GeV/c, and 0.6 GeV/c, respectively, to reduce combinatorial backgrounds. The charmed baryon Λ_c baryons produced from B meson decays and other b-baryon decays have a softer momentum spectrum than that from $\Lambda_b^0 \to \Lambda_c^+ \ell^- \bar{\nu}$ due to the presence of other particles sharing the b-hadron energy; to reject those backgrounds we only use Λ_c candidates with at least 5.0 GeV/c transverse momentum. The momentum requirement also reduces combinatorial backgrounds. The Λ_c vertex is formed from a fit of its three daughters to a common point; the confidence level of the fit is required to be larger than 5%. The average beam position obtained on a run-by-run basis is used as the primary vertex in the fit. To reduce combinatorial backgrounds, the Λ_c vertex is required to be inconsistent by at least 1σ with the primary vertex and to have a positive projection along its momentum vector, where σ is the standard error of the Λ_c vertex position estimated from the fit.

The specific ionization (dE/dx) information from the CTC is used to help identify the protons in the Λ_c reconstruction. Because of the large Landau tail of the ionization distribution, we take the 80% truncated mean of the measured charges from the CTC sense wires as the best estimator of the dE/dx. The probabilities for a track to be consistent with the proton, pion, and kaon hypotheses are then calculated using the measured dE/dx value and predictions for the assumed particle hypotheses. We define a likelihood ratio for a track being a proton to be the ratio of its probability to be a proton to the sum of its probabilities to be a proton, pion, or kaon. We ask that the proton candidate have a likelihood ratio to be a proton greater than 60%. This requirement reduces the background level in Λ_c candidates by a factor of 3, while keeping more than 80% of the signal events.

The Λ_c^+ candidate is then combined with a negatively charged lepton. The lepton is required to have a transverse momentum greater than 6 GeV/c. The $\Lambda_c^+ \ell^-$ pair is required to satisfy $3.5 < m_{\Lambda_c^+ \ell^-} < 5.6$ GeV/c^2. Background $\Lambda_c^+ \ell^-$ pairs produced from decay sources other than $\Lambda_b^0 \to \Lambda_c^+ \ell^- \bar{\nu}$ have softer momenta and small invariant mass. Examples of these background sources are B meson decays such as $\bar{B} \to \Lambda_c^+ D_s^- X$ where $D_s^- \to \ell^- X$, other Λ_b^0 decays such as $\Lambda_b^0 \to \Lambda_c^+ D_s^- X$ where $D_s^- \to \ell^- X$, and $\Lambda_b^0 \to \Lambda_c^{*+} \ell^- \bar{\nu} X$ where $\Lambda_c^{*+} \to \Lambda_c^+ \pi^+ \pi^-$. Although backgrounds from these sources are estimated to be less than a few percent, we increase the invariant mass cut from the kinematic limit (Λ_c mass) to 3.5 GeV/c^2 and require the $\Lambda_c^+ \ell^-$ pair to have a transverse momentum greater than 8 GeV/c to further suppress them. Other random combinatorial backgrounds are expected to have equal amounts of right sign ($\Lambda_c^+ \ell^-$) and wrong sign ($\Lambda_c^+ \ell^+$) pairs, so the wrong sign background is used as an estimate of such backgrounds.

Figure 1 shows the $pK^-\pi^+$ invariant mass distributions of the right sign and the wrong sign Λ_c^+ candidates passing our selection cuts. Semileptonic decays of B mesons, where the final state particles have been misidentified, are a source of flat background, which populates the right sign mass distribution more than the wrong sign. We fit the $pK^-\pi^+$ invariant mass distribution with a function consisting of a Gaussian signal and a linear background. The yield returned from the fit is 197 ± 25 right sign signal events. We analyze the wrong sign events in the same manner as for the right sign and find that the number of wrong sign events is consistent with zero.

The Λ_b^0 vertex is obtained by intersecting the trajectory of the lepton track with the flight path of the Λ_c candidate. The decay length of the Λ_b^0 in the transverse plane, L_{xy}, is defined as the displacement of the Λ_b^0 decay vertex from the primary vertex, projected onto the direction of the Λ_c-lepton system. We assume that the Λ_b^0 is produced at the primary vertex. We then relate the decay length to the Lorentz-invariant proper decay length by a Lorentz boost $\beta\gamma = p_t(\Lambda_b^0)/Mc$, where M is the Λ_b^0 mass [1] and $p_t(\Lambda_b^0)$ is the transverse momentum of

