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# Lifetime of B Hadrons from CDF

Ting Miao
Representing the CDF Collaboration

*Fermi National Accelerator Laboratory*
*P.O. Box 500, Batavia, Illinois 60510*

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# Lifetime of B Hadrons From CDF

TING MIAO
*Fermi National Accelerator Laboratory*
*Batavia, Illinois 60510, USA*
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A review of the lifetimes of $B$ hadrons measured by the CDF collaboration at Fermilab is presented. The data correspond to 110 pb$^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV. The inclusive $B$ hadron lifetime is measured using a high statistics sample of $B \rightarrow J/\psi X$ decays. Species specific lifetimes of the $B^+$, $B^0$, $B_s^0$, and $\Lambda_b^0$ are determined using both fully reconstructed decays and partially reconstructed decays consisting of a lepton associated with a charm hadron.

## 1 Introduction

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 non-spectator diagrams, such as final state quark interference and $W$ exchange, which play important roles in the large lifetime differences between charm hadrons [1]. 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% [2]. Precise measurements of $B$-hadron lifetimes probe these non-spectator diagrams. The large $b$ production cross section at Tevatron, the successful implementation of lepton triggers and the excellent vertexing ability of the SVX detector have enabled CDF to become a dominant force in this highly competitive field. We report here results [3] from CDF on the $B$ hadron lifetime both from fully and partially reconstructed decay modes.

Taking full advantage of the SVX, we use the decay length technique to extract the lifetime. The decay length $L$, which is calculated from the distance of the $B$ decay vertex and the beam position where we assume the $B$ is produced, is related to the lifetime $c\tau$ by the Lorentz boost $\beta\gamma$, $L = \beta\gamma c\tau$. In the fully reconstructed decay modes, the Lorentz boost is calculated from the $B$ mass and momentum, $\beta\gamma = p_B/m_B$. In the partially reconstructed decay modes, the Lorentz boost is calculated from the $B$ mass and the visible momentum, for example the sum of charm and lepton momenta, with a residual correction obtained from Monte Carlo. The RMS of the Tevatron beam profile is about 35 $\mu m$ in the $r-\phi$ plane and 30 cm in the $Z$ direction. We use only the transverse momentum $p_t$ and decay length $L_{r\phi}$ in the $r-\phi$ plane in the lifetime measurement. Due to the soft $B$ momentum produced ($\beta\gamma \approx 2-5$), the typical decay length is only on the order of 1000 $\mu m$ while the typical measurement error on it is 30 - 40 $\mu m$. We include the decay length measurement error into the fit by convoluting the pure exponential lifetime distribution with the error function, which is assumed to be a Gaussian. Background contributions are estimated from sideband events on the invariant mass spectra, from the wrong sign events and from Monte Carlo simulations. The data were taken during the 1992-1995 runs with CDF detector (RUN-I) and the integrated luminosity is 110 $pb^{-1}$. The dimuon samples are used for analyses involving $\psi$, and the inclusive lepton samples (electron and muon) are used for the semileptonic decay analyses.

## 2 Inclusive lifetime from $B \to J/\psi X$

We present the measurement of the average lifetime of b-hadrons produced in $p\bar{p}$ collisions weighted by their branching ratios into $J/\psi$ and their production cross sections. We use Run-1B dimuon data which corresponds to an integrated luminosity of 90 $pb^{-1}$. After all selection cuts and background subtraction we end up with a large sample of 62656 $J/\psi$'s decaying into $\mu^+\mu^-$ reconstructed in the SVX, shown in Fig. 1. There are two major background sources in the sample: (1)background from direct production of $p\bar{p}$ or other short-lived particles which we assume to have zero lifetime and whose fraction is obtained from lifetime fit; and (2)combinatorial background whose lifetime and fraction are obtained from $J/\psi$ sideband event.

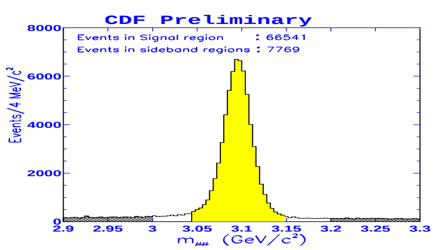


Figure 1: Invariant mass distribution of two oppositely charged muons. The hatched area indicates the $J/\psi$ signal region and the sideband regions used to estimate combinatorial background.

