Measurement of the Average Lifetime of B Hadrons Produced in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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The average b-hadron lifetime has been measured using a high statistics sample of $B \to J/\psi X$ decays recorded with the Collider Detector at Fermilab. The decay vertices of 5344 inclusive $J/\psi \to \mu^+\mu^-$ candidates have been reconstructed using information from a silicon vertex detector. The measured B lifetime, which is the average over all b hadrons produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV weighted by their branching ratios into J/ψ, is $1.46 \pm 0.06(\text{stat}) \pm 0.06(\text{syst})$ ps.

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Measurements of the b-hadron lifetime have improved significantly in the past two years. While earlier experiments at the SLAC and DESY e^+e^- storage rings PEP [1] and PETRA [2] were limited both by statistics and by the resolution of their tracking detectors, recent analyses of semileptonic B decays at the CERN e^+e^- collider LEP have resulted in smaller statistical uncertainties [3]. Systematic errors associated with the modeling of the semileptonic decays have become the dominant source of uncertainty. Measurement of the decay vertices of $B \to J/\psi X$ candidates provides an alternative method of determining the B lifetime with quite different systematic uncertainties. Until now, however, this technique has suffered from low statistics [4].

We report here a high statistics measurement of the B lifetime determined from a sample of $B \to J/\psi X \to \mu^+\mu^- X$ decays recorded by the Collider Detector at Fermilab (CDF) during the first half of the 1992–93 Tevatron run. The sample corresponds to an integrated luminosity of 10.1 ± 0.7 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. This is the first measurement of the average B lifetime from a hadron collider experiment. Because the B production cross section is large in $p\bar{p}$ collisions [5], it is now possible to obtain statistical uncertainties of $\sim 4\%$ for this mode, which has an effective branching ratio $B(B \to J/\psi X)B(J/\psi \to \mu^+\mu^-) = (7.7 \pm 1.3) \times 10^{-4}$ [6].

The CDF has been described in detail elsewhere [7]. For the 1992–93 collider run, a silicon vertex detector (SVX) has been installed [8]. The SVX consists of four layers of silicon-strip detectors with r-ϕ readout, that includes pulse height information. The pitch between readout strips is 60 μm, resulting in a spatial resolution of 13 μm. The first measurement plane is located 2.9 cm from the interaction point, leading to an impact parameter resolution of ~ 15 μm for high momentum tracks.

CDF uses a three-level trigger system. At level 1 the relevant trigger for this analysis requires the presence of two charged tracks in the central muon chambers, which cover the pseudorapidity range $|\eta| < 0.6$, where the pseudorapidity $\eta \equiv -\ln[\tan(\theta/2)]$. The efficiency of finding a muon at level 1 rises from 30% at transverse momentum $p_T = 1.5$ GeV/c to 93% at $p_T > 3$ GeV/c. Level 2 requires that at least one of the muon tracks match a charged track in the Central Tracking Chamber (CTC) found with the Central Fast Track (CFT) processor [9]. The efficiency of finding a track in the CFT rises from 50% at 2.6 GeV/c to 94% for $p_T > 3.1$ GeV/c. The level 3 software trigger requires the presence of two oppositely charged muon candidates with invariant mass between 2.8 and 3.4 GeV/c^2 [10]. A total of 18 451 J/ψ candidates satisfied this trigger and had both tracks reconstructed in the SVX.

To reduce the background in the dimuon sample, the following muon selection cuts were applied [11]: (1) The separation between the track in the muon chamber and the extrapolated CTC track was calculated in both the transverse and longitudinal planes. In each view, the difference was required to be less than 3.0 standard deviations (σ) from zero, where σ is the sum in quadrature of the multiple scattering and measurement errors. (2) The energy deposited in the hadronic calorimeter by each muon was required to be greater than 0.5 GeV, the smallest energy expected from a minimum ionizing particle. (3) The p_T of at least one of the muon tracks was required to be > 2.5 GeV/c.

To ensure that the J/ψ decay vertex was well measured, strict track quality cuts were imposed on the sample: (1) Both muon tracks were required to be reconstructed in the SVX with hits in at least three layers out of the four possible. (2) All SVX track residuals were required to be less than 4σ. The χ^2 contribution of these residuals was required to be less than 20. (3) SVX tracks where one or more hits were assigned to more than one track were removed. (4) SVX hits with total charge more than 4 times the average charge deposited by a minimum ionizing particle were removed. (5) The two muons were required to have track parameters consistent with a single decay vertex.

