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CDF

B States and Lifetimes at CDF

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The measurements at CDF of the masses and lifetimes of weakly decaying B hadrons are described.

1 Introduction

The mass and lifetime are the most fundamental properties of an elementary particle. They provide insights into the forces binding quarks to make hadrons and making the hadrons decay. The weakly decaying B hadrons provides such an opportunity.

The non-strange B mesons have been known for more than ten years, but the strange B meson and the b-flavored baryons are relatively new entries into the particle data book.

The first measurements of the lifetime of the B hadrons were performed in early 1980's. The result, of order 1 ps, lead to the determination of the Cabibbo-Kobayashi-Maskawa matrix element $|V_{cb}|$ with a surprisingly small value of about 0.04. This long lifetime has turned out to provide rich physics phenomena in B hadron decays and hold promises for the future.

The simple spectator decay model predicts that all the hadrons containing a heavy quark should have one, identical lifetime, that of the quark. This approximation would ultimately be true in the top quark, which decays even before physical hadrons are formed. In the charm hadrons, however, the prediction does not really hold; the D^+ and D^0 lifetimes differ by a factor of 2.5. The causes of lifetime differences in heavy hadrons include non-spectator decays, the W-exchange and the annihilation processes, and also the so-called Pauli interference effects. Obviously these mechanisms play an important role in the decays of charm hadrons. For the B hadrons, they are expected to produce smaller lifetime differences because of the heavier b quark mass. On the experimental side, the measurement of the individual B hadron lifetimes has become precise significantly in the past few years as the amount of available data has increased.

The CDF experiment has contributed to this field too. In this talk we describe CDF measurements of the masses and lifetimes of the following B hadrons, B^-, $\overline{B}^0$, $\overline{B}^0_s$ and Λ_b. Also we report on a search for the B_c^- meson, which is yet to be observed.

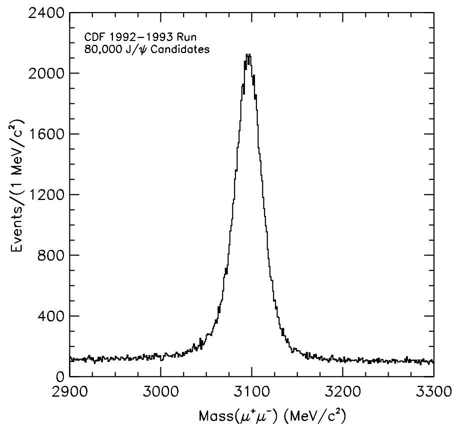

Figure 1: Dimuon invariant mass distribution near the J/ψ region.

2 *B* hadron masses

2.1 B meson masses

A precise measurement of the masses of B hadrons requires their fully reconstructed decays. In CDF we achieve this by using their decays involving a J/ψ, followed by its dimuon decay. Although this decay has a small combined branching fraction, of order 10^{-4}, a large production cross section of b quarks at the Tevatron enables us to collect and make use of relatively rare events.

We start with a reconstruction of a J/ψ with a dimuon pair. The events are triggered on the existence of two muons with at least 2 GeV/c in the transverse momentum (p_T). Figure 1 shows the invariant mass distribution of dimuons from a data sample taken during 1992-93, corresponding to an integrated luminosity of 20 pb^{-1}. We observe about 80 k J/ψ events on the mass peak whose rms width is about 17 MeV/c^2.

We then combine a J/ψ candidate with a "kaon" to form a B meson candidate. We use the following decay modes to reconstruct the B^-, $\overline{B}^0$ and $\overline{B}^0_s$ mesons: [a]

$$\begin{aligned} B^- &\rightarrow J/\psi K^-, \\ \overline{B}^0 &\rightarrow J/\psi \overline{K}^*(892)^0,\ \overline{K}^*(892)^0 \rightarrow K^-\pi^+, \\ \overline{B}^0_s &\rightarrow J/\psi\phi,\ \phi \rightarrow K^+K^-. \end{aligned}$$

[a] A reference to a particular charge state implies its charge conjugate as well.