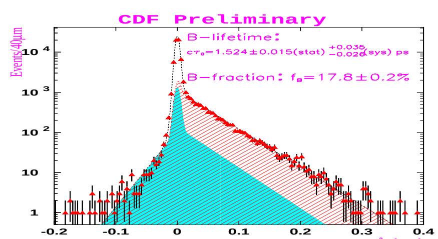


Figure 2: The proper decay length distribution. The dark-shaded area corresponds to the background and the light-shaded area the sum of the background and the $J/\psi$ from $B$ decays.

From the $J/\psi$ proper decay length distribution, shown in Fig. 2, we find that 17.8% of these events come from b-decays. We measure the average b-hadron lifetime to be

$$\tau_{b \to J/\psi} = 1.524 \pm 0.015^{+0.035}_{-0.026} \; ps$$

where the first error is the statistical error and second the systematic error. The precision of this measurement is significantly improved over our previous result [4] of $1.46 \pm 0.06 \pm 0.06 \; ps$ using a smaller data sample of 10 $pb^{-1}$.

## 3 $B^+$ and $B^0$ lifetimes

The lifetime results of $B^+$ and $B^0$ are updated using the full dataset both from fully reconstructed hadronic $B$ decays and partially reconstructed semileptonic $B$ decays. We find $824 \pm 36$ fully reconstructed events of $B^+ \to \Psi \mathbf{K}^+$, where $\Psi = J/\psi, \psi(2S)$ and $\mathbf{K}^+ = K^+, K^*(892)^+$, and $436 \pm 27$ events of $B^0 \to \Psi \mathbf{K^0}$ where $\mathbf{K^0} = K^0_s, K^*(892)^0$. The invariant mass distributions for $B^+$ and $B^0$ are shown in Fig. 3. Fitting the decay length distributions as shown in Fig. 4

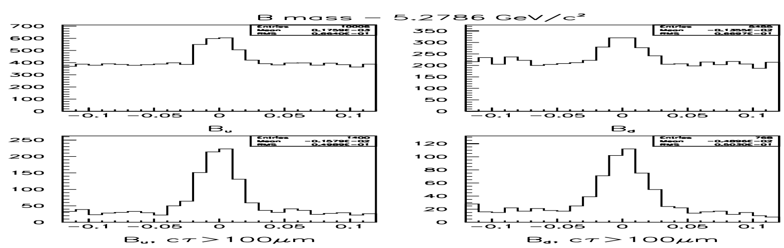


Figure 3: Invariant mass distribution of $B^+$ (left) and $B^0$ (right). The bottom plots are with $100\mu m$ lifetime cuts.

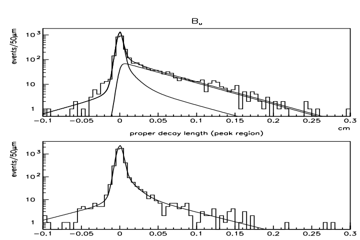


Figure 4: The proper decay length distribution of $B^+ \to \Psi \mathbf{K}^+$ for signal region events (top) and sideband region events (bottom). The curve are the fitting results.

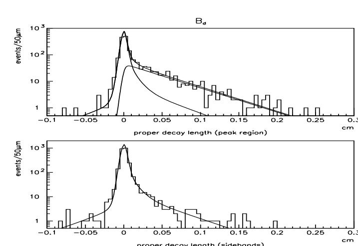


Figure 5: The proper decay length distribution of $B^0 \to \Psi \mathbf{K^0}$ for signal region events (top) and sideband region events (bottom). The curve are the fitting results.

and Fig. 5, we find $\tau(B^+) = 1.68 \pm 0.07 \pm 0.02 \; ps$, $\tau(B^0\;) = 1.58 \pm 0.09 \pm 0.02 \; ps$, and $\tau^+/\tau^0 = 1.06 \pm 0.07 \pm 0.01$.

