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Measurement of the Λ_b lifetime in the exclusive decay $\Lambda_b \to J/\psi\ \Lambda$

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We have measured the Λ_b lifetime using the exclusive decay $\Lambda_b \to J/\psi\ \Lambda$, based on 1.2 fb^{-1} of data collected with the D0 detector during 2002–2006. From 171 reconstructed Λ_b decays, where the J/ψ and Λ are identified via the decays $J/\psi \to \mu^+\mu^-$ and $\Lambda \to p\pi$, we measured the Λ_b lifetime to be $\tau(\Lambda_b) = 1.218^{+0.130}_{-0.115}(\text{stat}) \pm 0.042(\text{syst})$ ps. We also measured the B^0 lifetime in the decay $B^0 \to J/\psi(\mu^+\mu^-)K^0_S(\pi^+\pi^-)$ to be $\tau(B^0) = 1.501^{+0.078}_{-0.074}(\text{stat}) \pm 0.050(\text{syst})$ ps, yielding a lifetime

ratio of $\tau(\Lambda_b)/\tau(B^0) = 0.811^{+0.096}_{-0.087}(\text{stat}) \pm 0.034(\text{syst})$. These measurements are consistent with the current world averages and support the shorter lifetime of the Λ_b with respect to B mesons, in contrast to another recent measurement of significant precision [8].

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Lifetime measurements of b hadrons provide important information on the interactions between heavy and light quarks. At leading order in Heavy Quark Effective Theory (HQET) [1], light quarks are considered spectators and all b hadrons have the same lifetime. Differences arise at higher orders when corrections from interactions are taken into account. For HQET calculations of order $1/m_b^2$, where m_b is the mass of the b quark, the agreement between the predicted lifetimes and the experimental results is excellent for B mesons [2]. However, in the b baryon sector, the world average of measurements of $\tau(\Lambda_b)/\tau(B^0) = 0.844 \pm 0.043$ [3] is smaller than the prediction of the ratio at this order. Recently there have been significant improvements in theoretical calculations of $\tau(\Lambda_b)/\tau(B^0)$. Next-to-leading order effects in QCD [4], corrections at $\mathcal{O}(1/m_b^4)$ in HQET [5], and lattice QCD studies [6], have led to an improved theoretical prediction, $\tau(\Lambda_b)/\tau(B^0) = 0.88 \pm 0.05$ [7]. This value agrees with previous experiments to within the current theoretical and experimental uncertainties. However, a recent measurement [8] reports a value of the Λ_b lifetime consistent with B meson lifetimes, and the ratio $\tau(\Lambda_b)/\tau(B^0)$ consistent with unity. Additional precise measurements of the Λ_b lifetime and $\tau(\Lambda_b)/\tau(B^0)$ ratio may help settle this question.

In this Letter, we report measurements of the Λ_b lifetime using the exclusive decay $\Lambda_b \to J/\psi + \Lambda$, and its ratio to the B^0 lifetime using the $B^0 \to J/\psi + K^0_S$ decay channel. This B^0 decay channel is chosen because of its similar topology to the Λ_b decay. The J/ψ is reconstructed from the $\mu^+\mu^-$ decay mode, the Λ from $p\pi^-$, and the K^0_S from $\pi^+\pi^-$. Throughout this Letter, the appearance of a specific charge state also implies its charge conjugate. The data used in this analysis were collected during 2002–2006 with the D0 detector in Run II of the Tevatron Collider at a center-of-mass energy of 1.96 TeV, and correspond to an integrated luminosity of 1.2 fb^{-1}.

The D0 detector is described in detail elsewhere [9]. The detector components most relevant to this analysis are the central tracking and the muon systems. The former consists of a silicon microstrip tracker (SMT) and a central scintillating fiber tracker (CFT) surrounded by a 2 T superconducting solenoidal magnet. The SMT has a design optimized for tracking and vertexing for pseudorapidity of $|\eta| < 3$ [10]. For charged particles, the resolution on the distance of closest approach as provided by the tracking system is approximately 50 μm for tracks with $p_T \approx 1$ GeV/c, where p_T is the component of the momentum perpendicular to the beam axis. It improves asymptotically to 15 μm for tracks with $p_T > 10$ GeV/c. Preshower detectors and electromagnetic and hadronic calorimeters surround the tracker. The muon system is located beyond the calorimeter, and consists of multilayer drift chambers and scintillation counters inside 1.8 T toroidal magnets, and two similar layers outside the toroids. Muon identification for $|\eta| < 1$ relies on 10 cm wide drift tubes, while 1 cm mini-drift tubes are used for $1 < |\eta| < 2$.