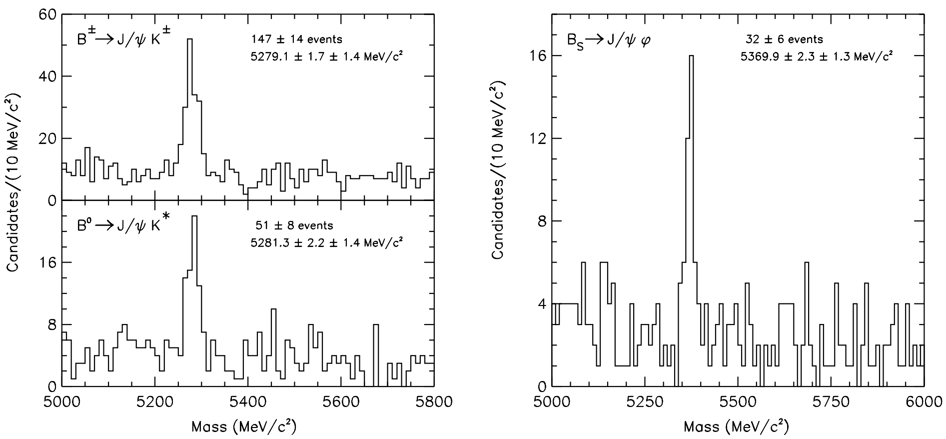

Figure 2: Fully reconstructed B meson decays used for mass measurement. Left: $J/\psi K^-$ (top) and $J/\psi \overline{K}^*(892)^0$ (bottom) invariant mass distributions. Right: $J/\psi\phi$ invariant mass distribution.

The resultant invariant mass distributions are shown in Figure 2. We observe signals of 147, 51 and 32 events, respectively, and find the masses to be $m(B^-) = 5279.1 \pm 1.7 \pm 1.4$ MeV$/c^2$, $m(\overline{B}^0) = 5281.3 \pm 2.2 \pm 1.4$ MeV$/c^2$ and $m(\overline{B}_s^0) = 5369.9 \pm 2.3 \pm 1.3$ MeV$/c^2$, where the first uncertainties are statistical and the second are systematic. These results have recently been published [1].

2.2 Λ_b baryon mass

The Λ_b baryon is reconstructed using the decay mode $\Lambda_b \to J/\psi\Lambda$, $\Lambda \to p\pi^-$ in a similar fashion as the B mesons. We use our full data sample taken from 1992 to 1996, corresponding to 110 pb^{-1} of integrated luminosity. The $J/\psi\Lambda$ invariant mass distribution is shown in Figure 3. In the signal region 38 events are observed with an estimated background of 18.3 events. The probability that a background of 18.3 events fluctuates and produces a peak of 38 events anywhere in the mass window between 5.4 and 5.8 GeV$/c^2$ is 1.2×10^{-3}, or the significance of the signal corresponds to roughly three standard deviations. From the above distribution, we determine the mass of the Λ_b baryon to be $m(\Lambda_b) = 5623 \pm 5$ (stat) ± 4 (syst) MeV$/c^2$.

The decay $\Lambda_b \to J/\psi\Lambda$ is topologically very similar to the $\overline{B}^0 \to J/\psi K_S^0$ decay. We do reconstruct the latter mode in our sample, and a comparison enables us to control systematic effects better. We find the mass difference

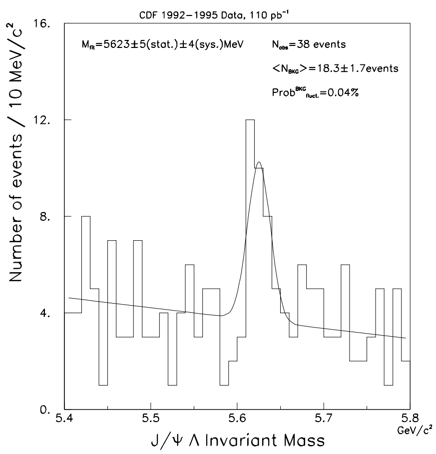

Figure 3: $J/\psi\Lambda$ invariant mass distribution.

between the two states to be $m(\Lambda_b) - m(\overline{B}^0) = 342 \pm 6$ MeV/c^2. Also we determine the relative production rates [2].

3 *B* hadron lifetimes

As mentioned earlier, the lifetime differences among various B hadrons are expected to be small. A theory predicts[3] that the B^- lifetime to be longer than the $\overline{B}^0$ lifetime by about 5% and the $\overline{B}^0$ and $\overline{B}^0_s$ lifetimes should be very similar, to order 1%. The b-flavored baryons are predicted to have shorter lifetimes than the $\overline{B}^0$ meson by about 10%. Therefore, a challenge to experiments is to measure the individual B hadron lifetimes as precisely as possible.

At CDF, the measurement of the B hadron lifetimes is performed using two different decay modes. One is to use the fully reconstructed decays involving J/ψ's, as in the mass measurements. The other is to use partially reconstructed semileptonic decays $\overline{B} \to \ell^- \bar{\nu} D X$, where a charm hadron D helps identify the parent B hadron species. We trigger on single electrons and muons at a typical p_T threshold of 8 GeV/c.