With its large branching fraction, semileptonic decay provides a high-statistics source for lifetime measurement. We measure the individual $B^+$ and $B^0$ lifetime using the $D\ell$ correlation in $B \to D\ell\nu$ where $D$ can be a $\overline{D}^0$ or $D^{*-}$. After $\overline{D}^0$ from $D^{*-}$ are explicitly excluded, the $\overline{D}^0\ell^+$ are usually originates from $B^+$ while $D^{*-}\ell^+$ comes from $B^0$. This simple picture is complicated by the existence of $D^{**}$ states which are the source of $\overline{D}^0$ and $D^{*-}$ that originates from a decay of $B \to D^{**}\ell\nu$. This cross talk has been decomposed using Monte Carlo. The reconstructed charm signals are shown in Fig. 6.

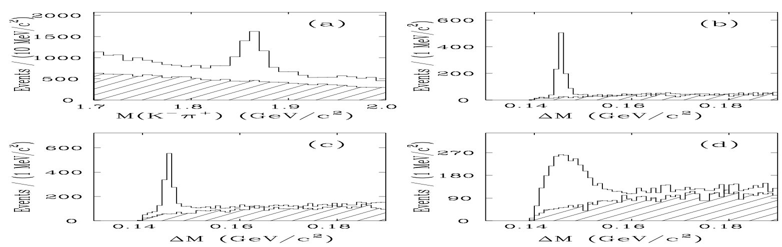


Figure 6: Reconstructed charm signals in lepton events. Four modes are shown: (a)$\overline{D}^0 \to K^+\pi^-$ (non-$D^{*-}$); (b)$D^{*-} \to \overline{D}^0\pi^-$ with $\overline{D}^0 \to K^+\pi^-$; (c)$D^{*-} \to \overline{D}^0\pi^-$ with $\overline{D}^0 \to K^+\pi^-\pi^-\pi^+$; (d)$D^{*-} \to \overline{D}^0\pi^-$ with $\overline{D}^0 \to K^+\pi^-\pi^0$. Plot (a) shows the $K^-\pi^+$ invariant mass spectra, and (b-d) shown the distributions of $\Delta M = M(D^{*-} - M(\overline{D}^0)$. Shaded histograms show wrong sign combinations. and in (a) they are scaled by 0.5 for display purpose.

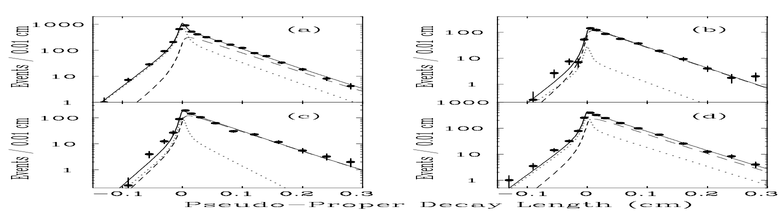


Figure 7: Distribution of psedu-proper decay lengths for the lepton-D signal samples (points). Also shown are results of lifetime fits, signal (dashed curve) and background (dotted curve) contributions, and the sum of the two (solid curve). The four decay modes (a-d) are the same as in the mass plots.

A combined lifetime fit to the $\overline{D}^0\ell^+$ and $D^{*-}\ell^+$ lifetime distribution shown in Figure 7 yields $\tau(B^+) = 1.64 \pm 0.06 \pm 0.05\, ps$, $\tau(B^0) = 1.48 \pm 0.04 \pm 0.05\, ps$, and $\tau^+/\tau^0 = 1.11 \pm 0.06 \pm 0.03$.

The combined $B^+$ and $B^0$ lifetime from CDF are

$$\tau(B^+) = 1.66 \pm 0.05 \; ps$$

$$\tau(B^0 \;) = 1.51 \pm 0.05 \; ps$$

$$\tau^+/\tau^0 = 1.09 \pm 0.05$$

which are the most precise measurements of $B^+$ and $B^0$ lifetimes to date.

## 4 $B_s$ lifetime

It has been suggested by recent theoretical calculation [2], in analogy to the neutral kaon system, that the lifetime difference between two $CP$ eigenstates produced by the $B_s^0$ and $\bar{B}_s^0$ mixing maybe as large as 30%. Such an effect could manifest itself as a difference in lifetimes measured in semileptonic $B_s$ decay, which is an almost equal mixture of the two $CP$ states, and in the decay $B_s \rightarrow J/\psi\phi$, which is expected to be dominated by the $CP$-even state. With precise measurement, we can compare the difference of the $B_s$ lifetime from semileptonic decay to that from $B \rightarrow J/\psi\phi$ to establish the existence of the two lifetime components.