The primary vertex of the $p\bar{p}$ interaction is determined for each event using the average position of the beam-collision in the plane perpendicular to the beam as a constraint. The precision of the primary vertex reconstruction is on average 20 μm in the plane perpendicular to the beam and about 40 μm along the direction of the beam.

We base our data selection on reconstructed charged tracks and identified muons. Although we do not require any specific trigger, most of the selected events satisfy dimuon or muon triggers. To avoid a trigger bias in the lifetime measurement, we reject events that depend on impact parameter based triggers. We start the Λ_b and B^0 reconstruction by searching for events with J/ψ mesons. We then search in these events for Λ and K^0_S particles. To reconstruct $J/\psi \to \mu^+\mu^-$ candidates, we select events with at least two muons of opposite charge reconstructed in the tracker and the muon system. The track of each muon candidate must either match hits in the muon system, or have calorimeter energies consistent with a minimum-ionizing particle along the direction of hits extrapolated from the tracking layers. For at least one of the muons, we require hits in all three layers of the muon detector. Both muons are required to have $p_T > 2.5$ GeV/c if they are in the region $|\eta| < 1$. The muon tracks are constrained to originate from a common vertex with a χ^2 probability greater than 1%, and each J/ψ candidate is required to have a mass in the range 2.80–3.35 GeV/c^2. The $\Lambda \to p\pi^-$ decays are reconstructed from two tracks of opposite charge constrained to a common vertex with a χ^2 probability greater than 1%. Each Λ candidate is required to have a mass in the range 1.100–1.128 GeV/c^2. The proton mass is assigned to the track of higher p_T, as observed in Monte Carlo studies. To suppress contamination from cascade decays of more massive baryons such as $\Sigma^0 \to \Lambda\gamma$ or $\Xi^0 \to \Lambda\pi^0$, we require the cosine of the angle between the $\boldsymbol{p}_T$ vector of the Λ and the vector from the J/ψ vertex to the Λ decay vertex to be larger than 0.9999. For Λ's that decay from Λ_b the cosine of this angle is very close to one. The $K^0_S \to \pi^+\pi^-$ selection follows the same criteria, except that for the K^0_S, the mass window is 0.460–0.525 GeV/c^2,

and pion mass assignments are used.

We reconstruct the Λ_b and B^0 by performing a constrained fit to a common vertex for either the Λ or K^0_S and the two muon tracks, with the latter constrained to the J/ψ mass of 3.097 GeV/c^2 [3]. Because of their long decay lengths, a significant fraction of Λ and K^0_S particles will decay outside the SMT. There is therefore no requirement of SMT hits on the tracks from Λ and K^0_S decays. To reconstruct the Λ_b (B^0), we first find the Λ (K^0_S) decay vertex, and then extrapolate the momentum vector of the ensuing particle and form a vertex together with the two muon tracks belonging to the J/ψ. If more than one candidate is found in the event, the candidate with the best χ^2 probability is selected as the Λ_b (B^0) candidate. The mass is required to be within the range 5.1–6.1 GeV/c^2 for Λ_b candidates and within 4.9–5.7 GeV/c^2 for B^0 candidates. For the choice of the final selection criteria, we optimize $S/\sqrt{S+B}$, where S and B are the number of signal (Λ_b) and background candidates, respectively, by using Monte Carlo estimates for S and data for B. For the Monte Carlo, we use PYTHIA [11] and EVTGEN [12] to produce and decay particles, respectively, and GEANT3 [13] to simulate detector effects. As a result of this optimization, the p_T of the Λ (K^0_S) is required to be greater than 2.4 (1.8) GeV/c, and the total momentum for both Λ_b and B^0 is required to be greater than 5 GeV/c. Finally, any candidate which has been identified as a Λ_b is removed from the B^0 sample.