The lifetime of B hadrons is short, about 1.5 ps, and its measurement is done through a measurement of decay length distributions. Let us define the proper decay length x of a B hadron by $x \equiv Lm/p$, where L is a measured B hadron decay length, m and p are the mass and momentum of the hadron. The proper decay length x should follow an exponential distribution $\exp(-\frac{x}{c\tau})$

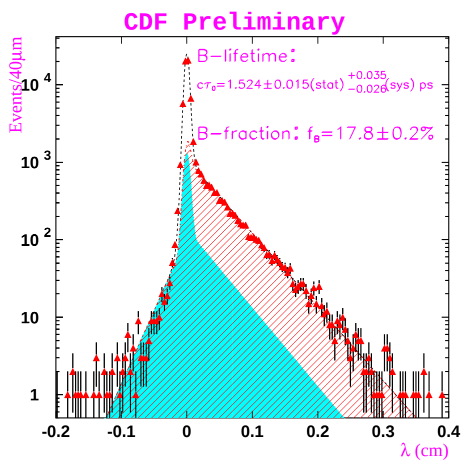

Figure 4: J/ψ decay length distribution.

where τ is the lifetime. We extract the lifetime by fitting an exponential function to an observed x distribution.

For fully reconstructed decays, the B hadron momentum p can be measured for each event and the estimate of the proper decay length x is precise. On the other hand, the semileptonic decays involve unobserved particles like neutrinos, and the extraction of a lifetime requires statistical corrections to an observed decay length distribution for the uncounted missing momentum.

The decay length is measured as follows. In all of the following analyses, the measurement is done in the plane transverse to the beam axis. The B hadron decay vertex is reconstructed from its decay products with the information from the silicon microstrip detector (SVX), which is located at radii between 2.9 and 7.9 cm from the beam axis. Another ingredient for a decay length measurement is the position of the B hadron production, or the primary vertex. At CDF, we approximate it with the average position of the Tevatron beam, whose shape is circular in the transverse plane with an rms spread of about 35 μm [4].

3.1 Average B hadron lifetime

We have already seen that B decays involving J/ψ's are reconstructed fully at CDF. However, by using the J/ψ alone, we can measure a B hadron lifetime. The advantage of this method is its increased statistics over fully reconstructed decays. The disadvantage is that we have no separation among various B hadron species. In this case what we measure is the lifetime averaged over various B hadrons weighted by their relative production rates and branching ratios into J/ψ.

A result from 13 pb^{-1} of data has already been published [4]. Here we describe an update to the measurement using 60 pb^{-1} of data. The J/ψ is reconstructed using its dimuon decays as in the mass measurements. The J/ψ decay vertex is reconstructed and it coincides with the B hadron decay vertex.

Since we reconstruct only the J/ψ among B hadron decay products, the B hadron momentum is not precisely measured for each event. To estimate a proper decay length we use the Lorentz boost factor of the J/ψ. Let us define a variable x' with $x' \equiv L/(\beta\gamma)_\psi$. This can be written using the true proper decay length of the B hadron x as

$$x' = \frac{L}{(\beta\gamma)_\psi} = \frac{L}{(\beta\gamma)_B}\frac{(\beta\gamma)_B}{(\beta\gamma)_\psi} = x\frac{(\beta\gamma)_B}{(\beta\gamma)_\psi} \equiv xF(p_T^\psi), \tag{1}$$

where in the last step we have introduced the ratio F of the $\beta\gamma$ factors. We use a variable λ defined with

$$\lambda \equiv \frac{x'}{\langle F(p_T^\psi)\rangle} = \frac{L}{(\beta\gamma)_\psi \langle F(p_T^\psi)\rangle}. \tag{2}$$

The ratio F has a mean value of 0.87 and shows only weak dependence on p_T of J/ψ. The λ distribution of the J/ψ's is shown in Figure 4. To describe the λ distribution, we consider three components: (a) J/ψ's coming from B decays, (b) J/ψ's produced either promptly or in the decay of short-lived particles, and (c) combinatorial background events under the J/ψ mass peak. The functional forms for those components are: (a) an exponential smeared with a Gaussian distribution for a finite decay length resolution, (b) a Gaussian distribution, and (c) a Gaussian distribution with positive and negative exponential tails. We fit the sum of these functions to the λ distribution and extract the lifetime. The shape and fraction of combinatorial background are determined with the J/ψ sideband and the invariant mass distribution. The fraction of J/ψ's from B decays is a free parameter in the fit. Our preliminary result is

$$\tau(B_{\text{ave}}) = 1.524 \pm 0.015\,(\text{stat})\,^{+0.035}_{-0.026}\,(\text{syst})\text{ ps}.$$

The result of the fit is also shown in Figure 4. The dark-shaded area corresponds to the background, and the light-shaded area corresponds to the sum of the background and the J/ψ's from B decays. We are left with a sizable contribution from the J/ψ's with no observable lifetime; the fraction of J/ψ's coming from B decays is only 18% in this sample.

