Measurement of the Λ_b^0 Lifetime in $\Lambda_b^0 \to J/\psi\Lambda^0$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We report a measurement of the Λ_b^0 lifetime in the exclusive decay $\Lambda_b^0 \to J/\psi\Lambda^0$ in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV using an integrated luminosity of 1.0 fb^{-1} of data collected by the CDF II detector at the Fermilab Tevatron. Using fully reconstructed decays, we measure $\tau(\Lambda_b^0) = 1.593\ ^{+0.083}_{-0.078}$ (stat.) $\pm$ 0.033 (syst.) ps. This is the single most precise measurement of $\tau(\Lambda_b^0)$ and is 3.2 σ higher than the current world average.

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The weak decay of quarks depends on fundamental parameters of the standard model, including elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix which describe mixing between quark families. Extraction of these parameters from weak decays is complicated since observed quarks are not free but are confined within color-singlet hadrons, as described by quantum chromodynamics (QCD). An essential tool used in this extraction is the heavy quark expansion (HQE) technique [1, 2]. In HQE, the total decay width of a heavy hadron is expressed as an expansion in inverse powers of the heavy quark mass m_q. Lifetime ratios of b-flavored hadrons are predicted to be unity through $O(1/m_b)$, and $O(1/m_b^2)$ corrections are small ($\lesssim 2\%$) [3]. Detailed analysis of $O(1/m_b^3)$ corrections to the lifetime ratio lead to an expected value of $\frac{\tau(\Lambda_b^0)}{\tau(B^0)} \simeq 0.94$ [4]. This theoretical prediction has been in poor agreement with measurements for more than a decade [5–9]. The current world average of the Λ_b^0 lifetime is 1.230 ± 0.074 ps, corresponding to a ratio of $\frac{\tau(\Lambda_b^0)}{\tau(B^0)} = 0.804 \pm 0.049$ [10]. Recent calculations including next-to-leading-order QCD and $O(1/m_b^4)$

corrections lower the prediction [11, 12], making it more consistent with the measurements.

In this Letter, we present a measurement of the Λ_b^0 lifetime, $\tau(\Lambda_b^0)$, in the fully reconstructed decay $\Lambda_b^0 \to J/\psi\Lambda^0$, with $J/\psi \to \mu^+\mu^-$ and $\Lambda^0 \to p\pi^-$. Charge conjugate modes are implied throughout. Our data sample consists of 1.0 fb^{-1} of $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected by the CDF II detector at the Fermilab Tevatron between February 2002 and February 2006. This is the first measurement of $\tau(\Lambda_b^0)$ using fully reconstructed decays that is competitive with the best previous measurements, which are based on semileptonic decays. As compared to fully reconstructed decays, measurements using partially reconstructed semileptonic decays have additional uncertainties due to the missing energy of the unobserved neutrino and the modeling of background from other b-flavored baryons.

As a check of our method, we also measure $\tau(B^0)$ using a sample of $B^0 \to J/\psi K_S^0$ decays, which has larger yield than the Λ_b^0 sample. This decay channel is topologically similar to $\Lambda_b^0 \to J/\psi\Lambda^0$, since both K_S^0 and Λ^0 decay with large displacement from the b-hadron-decay vertex. The analysis procedure for Λ_b^0 is developed using $B^0 \to J/\psi K_S^0$ only and checked using other b-meson decays containing a $J/\psi \to \mu^+\mu^-$ in the final state. The Λ_b^0 lifetime was not extracted until all procedures were established including the estimate of the systematic uncertainty.

The components of the CDF II detector relevant to this analysis are described briefly here; a more complete description can be found elsewhere [13]. Charged particles are reconstructed using an open-cell drift chamber called the central outer tracker (COT) [14] and 7 layers of silicon microstrip detectors with radii between 2.4 cm and 28 cm [15]. These are immersed in a 1.4 T solenoidal magnetic field and cover the range $|\eta| \leq 1$, where η is the pseudorapidity defined as $\eta \equiv -\ln\tan(\theta/2)$ and θ is the polar angle [16]. Four layers of planar drift chambers (CMU) [17] detect muons with transverse momentum $p_{\rm T} > 1.4$ GeV/c within $|\eta| < 0.6$. Additional chambers and scintillators (CMX) [18] cover $0.6 < |\eta| < 1.0$ for muons with $p_{\rm T} > 2.0$ GeV/c.