We determine the decay time of a Λ_b or B^0 by measuring the distance traveled by the b hadron candidate in a plane transverse to the beam direction, and then applying a correction for the Lorentz boost. We define the transverse decay length as $L_{xy} = \boldsymbol{L}_{xy} \cdot \boldsymbol{p}_T / p_T$ where $\boldsymbol{L}_{xy}$ is the vector that points from the primary vertex to the b hadron decay vertex and $\boldsymbol{p}_T$ is the transverse momentum vector of the b hadron. The event-by-event value of the proper transverse decay length, λ, for the b hadron candidate is given by:

$$\lambda = \frac{L_{xy}}{(\beta\gamma)^B_T} = L_{xy}\,\frac{cM_B}{p_T}, \qquad (1)$$

where $(\beta\gamma)^B_T$ and M_B are the transverse boost and the mass of the b hadron. In our measurement, the value of M_B in Eq. 1 is set to the Particle Data Group (PDG) mass value of Λ_b or B^0 [3]. We require the uncertainty on λ to be less than 500 μm.

We perform a simultaneous unbinned maximum likelihood fit to the mass and proper decay length distributions. The likelihood function $\mathcal{L}$ is defined by:

$$\begin{aligned}\mathcal{L} \;=\; & \frac{(n_s+n_b)^N}{N!}\exp\left(-n_s-n_b\right)\times \\ & \prod_{j=1}^{N}\left[\frac{n_s}{n_s+n_b}\mathcal{F}^j_{\rm sig}+\frac{n_b}{n_s+n_b}\mathcal{F}^j_{\rm bkg}\right],\end{aligned} \qquad (2)$$

where n_s and n_b are the expected number of signal and background events in the sample, respectively. N is the total number of events. $\mathcal{F}^j_{\rm sig}$ ($\mathcal{F}^j_{\rm bkg}$) is the product of three probability density functions that model the mass, proper decay length, and uncertainty on proper decay length distributions for the signal (background). We divide the background into two categories, prompt and non-prompt. The prompt background is primarily due to direct production of J/ψ's which are then randomly combined with a Λ or K^0_S candidate in the event. The non-prompt background is mainly produced by the combination of J/ψ mesons from b hadron decays with Λ or K^0_S candidates present in the event.

For the signal, the mass distribution is modeled by a Gaussian function, and the λ distribution is parametrized by an exponential decay convoluted with the resolution function:

$$G(\lambda_j,\sigma_j) = \frac{1}{\sqrt{2\pi}s\sigma_j}\exp\left[\frac{-\lambda_j^2}{2(s\sigma_j)^2}\right], \qquad (3)$$

where λ_j and σ_j represent λ and its uncertainty, respectively, for a given decay j, and s is a common scale parameter introduced in the fit to account for a possible mis-estimate of σ_j. The convolution is defined by:

$$S_\lambda(\lambda_j,\sigma_j) = \frac{1}{\lambda_B}\int_0^\infty G(x-\lambda_j,\sigma_j)\exp\left(\frac{-x}{\lambda_B}\right)dx, \qquad (4)$$

where $\lambda_B = c\tau_B$, and τ_B is the lifetime of the Λ_b (B^0). The distribution of the uncertainty of λ is modeled by an exponential function convoluted by a Gaussian.

For the background, the mass distribution of the prompt component is assumed to follow a flat distribution as observed in data when a cut of λ >100 μm is applied. The non-prompt component is modeled with a second-order polynomial function. The λ distribution is parametrized by the resolution function for the prompt component, and by the sum of negative and positive exponential functions for the non-prompt component. A positive and a negative exponential functions model combinatorial background, and an exponential function accounts for long-lived heavy flavor decays. The distribution of the uncertainty of λ is modeled by two exponential functions convoluted by a Gaussian.

We minimize $-2\ln\mathcal{L}$ to extract: $c\tau(\Lambda_b) = 365.1^{+39.1}_{-34.7}$ μm and $c\tau(B^0) = 450.0^{+23.5}_{-22.1}$ μm. From the fits, we obtain $s = 1.41 \pm 0.05$ for the Λ_b and $s = 1.41 \pm 0.03$ for the B^0. The numbers of signal decays are 171 ± 20 Λ_b and 717 ± 38 B^0. Figures 1 and 2 show the mass and λ distributions for the Λ_b and B^0 candidates. Fit results are superimposed. Table I summarizes the systematic uncertainties in our measurements. The contribution from possible misalignment of the SMT detector was estimate to be 5.4 μm [14]. We estimate the systematic uncertainty due to the models for the λ and mass distributions by varying the parametrizations of the different components: (i) the resolution function is modeled by two Gaussian functions instead of one, (ii)