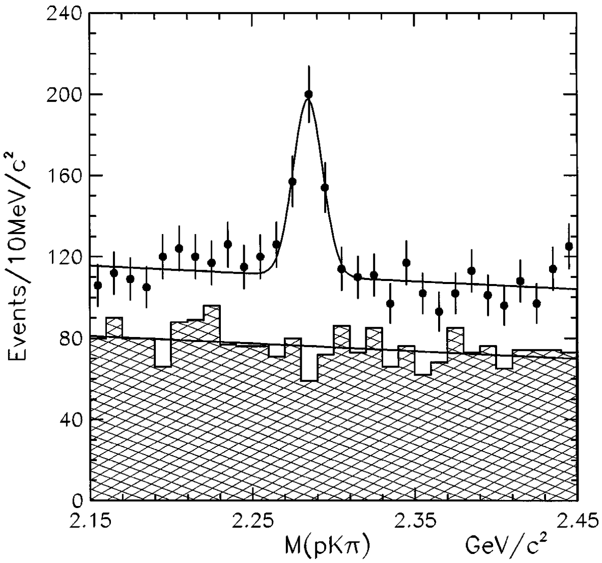

FIG. 1. Invariant mass of $pK^-\pi^+$ for right sign (points with error bars) and wrong sign events (shaded area). The fit yields 197 ± 25 right sign events. There is no evidence of a Λ_c signal in wrong sign combinations. The signal region is defined to be 2.260–2.308 GeV/c^2 and the two sideband regions are 2.176–2.224 GeV/c^2 and 2.376–2.424 GeV/c^2.

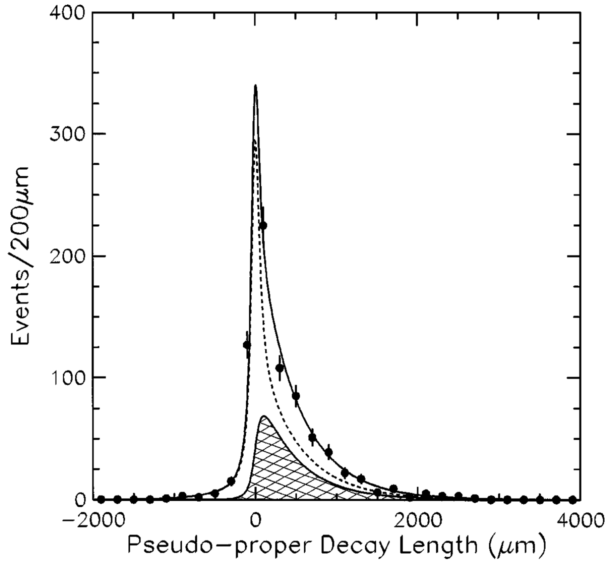

FIG. 2. Pseudoproper decay length distribution from signal region events. The points with error bars are data, the solid line is the fit result, the shaded area is the signal distribution, and the dashed line is the background contribution.

Λ_b^0. Since we cannot fully reconstruct the Λ_b^0 in the semileptonic decay due to the undetected neutrino, we use the momentum of the Λ_c-lepton pair $p_t(\Lambda_c \ell)$ as an estimate of the Λ_b^0 momentum, resulting in a pseudoproper decay length $X = L_{xy}M/p_t(\Lambda_c \ell)$. A residual correction between $p_t(\Lambda_c \ell)$ and $p_t(\Lambda_b^0)$ is performed during the lifetime fit. The distribution of the momentum ratio $K \equiv p_t(\Lambda_c \ell)/p_t(\Lambda_b^0)$, called the K factor, is obtained from Monte Carlo calculation. It has an average value of about 0.87 with an rms width of 0.11, and is approximately independent of $p_t(\Lambda_c \ell)$ and the lepton momentum.

An unbinned maximum likelihood fitting method is used to extract the Λ_b^0 lifetime from the data. The pseudoproper decay length X and its error are the input variables. The signal region events have the $pK^-\pi^+$ invariant mass within 2.260–2.308 GeV/c^2. Events from two sideband regions (2.176–2.224 GeV/c^2 and 2.376–2.424 GeV/c^2) in the $pK^-\pi^+$ invariant mass distribution are used as the background sample to obtain the parameters of the background shape. We fit the signal region events and background sample simultaneously using the log-likelihood function, $\ln \mathcal{L} = \sum_{i=1}^{N_s} \ln[(1 - f_b)\mathcal{F}_s + f_b \mathcal{F}_b] + \sum_{i=1}^{N_b} \ln \mathcal{F}_b$, where N_s and N_b are the numbers of events in the signal region and background sample. The signal function, $\mathcal{F}_s$, is assumed to be a pure exponential lifetime distribution, convoluted with a Gaussian resolution function and with the K factor distribution obtained from Monte Carlo. The background function, $\mathcal{F}_b$, is described by a sum of a Gaussian distribution centered at zero, symmetrical positive and negative exponential tails, and a positive decay exponential to characterize the heavy flavor decay in the background sample. Like the signal function, the background function is also convoluted with a Gaussian resolution function and the K factor distribution. The background fraction, f_b, is determined by fitting the Λ_c mass distribution. Figure 2 shows the pseudoproper decay length distribution of the signal region with the fit superimposed. Figure 3 shows the same distribution for the background sample. The Λ_b^0 lifetime as obtained by our fitting procedure, is $c\tau_{\Lambda_b^0} = 396 \pm 46$ μm.