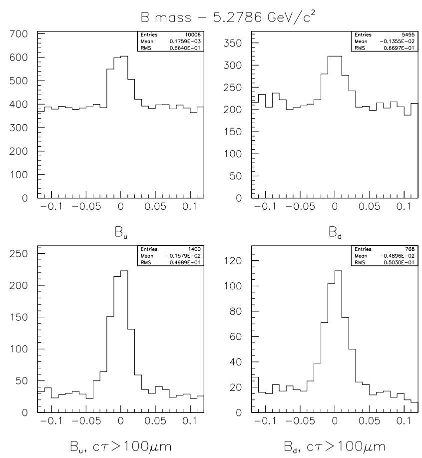

Figure 5: $\Psi\overline{\mathbf{K}}$ invariant mass distributions without (top) and with 100 μm decay length cut (bottom).

3.2 B^- and $\overline{B}^0$ lifetimes

The B^- and $\overline{B}^0$ mesons are reconstructed fully using their decays into J/ψ's as in the mass measurement. For the lifetime measurement, we use all of the following modes for the B meson reconstruction in order to increase statistics. The decays can be expressed as $\overline{B} \rightarrow \Psi\overline{\mathbf{K}}$, where Ψ is either J/ψ or $\psi(2S)$, and $\overline{\mathbf{K}}$ is either K^-, $K^*(892)^-$, K_S^0 or $\overline{K}^*(892)^0$. The $\psi(2S)$ is reconstructed with its $J/\psi\pi^+\pi^-$ decay, K_S^0 with $\pi^+\pi^-$ decay, and $K^*(892)^-$ with $K_S^0\pi^-$ decay. The result with 20 pb^{-1} of data has been published [5].

The $\Psi\overline{\mathbf{K}}$ invariant mass distributions from 110 pb^{-1} of data are shown in Figure 5. The numbers of signal events are 820 and 440 for B^- and $\overline{B}^0$ mesons, respectively. The proper decay length distributions are shown in in Figure 6. They contain two contributions, the B meson decay signal and the combinatorial background. The signal is described as an exponential decay function smeared with a Gaussian distribution. The decay length distribution of combinatorial background is modelled using the sideband events. We use the same functional form as in the average B lifetime analysis. We find the lifetimes and their ratio to be

$$\tau(B^-) = 1.68 \pm 0.07 \pm 0.02 \text{ ps},$$
$$\tau(\overline{B}^0) = 1.58 \pm 0.09 \pm 0.02 \text{ ps},$$
$$\tau(B^-)/\tau(\overline{B}^0) = 1.06 \pm 0.07 \pm 0.01.$$

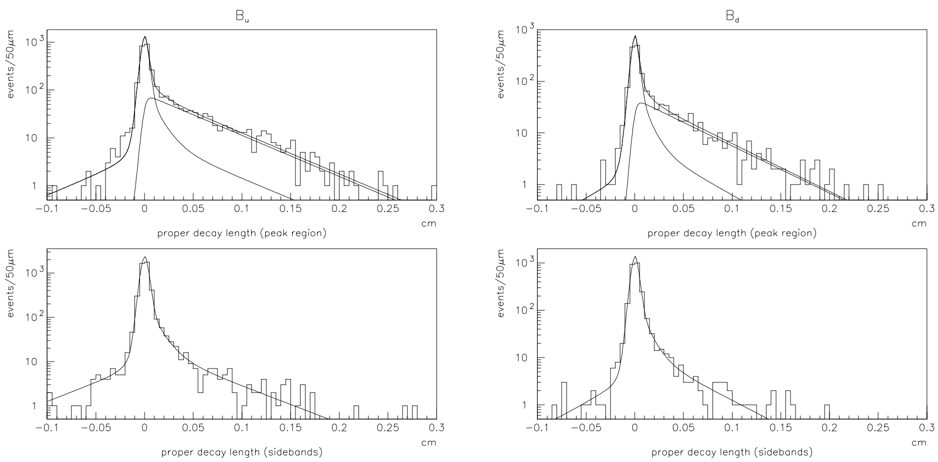

Figure 6: The proper decay length distributions of charged and neutral B mesons reconstructed via the decay modes $\overline{B} \to \Psi\overline{\mathbf{K}}$.