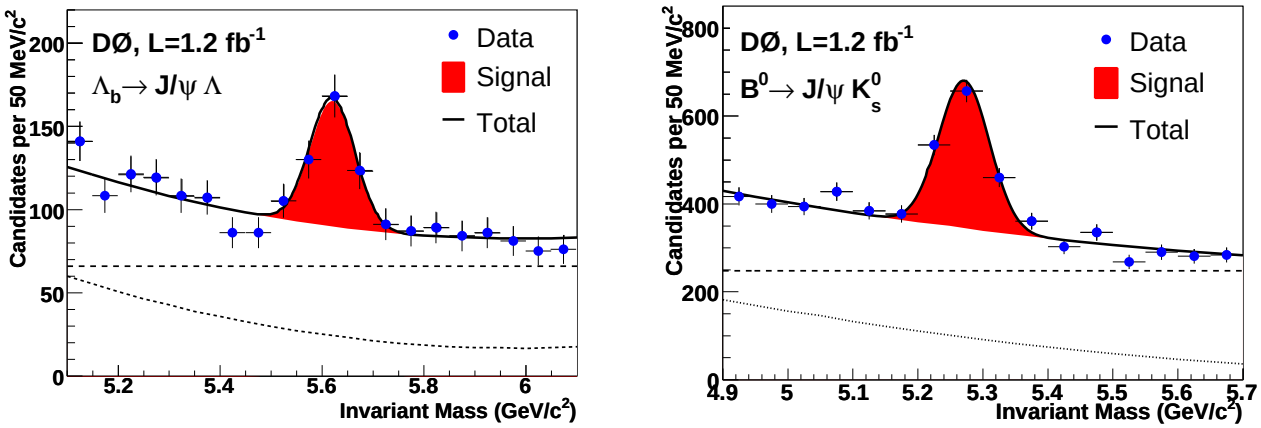

FIG. 1: Invariant mass distribution for Λ_b(left) and B^0(right) candidates, with the fit results superimposed. The dashed line represents the prompt background component and the dotted line the non-prompt background component. The shaded region represents the signal.

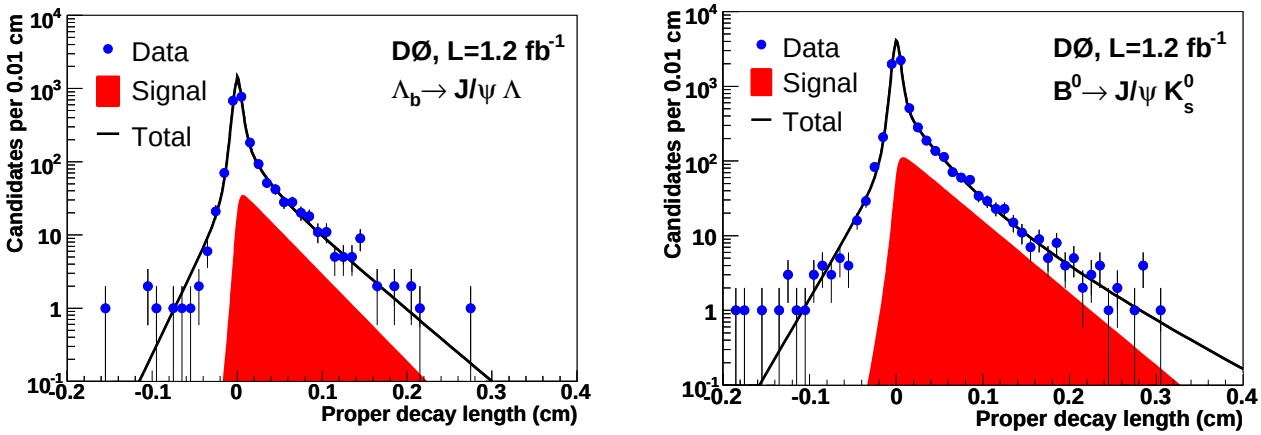

FIG. 2: Proper decay length distribution for Λ_b(left) and B^0(right) candidates, with the fit results superimposed. The shaded region represents the signal.

the exponential functions in the non-prompt background are replaced by exponentials convoluted with the resolution function, (iii) a uniform background is added to account for outlier events (this has only a negligible effect), (iv) the positive and negative exponentials describing combinatorial non-prompt background are assumed to be symmetric, and (v) for the mass distribution of the non-prompt background, a linear function is used instead of the nominal quadratic form. To take into account correlations between the effects of the different models, a fit that combines all different model changes is performed. We quote the difference between the result of this fit and the nominal fit as the systematic uncertainty.