As a check against bias from the event selection and the fitting procedure, we measure the lifetime of Λ_c using the

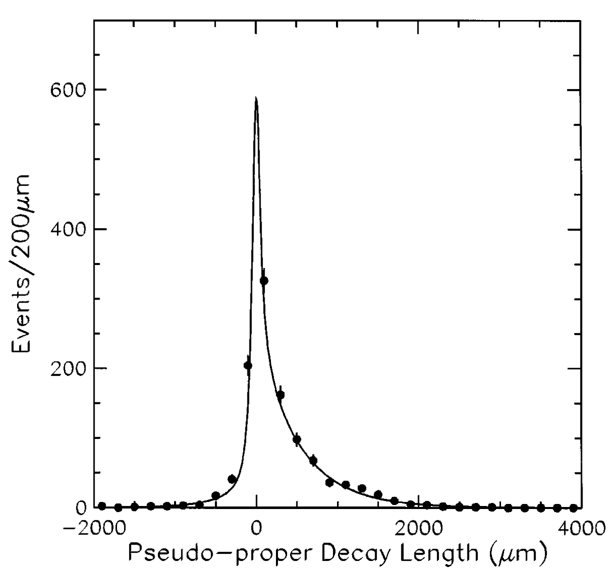

FIG. 3. Pseudoproper decay length distribution from the $pK^-\pi^+$ invariant mass sideband sample. The points with error bars are data points and the solid line is the fit result. Most of this background is from b-hadron decays.

TABLE I. Summary of systematic errors in the Λ_b^0 lifetime measurement.

Source	$\Delta c\tau_{\Lambda_b^0}$ (μm)
Event selection cut	11
Function shape	9
Fitting procedure	7
K factor	14
Sum in quadrature	21

same events as for the Λ_b^0 lifetime extraction. We obtain $c\tau_{\Lambda_c} = 66 \pm 16$ μm, which is in good agreement with the world average value of 60 ± 3 μm [1].

We have considered the following sources of systematic uncertainty on the lifetime result and give our estimate of their magnitude in Table I. The error associated with the bias introduced by the event selection requirements is studied with Monte Carlo samples and by varying the cuts systematically in the data. The error from uncertainties in the function shapes of signal and background is estimated by changing the functional forms and by using different background samples. We change the functional forms by adding another positive lifetime component to the background function, using simple exponential functions in the background function instead of exponential functions convoluted with resolution functions, using two Gaussian resolution functions instead of one single Gaussian function, and adding an exponential tail to the resolution function. We use different background samples obtained by widening and repositioning the Λ_c sideband regions. A two-step fitting procedure is used to check bias introduced by the simultaneous fitting procedure of the signal and background events. In the two-step fit procedure, we determine the parameters of the background function by fitting the background sample first and then we fit the signal region events with a fixed background shape. We take the difference of lifetimes from the two-step fit and the simultaneous fit as an estimate of the error introduced from the fitting procedure. We estimate the error associated with the K factor from various sources. We vary the Λ_b^0 lifetime, the b quark momentum spectrum, the Λ_b^0 fragmentation spectrum, the value of Λ_b^0 production polarization, and the lepton trigger efficiency simulation in Monte Carlo. We allow $\Lambda_b^0 \to \Lambda_c^{*+}\ell^-\bar{\nu}$, where $\Lambda_c^{*+} \to \Lambda_c^+\pi^+\pi^-$, to contribute up to 50% of the $\Lambda_c^+\ell^-$ pairs produced in Monte Carlo [11]. We vary the decay model from a simple phase space decay model to a heavy quark effective theory inspired decay model [12]. Adding all sources of systematic error in quadrature, we find $c\tau_{\Lambda_b^0} = 396 \pm 46 \pm 21$ μm and $\tau_{\Lambda_b^0} = 1.32 \pm 0.15 \pm 0.07$ ps.

In conclusion, from an unbinned maximum likelihood fit to the proper decay length distribution of 197 ± 25 signal events of $\Lambda_b^0 \to \Lambda_c^+\ell^-\bar{\nu}$, we obtain the result for the Λ_b^0 lifetime, $\tau_{\Lambda_b^0} = 1.32 \pm 0.15 \pm 0.07$ ps. Using this result and the average B^0 lifetime, $\tau_{B^0} = 1.56 \pm 0.05$ ps [13], we calculate the lifetime ratio $\tau_{\Lambda_b^0}/\tau_{B^0} = 0.85 \pm 0.10 \pm 0.05$, where the first error is the statistical error from our Λ_b^0 result and the second error is the combination of our systematic error and the error on B^0 lifetime. This is in good agreement with the QCD prediction [3] of $\tau_{\Lambda_b^0}/\tau_{B^0} \approx 0.9$.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Science and Culture of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the A. P. Sloan Foundation; and the Alexander von Humboldt-Stiftung.

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