The invariant mass distribution of the final dimuon sample is shown in Fig. 1. The grey-hatched area indicates the J/ψ signal region, defined to be ± 50 MeV/c^2 around the J/ψ mass. This region contains 5667 events. The cross-hatched area shows the two sideband regions, one with mass from 2.9 to 3.0 GeV/c^2, and the other from 3.2 to 3.3 GeV/c^2. The sidebands contain 646 events. These sidebands were used to determine the shape of the lifetime distribution for background events in the J/ψ signal region. After background subtraction the number of J/ψ's in the signal region is found to be 5344 ± 73. The fitted J/ψ mass is $3094.3 \pm 0.2 \pm 0.5$ MeV/c^2 with a mass resolution of 16 ± 0.2 MeV/c^2.

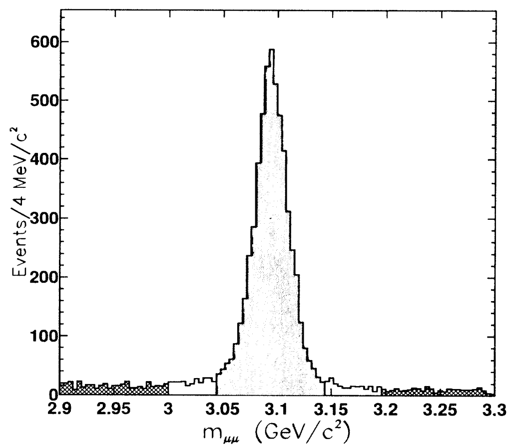

FIG. 1. Invariant mass distribution of two oppositely charged muons. The grey-hatched area indicates the J/ψ signal region and the cross-hatched areas show the sideband regions.

For each J/ψ in the sample, a two dimensional decay distance L_{xy} was calculated. L_{xy} is the projection of the vector $\mathbf{X}$, pointing from the primary to the secondary vertex, onto the transverse momentum of the J/ψ:

$$L_{xy} \equiv \frac{\mathbf{X} \cdot \mathbf{p}_T^{\psi}}{|\mathbf{p}_T^{\psi}|} .$$

The position of the secondary vertex is obtained by constraining the two muon tracks to come from a common decay vertex. The primary vertex position is approximated by the mean beam position, determined run by run by averaging over many events. We favored the beam position over a primary vertex determined event by event because it is always available and unbiased. The transverse profile of the beam is circular and has a rms of ~ 38 μm. Studies have shown that with the low multiplicity of $b\bar{b}$ events it is not always possible to reconstruct the primary vertex and the resolution is not more precise. In addition there are always two b hadrons in the event. If tracks from b decay are used in the determination of the primary vertex a systematic bias to the b lifetime measurement is introduced. The mean uncertainty of L_{xy} is ~ 60 μm, where the dominant contributions are the uncertainty in determining the primary and secondary vertex positions. These two uncertainties are approximately equal in size.

To convert the transverse decay length into a proper lifetime, the relativistic quantity $(\beta\gamma)_B$ of the b hadron must be determined. Since the J/ψ's selected by the dimuon trigger typically carry most of the momentum of the B, the $(\beta\gamma)_\psi$ of the J/ψ is a good first approximation to $(\beta\gamma)_B$. Using a Monte Carlo procedure, a $(\beta\gamma)$ correction factor F was calculated as a function of p_T^ψ. Figure 2(a) shows the parametrization of $F(p_T^\psi)$ used to calculate the B lifetime, along with the upper and lower bands of the systematic uncertainty on $F(p_T^\psi)$. These bands were obtained by varying the production and decay models as described below. Figure 2(b) shows the background subtracted p_T spectrum of ψ candidates. To ensure that the ψ come from b decays the proper decay length was required to be $\lambda > 200$ μm for this figure. F varies only weakly over the p_T range of the J/ψ in our sample and is ~ 0.87. The calculation of $F(p_T^\psi)$ used a b-quark p_T spectrum generated from the next-to-leading order QCD calculation [12]. To estimate the systematic uncertainties in the shape of this cross section, it was compared to simple power law spectra which reproduced softer or harder p_T spectra than that of our data. The b quarks were then fragmented using the Peterson fragmentation function [13] where the fragmentation parameter and its uncertainty ($\epsilon = 0.006 \pm 0.002$) have been taken from Ref. [14]. The b hadrons were forced to decay into $J/\psi + X$. The J/ψ spectrum in the B rest frame was obtained from the experimental results of ARGUS and CLEO [15]. We also used their results to set bounds on the polarization when modeling the decay $J/\psi \to \mu^+\mu^-$ [16]. The resulting muons were passed through a computer simulation of the detector and trigger. The systematic uncertainty associated with modeling the decay of b baryons and higher mass b mesons has been studied using Monte Carlo calculations assuming the probability for a b quark to fragment into