The lifetime measurement of fully reconstructed $B_s$'s is very similar to that of $B \rightarrow \Psi \mathbf{K}$. From $58 \pm 12$ events of $B_s \rightarrow J/\psi\phi$ with $\phi \rightarrow K^+K^-$, as shown as in Fig. 8, we fit the proper decay length as shown in Fig. 9 and find

$$\tau_{B_s \rightarrow J/\psi\phi} = 1.34^{+0.23}_{-0.19} \pm 0.05 \; ps.$$

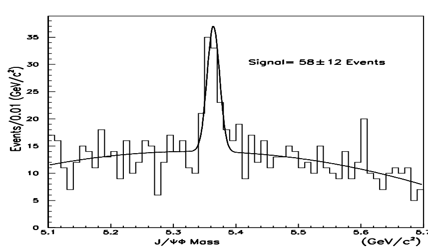


**Figure 8: The invariant mass distribution of the $B_s \rightarrow J/\psi\phi$ candidates.**

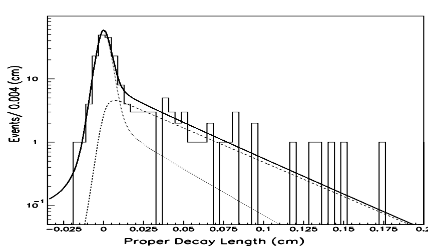


**Figure 9: The proper decay length distribution of $B_s \rightarrow J/\psi\phi$.**

The semileptonic decay of $B_s$ is reconstructed from $B_s^0 \rightarrow D_s^- \ell^+ \nu$. The $D_s^-$ is reconstructed through the decay $D_s^- \rightarrow \phi\pi^-$, with $\phi \rightarrow K^+K^-$. The

$\phi\pi^-$ invariant mass spectra for right-sign $D_s^-\ell^+$ signal and wrong-sign $D_s^-\ell^-$ background are shown in Fig. 10. We find a signal of $254 \pm 21$ events in the peak and also see evidence of the Cabibbo-suppressed decay $D^- \rightarrow \phi\pi^-$. As expected, there is no evidence for any enhancement in the wrong-sign mass spectrum. Having found the $D_s$ decay vertex and reconstructing the $p_t$ of the $D_s^-$ , we define the $B_s^-$ decay vertex to be the intersection of the $D_s^-$ and the lepton in the transverse plane. The proper decay length is then calculated from the $B_s$ decay vertex together with the $\beta\gamma$ estimated using the $p_t$ of the $D_s - \ell$ system with a residual correction obtained from Monte Carlo. Using a single lifetime assumption, we fit the proper decay length distribution, as shown in Fig. 11. We find

$$\tau_{B_s \rightarrow D_s \ell \nu} = 1.37^{+0.14}_{-0.12} \pm 0.04 \ ps$$

We also attempted to fit the data with two lifetime components, $\overline{c\tau} + \Delta c\tau/2$ and $\overline{c\tau} - \Delta c\tau/2$, where $\overline{c\tau}$ is fixed to the single lifetime fitting result. We find $\Delta c\tau = 0.68^{+0.42}_{-0.68} \ ps$. With current available data, we are not yet statistically sensitive to the existence of two lifetime components in $B_s$ either from semileptonic decay or from comparing it to $B_s \rightarrow J/\psi\phi$.

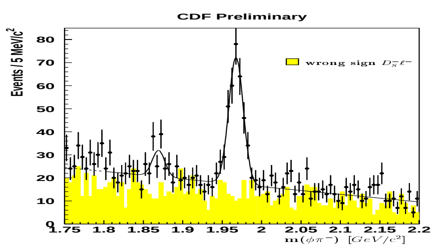


Figure 10: The invariant mass distribution of the $D_s^- \rightarrow \phi\pi^-$ for right sign $D_s^-\ell^+$ combinations with results of the fit superimposed The dashed histogram shows the wrong-sign distribution.