A sample of $J/\psi \to \mu^+\mu^-$ candidates, collected using a dimuon trigger, is selected to begin the reconstruction of Λ_b^0 and B^0 candidates. At level 1 of a three-level trigger system, the eXtremely Fast Tracker (XFT) [19] uses COT information to fit tracks. Those tracks with $p_{\rm T} > 1.5(2.0)$ GeV/c are extrapolated to the CMU (CMX) chambers and compared with the positions of muon-chamber tracks. The event passes level 1 if two or more XFT tracks are matched to muon-chamber tracks. Opposite-charge and opening-angle requirements are imposed at level 2. At level 3, full tracking information is used to reconstruct $J/\psi \to \mu^+\mu^-$ candidates. Events with a candidate in the mass range 2.7 to 4.0 GeV/c^2 are accepted at level 3 and permanently recorded for further analysis.

Tracks from two triggered muons are constrained to originate from a common vertex to make a $J/\psi \to \mu^+\mu^-$ candidate. To ensure a high-quality vertex for the lifetime measurement, each muon track is required to have at least 3 axial hits in the silicon system. The reconstructed $\mu^+\mu^-$ invariant mass is required to be in the range $3.014 < M_{\mu^+\mu^-} < 3.174$ GeV/c^2. This corresponds to approximately $\pm 4\sigma$ of the reconstructed width, which is dominated by the resolution [20].

We construct $K_S^0 \to \pi^+\pi^-$ and $\Lambda^0 \to p\pi^-$ candidates from pairs of oppositely-charged tracks fit to a common vertex. Since many K_S^0 and Λ^0 decays occur outside some layers of the silicon system due to their long lifetime, their tracks are not required to have silicon hits. We suppress K_S^0 and Λ^0 cross contamination by rejecting K_S^0 (Λ^0) candidates with proton-pion (dipion) invariant mass in the range [1.1085, 1.1235] ([0.48175, 0.5115]) GeV/c^2.

The B^0 and Λ_b^0 candidates are reconstructed by associating J/ψ candidates with K_S^0 or Λ^0 candidates in each event. We choose further selection requirements for our b-hadron samples that optimize $S/\sqrt{S+B}$ where S and B are the numbers of signal and background events, respectively. In the optimization procedure, S is estimated using a Monte Carlo simulation, while B is estimated using the b-hadron invariant mass sidebands, which are chosen to exclude the data used in the lifetime fits to avoid any potential bias.

The selection requirements resulting from the optimization are described below. We require $0.473 < M_{\pi\pi} < 0.523$ GeV/c^2 and $p_{\rm T} > 1.5$ GeV/c for K_S^0 candidates. For Λ^0 candidates, we require $1.107 < M_{p\pi} < 1.125$ GeV/c^2 and $p_{\rm T} > 2.6$ GeV/c. We require $L_{xy}^{V^0}/\sigma_{L_{xy}^{V^0}} > 6$ for K_S^0 and $L_{xy}^{V^0}/\sigma_{L_{xy}^{V^0}} > 4$ for Λ^0, where $L_{xy}^{V^0}$ is defined as the distance from the J/ψ vertex to the $V^0(\equiv K_S^0,\ \Lambda^0)$ vertex projected onto the V^0 transverse momentum vector and $\sigma_{L_{xy}^{V^0}}$ is its estimated uncertainty. Both B^0 and Λ_b^0 candidates are required to have $p_{\rm T} > 4.0$ GeV/c. Finally, the χ^2 of a b-hadron kinematic fit is required to be less than 26 for 5 degrees of freedom. This fit finds the best b-hadron decay vertex and momentum subject to the constraints that the muon tracks originate from a common vertex, the K_S^0 or Λ^0 tracks originate from a common vertex with combined momentum pointing back in three dimensions to the dimuon vertex, and the invariant mass of the two muons is equal to the world average J/ψ mass [10]. The invariant mass distributions of the B^0 and Λ_b^0 candidates passing these requirements are shown in Fig. 1. The yields are $N(B^0 \to J/\psi K_S^0) = 3376 \pm 88$ (stat.) and $N(\Lambda_b^0 \to J/\psi\Lambda^0) = 538 \pm 38$ (stat.).