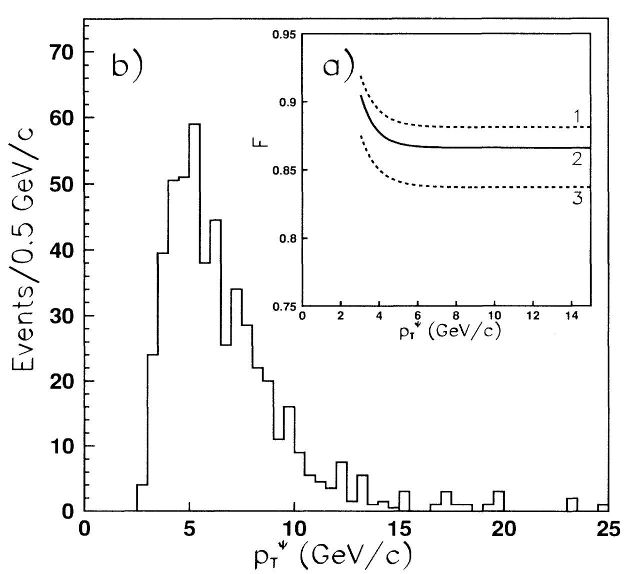

FIG. 2. (a) Correction factor $F(p_T^\psi)$ with the upper and lower bands of the systematic uncertainty. (b) Background subtracted J/ψ p_T spectrum requiring $\lambda > 200$ μm.

the various possible b-flavored mesons and baryons to be $B_u : B_d : B_s : B_{\text{baryon}} = 0.375 : 0.375 : 0.15 : 0.10$. The contribution to the systematic error was found to be 0.15%. The best estimate of the proper b hadron decay length is

$$\lambda = L_{xy} \frac{M_\psi}{p_T^\psi F(p_T^\psi)} .$$

In order to obtain the B lifetime from the λ distribution, we fit to three sources of dimuon events in the J/ψ invariant mass region.

(i) J/ψ's from B decays: this part is parametrized by a Gaussian function convoluted with an exponential. The fit parameter f_b gives the fraction of J/ψ coming from b decay.

(ii) J/ψ's directly produced in $p\bar{p}$ collisions, or resulting from the decay of intermediate states which are sufficiently short lived so that their vertex is indistinguishable from the primary vertex (e.g., from χ_c's): this part is parametrized by a Gaussian function.

(iii) Background coming from processes whose invariant mass falls accidentally in the J/ψ mass window: these events include dimuons from Drell-Yan production, double semileptonic b decays, meson decays in flight, and residual hadron punchthrough. The shape of this contribution is obtained by fitting the corresponding J/ψ sideband distributions. The fit is parametrized as the sum of a Gaussian function and two exponentials, one above the Gaussian and one below, each with a different slope. Since the dimuon sample contains events from sequential b decays ($b \to c\mu\nu \to s\mu\nu\mu\nu$), the λ distribution is expected to be asymmetric. The background fraction, f_{BGR}, is determined from the sidebands and is not a free parameter in the fit to the signal region.

Figure 3(a) shows the result of an unbinned likelihood fit to the data. The dark-shaded area is the contribution obtained from a fit to the λ distribution of the J/ψ sidebands [see Fig. 3(b)]. The light-shaded area shows the sum of the background distribution and the Gaussian function convoluted with the exponential from b decay. The remaining Gaussian centered at 0 (unshaded area) is due to prompt decays. The fit results in

$$\tau_B = 1.46 \pm 0.06(\text{stat}) \text{ ps and } f_b = 15.1 \pm 0.6\%(\text{stat}) .$$

The fit parameter f_b obtained in the above procedure does not provide an unbiased measurement of the fraction of J/ψ's coming from b decay. The applied track quality cuts favor isolated muons and systematically decrease this fraction.

Our estimates of the systematic uncertainties on the above measurement are listed in Table I. The systematic uncertainty in the production and decay kinematics is estimated to be 3% and comes from studying the parameters of our model, including the b-quark production spectrum, J/ψ momentum spectrum in the B rest frame, J/ψ polarization and fragmentation.