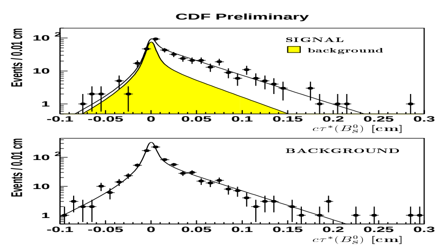


Figure 11: Proper decay length distribution for the $D_s\ell^+$ signal sample (top) and background sample (bottom). The shaded curve represents the contribution from combinatorial background.

## 5 $\Lambda_b$ lifetime

The $W$ exchange diagram for baryons is not helicity suppressed and can make a sizable contribution to the lifetime difference between b-baryons and b-mesons. In particular, the lifetime of $\Lambda_b$ is expected to be smaller than that of the $B^0$, but the difference is expected to be no more than 10% [2].

We search for the decay $\Lambda_b^0 \rightarrow \Lambda_c^+ \ell^- \bar{\nu}$ by detecting a $\Lambda_c^+ \ell^-$ (right sign) pair with invariant mass in the kinematically allowed range $m_{\Lambda_c} < m_{\Lambda_c \ell} < m_{\Lambda_b^0}$.

The charmed baryon $\Lambda_c$ is fully reconstructed through its decay to $pK^-\pi^+$. The specific ionization ($dE/dx$) information from the CDF central tracking chamber is used to help identify the protons in the $\Lambda_c$ reconstruction. Fig. 12 shows the $pK^-\pi^+$ invariant mass distributions of the right sign and the wrong sign events. The yield returned from a fit to the invariant mass distributions is $197 \pm 25$ 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. As in the $B_s$ semileptonic decay lifetime analysis, the $\Lambda_b^0$ vertex is obtained by intersecting the trajectory of the lepton track with the flight path of the $\Lambda_c$ candidate. The proper decay length is then calculated from the $\Lambda_b^0$ decay vertex together with the $\beta\gamma$ estimated using the $p_t$ of the $\Lambda_c - \ell$ system with a residual correction obtained from Monte Carlo. Figure 13 shows the proper decay length distribution of the signal region with the fit superimposed. We find

$$\tau_{\Lambda_b} = 1.32 \pm 0.15 \pm 0.07 \ ps$$

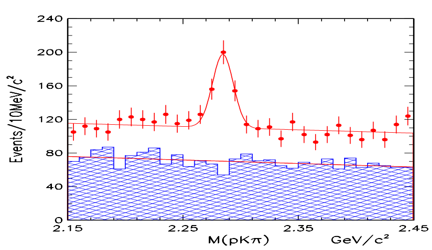


Figure 12: Invariant mass of $pK^-\pi^+$ for right sign (points with error bars) and wrong sign events (shaded area). The fit yields of $197 \pm 25$ right sign events. There is no evidence of a $\Lambda_c$ signal in wrong sign combinations.

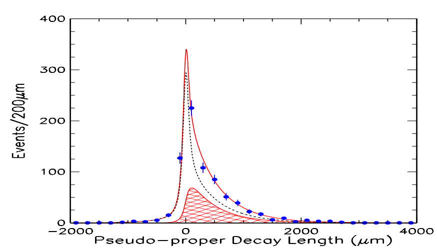


Figure 13: Pseudo-proper decay length distribution from the $pK^-\pi^+$ invariant mass sideband sample. The points with error bars are data points and the solid line is the fit result. Most of this background is from b-hadron decays.

Using this result and the average $B^0$ lifetime [1], $\tau_{B^0} = 1.56 \pm 0.05$ ps, 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 $\Lambda_b^0$ 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 [2] of $\tau_{\Lambda_b^0}/\tau_{B^0} \approx 0.9$.

## 6 Outlook

With its large data sample and excellent detector performance, CDF has emerged as a strong force in the field of precise lifetime measurement in the past few years. Much effort is still being put into finishing the analysis of the existing data sample. We can expect excellent new results in the near future. In the run-II period, with its enhanced tracking ability, increased geometric coverage of calorimeters, improved SVX detector, and large increase in the luminosity expected from the Tevatron upgrade with Main Injector,CDF will yield many exciting results in heavy flavor physics.

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