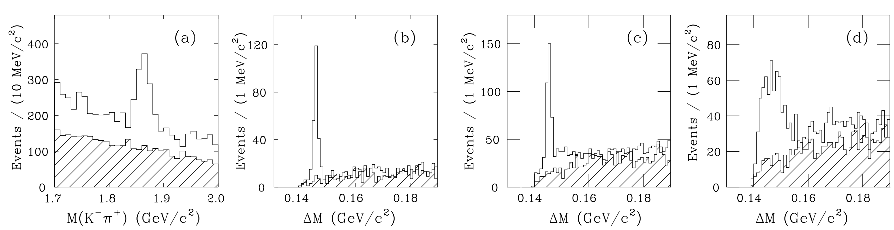

Figure 7: Reconstructed charm signals in lepton events. Four modes are shown: (a) $D^0 \to K^-\pi^+$ (non-D^{*+}), (b) $D^{*+} \to D^0\pi^+, D^0 \to K^-\pi^+$, (c) $D^{*+} \to D^0\pi^+, D^0 \to K^-\pi^+\pi^+\pi^-$ and (d) $D^{*+} \to D^0\pi^+, D^0 \to K^-\pi^+\pi^0$. Plot (a) shows the $K^-\pi^+$ invariant mass spectra, and (b-d) show the distributions of $\Delta m \equiv m(D^{*+}) - m(D^0)$. Shaded histograms show wrong sign combinations, and in (a) they are scaled by 0.5 for display purposes.

The B^- and $\overline{B}^0$ meson lifetimes are also measured using the semileptonic decay $\overline{B} \to \ell^-\bar{\nu}DX$, where D is either a D^0 or D^{*+} meson.

The D^0 meson is reconstructed with $D^0 \to K^-\pi^+$ mode, excluding events that are consistent with the $D^{*+} \to D^0\pi^+$ decay chain. The D^{*+} meson is reconstructed with the $D^{*+} \to D^0\pi^+$ mode using two fully reconstructed D^0 decay modes, $D^0 \to K^-\pi^+$ and $D^0 \to K^-\pi^+\pi^+\pi^-$, and one partially reconstructed mode $D^0 \to K^-\pi^+\pi^0$. In the last mode we do not include π^0 and treat the $K^-\pi^+$ pair as a D^0. The reconstructed charm signals are shown in Figure 7, where single electron and muon samples from 1992-93 (20 pb^{-1}) are used. The signals are apparent, and no significant signals are observed in "wrong sign" ($D\ell^+$) combinations.

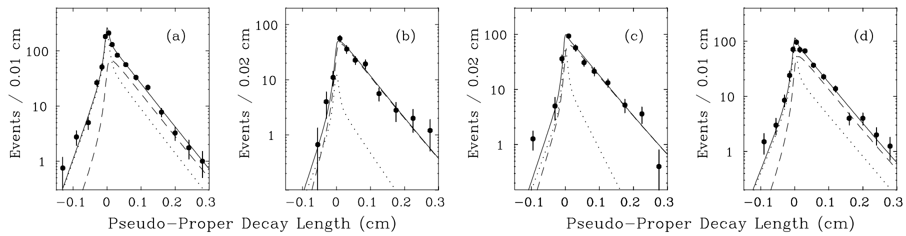

Figure 8: Distributions of pseudo-proper decay lengths for the lepton-D signal samples (points). Also shown are results of lifetime fits, signal (dashed curve) and background (dotted curve) contributions, and the sum of the two (solid curve). The four decay modes (a-d) are the same as in Figure 7.

Since the D^0 meson has a detectable finite lifetime, its decay vertex does not coincide with the B meson vertex. The B meson vertex is obtained as the intersection of the lepton track and the flight path of the D^0 meson, and the B meson decay length L is defined as the distance between the primary and B decay vertices. As the best estimate of the proper decay length, we define the pseudo-proper decay length ξ as

$$\xi \equiv L \frac{m_B}{p_T^{\ell^- D^0}}, \tag{3}$$

where m_B is the B meson mass, and $p_T^{\ell^- D^0}$ is the transverse momentum of the lepton-D^0 system. The variable ξ is related to the true proper decay length x by $\xi = x/\kappa$, where κ is the momentum ratio $\kappa \equiv p_T^{\ell^- D^0}/p_T^B$. The κ distribution is modelled and has a mean value of 0.85 and an rms width of 0.11, and is approximately independent of $p_T^{\ell^- D^0}$ and the D^0 decay mode. To extract the lifetime, we fit a signal probability distribution function to an observed ξ distribution. The signal function is an exponential decay function smeared with a Gaussian distribution and the κ distribution. Figure 7 also shows the ξ distributions of the events in the signal regions. Also shown by the curves are the results of the lifetime fits.