The lifetime of a B^0 and Λ_b^0 is determined from the distribution of proper decay time t given by $ct \equiv L_{xy}^b/(\beta\gamma)_{\rm T}^b = L_{xy}^b c\, {\rm M}_b/p_{\rm T}^b$, where L_{xy}^b is the distance traveled by each b-hadron candidate along the direction

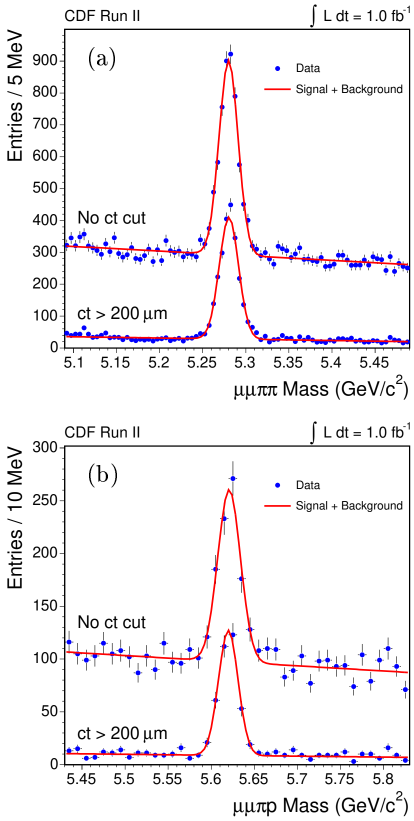

FIG. 1: Invariant mass distribution of (a) $B^0 \to J/\psi K^0_S$ and (b) $\Lambda^0_b \to J/\psi \Lambda^0$ candidates. The distributions with $ct > 200\ \mu$m, where t is the proper decay time, illustrate that the majority of backgrounds originate from the primary interaction vertex. The distributions are fit to the sum of a Gaussian signal and linear background.

of its transverse momentum p_T^b and $(\beta\gamma)^b_T \equiv p^b_T/(cM_b)$ is the transverse boost, where M_b is the world average mass of the b hadron [10]. Since the J/ψ vertex occurs at the same point as the b hadron decay and is well determined, it is used as the b-hadron decay vertex. The b hadron is assumed to originate from the average beamline determined on a run-by-run basis using inclusive jet data. The primary vertex for a given event is the $x-y$ position of this beamline at the average z coordinate of the muon tracks at their closest approach to the beamline.

The lifetimes are extracted using the maximum likelihood method. The likelihood function $\mathcal{L}$ is multivariate, and is constructed from the products of single variable probability density functions describing the distributions of the invariant mass m_i, ct_i, and their respective estimated resolutions σ^m_i and σ^{ct}_i. It is given by

$$\mathcal{L} = \prod_{i=1}^{N} \Big[(1-f_B)\ \mathcal{P}^{ct}_S(ct_i|\sigma^{ct}_i)\ \mathcal{P}^{\sigma^{ct}}_S(\sigma^{ct}_i)\ \mathcal{P}^m_S(m_i|\sigma^m_i) + f_B\ \mathcal{P}^{ct}_B(ct_i|\sigma^{ct}_i)\ \mathcal{P}^{\sigma^{ct}}_B(\sigma^{ct}_i)\ \mathcal{P}^m_B(m_i|\sigma^m_i) \Big] ,$$

where N is the number of events in the b-hadron mass window, f_B is the background fraction, and $\mathcal{P}^{ct}$, $\mathcal{P}^{\sigma^{ct}}$, and $\mathcal{P}^m$ are probability density functions for ct, σ^{ct}, and mass, respectively. The mass resolution probability distributions $\mathcal{P}^{\sigma^m}(\sigma^m_i)$ do not appear in $\mathcal{L}$ because they are equal for signal and background, within the available statistics. Since this is not true for the ct resolution distributions, $\mathcal{P}^{\sigma^{ct}}$ must be included in $\mathcal{L}$ [21].

The mass distribution is modeled as the sum of a Gaussian signal and linear background, where the Gaussian width σ^m_i is scaled by a parameter to account for misestimation of the mass resolutions. The ct distribution is modeled by the sum of five components, all convoluted with a Gaussian resolution function with a scale factor parameter for the σ^{ct}_i: a positive exponential $(e^{-ct_i/c\tau}/c\tau)$ for the signal, a $\delta-$function representing the zero-lifetime component, one negative and two positive exponentials accounting for mismeasured decay vertices and background from other heavy-flavor decays. The relative contribution of each of the background components is determined by the fit. The σ^{ct} distribution is modeled by a Gaussian convoluted with an exponential for both signal and background.