The lifetime of the background events under the $\Lambda_b(B^0)$ signal is mostly modeled by events in the low and high mass sideband regions with respect to the peak. To estimate the effect of any difference between the lifetime distributions of these two regions, we perform separate fits to the Λ_b (B^0) mass regions of 5.1–5.8 and 5.4–6.1 GeV/c^2 (4.9–5.45 and 5.1–5.7 GeV/c^2) where the contributions from high and low mass background events are reduced, respectively. The largest difference between these fits and the nominal fit is quoted as the systematic uncertainty due to this source.

We also study the contamination of the Λ_b sample by B^0 events that pass the Λ_b selection. From Monte Carlo studies, we estimate that 6.5% of B^0 events pass the Λ_b selection criteria. However, the invariant mass of B^0 events which contaminate the Λ_b sample is distributed almost uniformly across the entire Λ_b mass range, and their proper decay lengths therefore tend to be incorporated in the long-lived component of the background. To estimate the effect due to this contamination, we remove from the Λ_b sample any event which also passes the B^0

TABLE I: Summary of systematic uncertainties in the measurement of $c\tau$ for Λ_b and B^0 and their ratio. The total uncertainties are determined by combining individual uncertainties in quadrature.

Source	Λ_b (μm)	B^0 (μm)	Ratio
Alignment	5.4	5.4	0.002
Distribution models	6.6	2.8	0.020
Long-lived components	6.0	13.6	0.022
Contamination	7.2	–	0.016
Total	12.7	14.9	0.034

selection criteria, and we perform a fit to the remaining events. The difference between this and the nominal fit is quoted as the systematic uncertainty due to the contamination. For the B^0, we do not consider this source of systematic uncertainty since any event identified as Λ_b is removed from the B^0 sample.

We perform several cross-checks of the lifetime measurements. The J/ψ vertex is used instead of the b hadron vertex, the mass windows are varied, the reconstructed b hadron mass is used instead of the PDG [3] value, and the sample is split into different pseudorapidity regions and different regions of azimuth. All results obtained with these variations are consistent with our measurement. We also cross-check the fitting procedure and selection criteria by measuring the Λ_b lifetime in Monte Carlo events. The lifetime obtained was consistent with the input value.

The results of our measurement of the Λ_b and B^0 lifetimes are summarized as:

$$c\tau(\Lambda_b) = 365.1^{+39.1}_{-34.7}\ (\text{stat}) \pm 12.7\ (\text{syst})\ \mu\text{m}, \quad (5)$$
$$c\tau(B^0) = 450.0^{+23.5}_{-22.1}\ (\text{stat}) \pm 14.9\ (\text{syst})\ \mu\text{m},$$

from which we have:

$$\tau(\Lambda_b) = 1.218^{+0.130}_{-0.115}\ (\text{stat}) \pm 0.042\ (\text{syst})\ \text{ps}, \quad (6)$$
$$\tau(B^0) = 1.501^{+0.078}_{-0.074}\ (\text{stat}) \pm 0.050\ (\text{syst})\ \text{ps}.$$

These can be combined to determine the ratio of lifetimes:

$$\frac{\tau(\Lambda_b)}{\tau(B^0)} = 0.811^{+0.096}_{-0.087}\ (\text{stat}) \pm 0.034\ (\text{syst}), \quad (7)$$

where we determine the systematic uncertainty on the ratio by calculating the ratio for each systematic source and quoting the deviation in the ratio as the systematic uncertainty due to that source. We combine all systematics in quadrature as shown in Table I. The main contribution to the systematic uncertainty of the lifetime ratio is due to the long-lived component of the B^0 sample. This is expected since the B^0 is more likely than the Λ_b to be contaminated by mis-reconstructed B mesons due to its lower mass. The ratio of lifetimes, using the world average B^0 lifetime $\tau(B^0) = 1.527 \pm 0.008$ ps [3], is

$$\frac{\tau(\Lambda_b)}{\tau(B^0)} = 0.797^{+0.089}_{-0.080}. \quad (8)$$

In conclusion, we have measured the Λ_b lifetime in the fully reconstructed exclusive decay channel $J/\psi\Lambda$. The measurement is consistent with the world average [3], and the ratio of Λ_b to B^0 lifetimes is consistent with the most recent theoretical predictions [7].

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