The $\ell^- D^0$ combination consists mostly of B^- decays, and the $\ell^- D^{*+}$ combination consists mostly of $\overline{B}^0$ decays. The separation is perfect if no D^{**}'s are produced in semileptonic B decays. That is not the case, and we estimate the fraction of B^- in the $\ell^- D^0$ sample to be $0.85\,^{+0.05}_{-0.12}$, and the fraction in the $\ell^- D^{*+}$ sample to be $0.10\,^{+0.09}_{-0.10}$. To extract the B^- and $\overline{B}^0$ lifetimes, the ξ distributions of the two samples are fit simultaneously using a

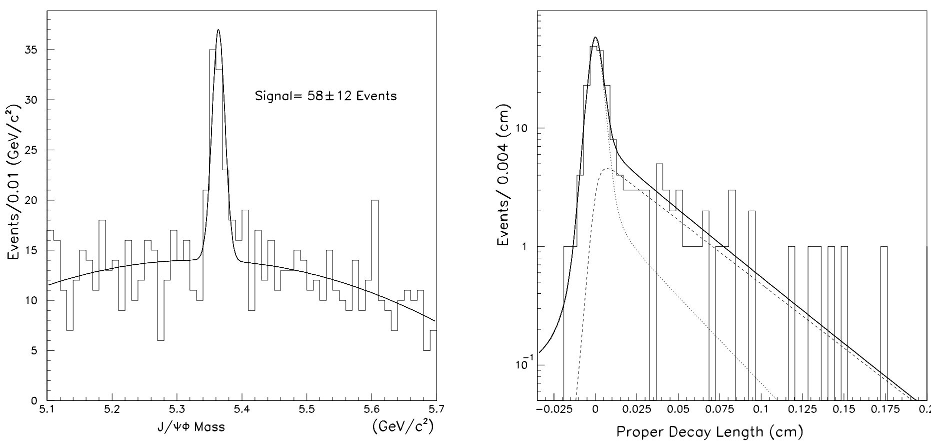

Figure 9: The $\overline{B}_s^0$ lifetime measurement using $\overline{B}_s^0 \to J/\psi\phi$ decay mode. The $J/\psi\phi$ invariant mass distribution (left) and the proper decay length distribution (right).

signal probability distribution which has two meson components. We find

$$\tau(B^-) = 1.56 \pm 0.13 \pm 0.06 \text{ ps},$$
$$\tau(\overline{B}^0) = 1.54 \pm 0.08 \pm 0.06 \text{ ps},$$
$$\tau(B^-)/\tau(\overline{B}^0) = 1.01 \pm 0.11 \pm 0.02,$$

where the first uncertainties are statistical and the second are systematic. The result has recently been published [6].

3.3 $\overline{B}_s^0$ *lifetime*

The strange B meson, $\overline{B}_s^0$, may exhibit a very interesting phenomenon in its lifetime. There should exist two mass eigenstates that are combinations of the flavor eigenstates $\overline{B}_s^0$ and B_s^0, just like in the neutral kaon system. And some theory predicts that the lifetime difference between the two mass eigenstates could be as large as 20%.

Physically the lifetime difference would manifest itself as the difference between the lifetime when it is measured with the semileptonic decay $\overline{B}_s^0 \to \ell^- \bar{\nu} D_s^+ X$, and when it is measured with a final state which is dominated by one of the CP eigenstate, for example, $J/\psi\phi$. The former is expected to be almost an equal mixture of two mass eigenstates and should measure the average lifetime of the two states. Even using only the semileptonic decays, we should see two components in its decay length distribution once we collect large statistics sample. A more sophisticated way of looking into this phenomenon is