We fit over the mass range [5.170, 5.390] and $[5.521, 5.721]$ GeV$/c^2$ for B^0 and Λ^0_b, respectively. These ranges provide a sufficient sideband to constrain the background shape while avoiding regions where the mass distribution has complex structure. For both B^0 and Λ^0_b, we require $\sigma^m_i < 20$ MeV$/c^2$ and fit over the range [-2000, 4000] μm in ct and [0, 100] μm in σ^{ct}. We maximize the likelihood to determine the best values of all fit model parameters, including the signal lifetimes $c\tau(B^0) = 456.8\ ^{+9.0}_{-8.9}\ \mu$m and $c\tau(\Lambda^0_b) = 477.6\ ^{+25.0}_{-23.4}\ \mu$m. Fit projections are shown in Fig. 2.

Systematic uncertainties come from four main sources: fitting procedure and model, primary vertex determination, alignment of detector elements, and K^0_S or Λ^0 pointing requirement in the B^0 or Λ^0_b kinematic fit. The fitting bias is determined using a simple Monte Carlo simulation in which events are distributed according to the fit model. The bias was found to be less than 0.4 μm and 0.5 μm for B^0 and Λ^0_b, respectively. The systematic uncertainties due to ct resolution and mass resolution are estimated by including additional Gaussian components to their respective parts of the model in separate fits to the data and observing the deviations from the nominal result. We estimate the contribution from our mass background model by fitting with a uniform rather than linear background shape. The systematic uncertainty due to the ct background model is estimated by fitting with two or four background exponentials convoluted with the resolution function and fitting with two, three, or four background exponentials without convolution. We study a possible mass dependence in the ct background shape by separately fitting for B^0 (Λ^0_b) lifetime in the following low and high mass regions: [5.170, 5.3225] ([5.521, 5.651])

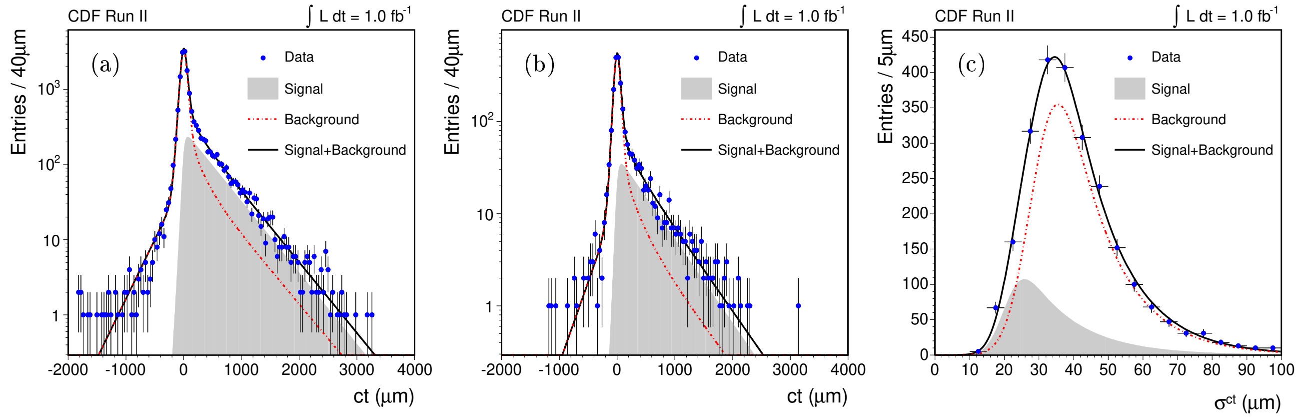

FIG. 2: (a) ct fit projection for $B^0 \to J/\psi K^0_S$ candidates; and (b) ct and (c) σ^{ct} fit projections for $\Lambda^0_b \to J/\psi \Lambda^0$ candidates.

and [5.2375, 5.390] ([5.591, 5.721]) GeV/c^2. The observed shifts are consistent with the statistical differences of the two samples for both modes. We use the average shift of 1.9 μm and 4.1 μm for B^0 and Λ^0_b, respectively, as an estimate of the systematic uncertainty due to a mass-dependent ct background. We estimate the systematic uncertainty due to our σ^{ct} and σ^m distribution models by the observed shift between simple Monte Carlo events generated with the data distributions but fit with our model compared with simple Monte Carlo events both generated and fit with our model. Using the same simple Monte Carlo technique, we estimate the systematic uncertainty due to a correlation between the ct and σ^{ct} for the background component by generating simple Monte Carlo data sets with the correlation observed in the data and fitting with our baseline model where this correlation is absent.