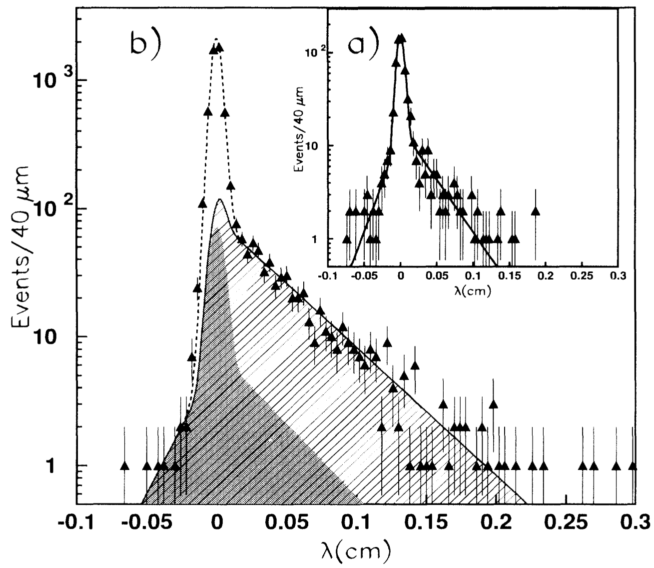

FIG. 3. (a) The distribution in λ, the proper decay length, of data in the sideband regions. The solid line shows the results of a maximum likelihood fit. (b) The distribution in λ of data in the signal region. The curves are the result of the unbinned likelihood fit described in the text.

TABLE I. Systematic uncertainties on the average b-hadron lifetime

Description	Contribution
Production and decay kinematics	3.0 %
Uncertainty in $c\tau$ resolution	1.6 %
Residual misalignment	2.0 %
Beam stability	1.0 %
Trigger bias	1.4 %
Background parametrization	0.5 %
Total	4.3 %

The result of the maximum likelihood fit depends on the error on the decay length calculated for each event. The uncertainty in the decay vertex resolution has been studied using several independent data sets. Studies of a sample of prompt $\Upsilon(1S) \to \mu^+\mu^-$ events and of a high statistics sample of tracks selected from jet events indicate that the resolution function for tracks from the primary vertex is symmetric. A fit to the jet sample results in a mean decay length of 0.2 ± 0.9 μm, consistent with zero. The resolution obtained from this fit agrees to within 5% with the mean of the resolution obtained event by event from our vertex-constrained fit. Therefore we have varied these errors by an overall scale factor ($\pm 5\%$) and studied the result of this variation on the fit. This gives an additional 1.6% uncertainty in the lifetime.

The uncertainty due to residual misalignment of the SVX has been studied by varying the alignment correction constants resulting in an estimate of 2%. The variation in the beam position within a run has been measured to be less than 4 μm, which leads to a 1% systematic uncertainty on the $c\tau$ measurement. The effect of impact parameter bias in the CFT and level 3 trigger gives an estimated uncertainty of 1.4%, while the systematic error due to the background parametrization was estimated to be 0.5% by varying the slope of the two exponentials in this parametrization by one sigma.

In conclusion, we have measured the average lifetime for b hadrons produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. For a sample of b hadrons decaying into $J/\psi X$, the lifetime is determined to be

$$\tau_B = 1.46 \pm 0.06(\text{stat}) \pm 0.06(\text{syst}) \text{ ps}.$$

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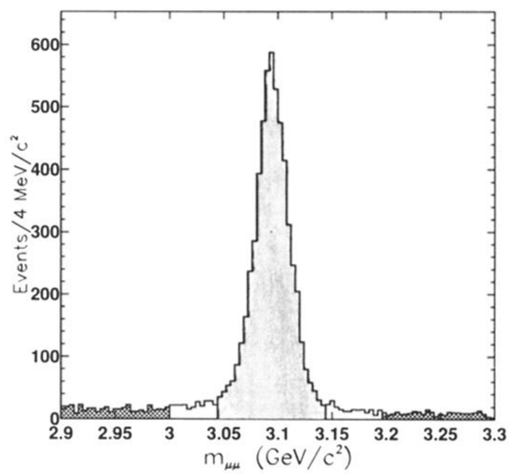

FIG. 1. Invariant mass distribution of two oppositely charged muons. The grey-hatched area indicates the J/ψ signal region and the cross-hatched areas show the sideband regions.