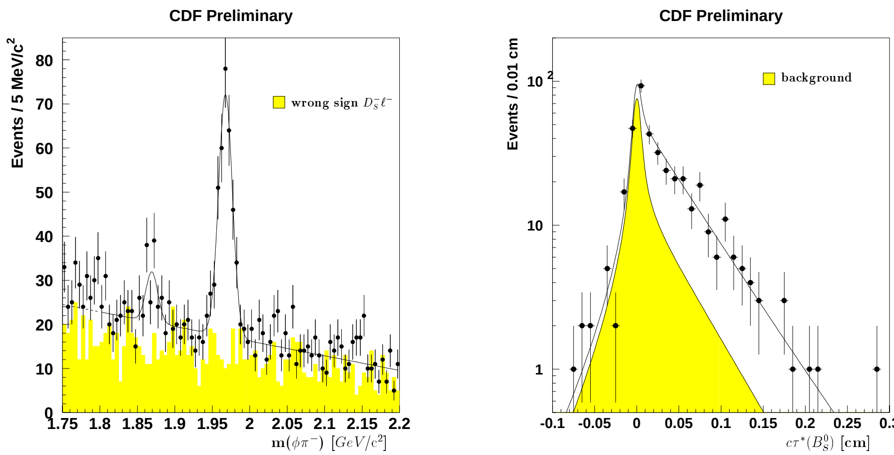

Figure 10: Left: $\phi\pi^+$ invariant mass distribution reconstructed around a lepton. The peak corresponds to the D_s^+ meson. Shaded histogram shows the spectrum of wrong sign combinations. Right: Pseudo-proper decay length distribution of the events in the D_s^+ signal region. The background contribution is shown by the shaded area. Solid curve is the result of lifetime fit and corresponds to the sum of signal and background.

to use the $J/\psi\phi$ decay mode and measure its time development of the relative amount of two CP eigenstates.

These measurements present a challenge to experiments, because a high precision is necessary to establish the expected difference. Nevertheless, at CDF we have measurements of the $\overline{B}_s^0$ lifetime using the two modes above. A result from the data taken during 1992-93 has been published [7]. Here we report on an updated measurement using the full data sample available.

The exclusive decay $\overline{B}_s^0 \to J/\psi\phi, \phi \to K^+K^-$ is reconstructed, as seen in the $J/\psi\phi$ invariant mass distribution shown in Figure 9. We observe a signal of 58 events. The proper decay length distribution is also shown in Figure 9, and we extract the lifetime to be [8]

$$\tau(\overline{B}_s^0) = 1.34 \, ^{+0.23}_{-0.19} \, (\text{stat}) \pm 0.05 \, (\text{syst}) \text{ ps}.$$

The semileptonic decay mode $\overline{B}_s^0 \to \ell^- \bar{\nu} D_s^+ X$ is also used to measure the $\overline{B}_s^0$ meson lifetime. The D_s^+ meson is reconstructed near a lepton using the decay mode $D_s^+ \to \phi\pi^+$, $\phi \to K^+K^-$. Figure 10 shows the $\phi\pi^+$ invariant mass spectrum near the D_s^+ region. A signal of about 250 events is observed in the 110 pb^{-1} of data. A hint of the Cabibbo-suppressed decay $D^+ \to \phi\pi^+$ may also be seen. Again, no significant signal is observed in the "wrong sign" combination (D_s^- with ℓ^-). The distribution of the pseudo-proper decay

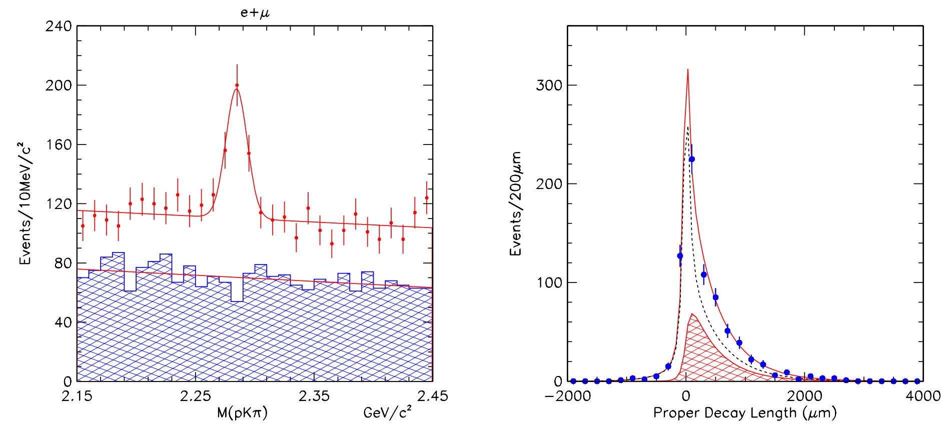

Figure 11: Left: $pK^-\pi^+$ invariant mass distribution reconstructed around a lepton. The peak corresponds to the Λ_c^+ baryon. Shaded histogram shows the spectrum of wrong sign combinations ($\Lambda_c^+\ell^+$). Right: Pseudo-proper decay length distribution of the events in the Λ_c^+ signal region (points). The signal and background contributions are shown by the shaded area and the dashed curve, respectively. The solid curve corresponds to the sum of signal and background.

length, defined in the same way as in the non-strange B meson decays, is also shown in Figure 10. Our preliminary result is

$$\tau(\overline{B}_s^0) = 1.37\ ^{+0.14}_{-0.12}\ (\text{stat}) \pm 0.04\ (\text{syst})\ \text{ps}.$$

3.4 Λ_b lifetime

Because the W-exchange process is not helicity-suppressed in baryon decays, a shorter b-baryon lifetime is predicted than meson lifetimes. And it does indeed seem to be the case for the Λ_b baryon, where we observe $\tau(\Lambda_b)/\tau(\overline{B}^0) = 0.76 \pm 0.05$ as a world average; the value is even smaller than the theory prediction of about 0.9.