We estimate the systematic uncertainty due to our primary vertex determination by comparing different choices of the z coordinate used to evaluate the run-averaged beamline. We estimate uncertainties due to any residual misalignments of the silicon detector using Monte Carlo samples generated with radial displacements of individual sensors (internal alignment) and relative translation and rotation of the silicon detector with respect to the COT (global alignment). We also study the resolution and bias on the V^0 pointing to the J/ψ vertex in data. If these were strongly ct-dependent, the kinematic fit quality requirement could bias the b-hadron lifetime. We observe no lifetime bias and assign uncertainties of 0.6 μm for B^0 and 5.4 μm for Λ^0_b based on the statistical precision of our study.

The systematic uncertainties are summarized in Table I. We obtain total systematic uncertainties of 4.9 μm for B^0 and 9.9 μm for Λ^0_b by adding the individual uncertainties in quadrature.

A number of cross checks on the analysis procedure are performed. We measure the B^+ and B^0 lifetimes which are statistically consistent with the world average values in the following decay modes: $B^0 \to \psi^{(\prime)} K^0_S$, $B^0 \to \psi^{(\prime)} K^{*0}(K^{*0} \to K^+\pi^-)$, $B^+ \to \psi^{(\prime)} K^+$, and $B^+ \to \psi K^{*+}(K^{*+} \to K^0_S \pi^+)$, with $\psi^{(\prime)} \to \mu^+\mu^-$ and $\psi' \to \psi\pi^+\pi^-$. We search for unexpected lifetime dependence on the V^0 and b-hadron kinematics, data-taking period, number of tracks in the event, and use of silicon hits on V^0 daughter and muon tracks; no dependence is observed. Finally, we determine the lifetime using two alternative techniques which give results consistent with our baseline fit: a ct-only binned fit applied to sideband-subtracted data and a fit to the mass distribution in ct bins which is insensitive to details of the ct background shape.

TABLE I: Systematic uncertainties (in μm) for the measurement of $c\tau(B^0)$ and $c\tau(\Lambda^0_b)$. The total uncertainties are the individual uncertainties added in quadrature.

Source	$c\tau(B^0)$	$c\tau(\Lambda^0_b)$
Fitter Bias	0.4	0.5
Fit Model:		
ct Resolution	3.1	5.5
Mass Signal	0.7	2.3
Mass Background	0.1	0.1
ct Background	0.5	0.7
σ^{ct} Distribution Modeling	0.1	0.2
σ^m Distribution Modeling	0.6	0.2
Mass-ct Background Correlation	1.9	4.1
ct-σ^{ct} Background Correlation	0.3	1.3
Primary Vertex Determination	0.2	0.3
Alignment		
SVX Internal	2.0	2.0
SVX/COT Global	2.2	3.2
V^0 Pointing	0.6	5.4
Total	4.9	9.9

In summary, we measure

$$\tau(\Lambda^0_b) = 1.593\ ^{+0.083}_{-0.078}\ \text{(stat.)} \pm 0.033\ \text{(syst.) ps}.$$

As a cross check, we also measure $\tau(B^0) = 1.524 \pm 0.030$ (stat.) $\pm$ 0.016 (syst.) ps which is consistent with the world average $\tau(B^0) = 1.530 \pm 0.009$ ps. Our measurement of $\tau(\Lambda_b^0)$ is consistent with the DØ result in the same channel [7] at the 1.7σ level and is the first measurement using a fully reconstructed mode that reaches a precision comparable with the previous best measurements based on semileptonic decays of the Λ_b^0. It is also comparable in precision to the current world average, but is 3.2 σ higher [10]. Forming a ratio with the world average B^0 lifetime, we determine

$$\frac{\tau(\Lambda_b^0)}{\tau(B^0)} = 1.041 \pm 0.057\ (\text{stat.} + \text{syst.}).$$

This ratio is consistent with the higher end of the theory predictions [4, 11, 12].

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