The Λ_b baryon lifetime is measured at CDF using the semileptonic decay $\Lambda_b \to \ell^-\bar{\nu}\Lambda_c^+ X$, where the Λ_c^+ baryon is reconstructed with its $pK^-\pi^+$ decay mode. Figure 11 shows the $pK^-\pi^+$ invariant mass distribution for events with single leptons from 110 pb^{-1} of data. A signal of 200 events is seen. The pseudo-proper decay length distribution is also shown in Figure 11. We find the lifetime to be [9]

$$\tau(\overline{B}_s^0) = 1.33 \pm 0.16\ (\text{stat}) \pm 0.07\ (\text{syst})\ \text{ps}.$$

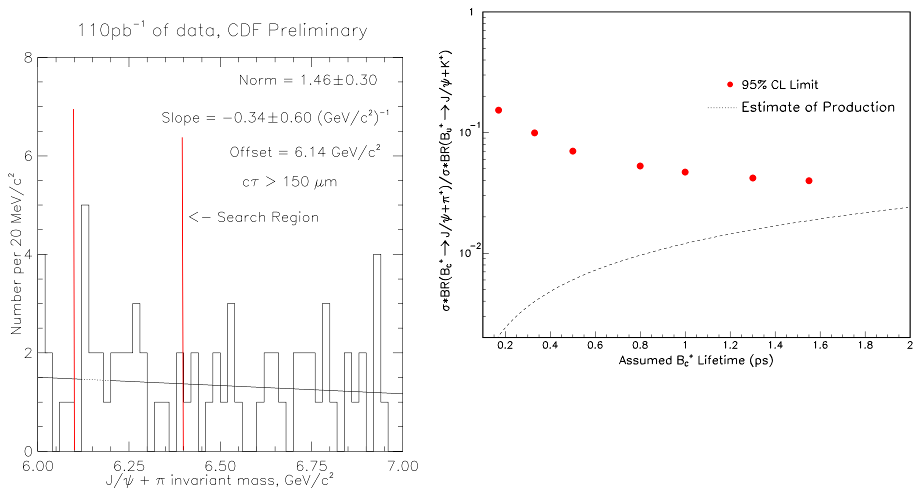

Figure 12: Left: $J/\psi\pi^-$ invariant mass distribution. Right: Limit on the B_c^- production.

4 Search for B_c^- meson

The B_c^- meson ($\equiv b\bar{c}$) is unique in that it is a bound state of two heavy quarks of different flavors. The state has not been observed yet.

The mass should be reliably estimated from the QCD potential models because they have successfully explained the energy levels of the charmonium and bottomonium states. The B_c^- decay could proceed in three ways: (a) decay of the b quark, (b) decay of the $\bar{c}$ quark and (c) the annihilation of the b and $\bar{c}$ quarks into W^-. Various theories predict these properties, the mass, the lifetime and the partial decay widths for various exclusive final states. One of them predicts [10] the mass of 6256 ± 20 MeV$/c^2$ and the lifetime of 1.35 ± 0.15 ps. Some others predict a substantially shorter lifetime value, as low as 0.4 ps [11].

The production of the B_c^- meson at high energy hadron-hadron collisions should be due mainly to the production of a b quark followed by its hadronization into B_c^- by creation of a $c\bar{c}$ pair from vacuum. It is expected that the probability that the b quark hadronizes into B_c^- is of order 10^{-3}.

Experimentally, the decay mechanism (a) provides a very attractive signature, namely the existence of a J/ψ in the final state. It is expected that the inclusive branching fraction into J/ψ is about 10%, which is significantly higher than in other B hadrons.

At CDF we look for the decay $B_c^- \to J/\psi\pi^-$. Figure 12 shows the invariant mass distribution, where no significant signal is observed. Therefore we place an upper limit on the B_c^- production relative to an observed $B^- \to J/\psi K^-$ decay, which is very similar kinematically and topologically. The limit, as a function of the assumed B_c^- lifetime, is also presented in Figure 12. The points show the 95% CL upper limit. We change our decay length cut with an increasing B_c^- lifetime. Also included in the Figure is a theoretical prediction, assuming a fixed partial decay width irrespective of the lifetime, and the 10^{-3} probability for B_c^- production in the b quark fragmentation.

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