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Rare B Decays from the CDF Experiment

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The high cross-section for the production of b quarks at the Tevatron hadron collider make it an ideal place to search for rare B meson species and very low branching fraction decay modes of the more common B mesons. This paper reports the recent discovery of the B_c meson by the CDF collaboration. It also discusses the observation of rare B meson final states involving $\psi(2S)$ mesons and searches for ultra-rare decays such as $B \rightarrow \mu^+\mu^-$.

1. Introduction

Hadron colliders in general, and the Tevatron in particular, are an ideal place to study rare B meson production and decay. The enormous b quark production cross-section produced in excess of 10^8 $b\bar{b}$ pairs into the acceptance of the CDF detector during the last run. The main challenge is to isolate these pairs from an even higher QCD background. The first step in that process involved the trigger used to select the events for later analysis. To date the CDF experiment concentrates on B meson final states with one or more leptons. The presence of these leptons is crucial for triggering. All of the channels discussed in this paper involve a pair of muons, usually forming a J/ψ meson, in the final state. For example Fig. 1 shows our fully reconstructed $B^+ \rightarrow J/\psi K^+$ signal with several hundred B candidates. The exact number of candidates depends on the purity desired. We use this signal to normalise our other observations as several experimental and theoretical uncertainties cancel in the estimation of the branching fraction for a rare B meson relative to that of a known final state.

The second key to being able to identify and fully reconstruct these states is the silicon vertex detector in the CDF experiment. Impact parameter resolutions of better than $15 \mu\text{m}$ at high momentum, over two thirds of the solid angle covered by the CDF lepton triggers, make it possible to reconstruct the decay points of the relatively long lived B mesons and efficiently separate them from the QCD background.

The rest of this paper is organised as follows. Section 2 describes the recent discovery of the B_c meson. Following that section 3 gives a brief overview of measurements of the branching fractions of B meson final states into $\psi(2S)$ mesons. Section 4 summarises CDF's limits on very rare and forbidden B meson decays involving pairs of charged leptons in the final state.

2. The Discovery of the B_c Meson

The B_c meson is expected to be a tightly bound $b - c$ quark system. We search for it in fully reconstructed final states, such as $J/\psi\pi$ but find that the low branching fraction to states such as this hinders further study in the data currently have available. The discovery reported here and detailed in [1] [2] involves partially reconstructed final states such as $J/\psi l\nu$. Our inability to reconstruct the neutrino momentum results in a smeared mass distribution; however the larger branching fraction into these final states more than compensates. We reconstruct the J/ψ candidate in $\mu^+\mu^-$ and search for associated leptons, either electrons or muons, to distinguish the B_c signal from background.

Depending on the binding energy of the $b - c$ quark system the mass of the B_c meson should be about $m_b + m_c \approx 6.3 \text{ GeV}/c^2$. By the same token expectations for the lifetime of this meson range from 0.3 ps, if the the two quarks behave independently and the c quark decays first, to 1.5 ps, if the dynamics of the meson bound state are such that the lifetime of the b quark dominates.

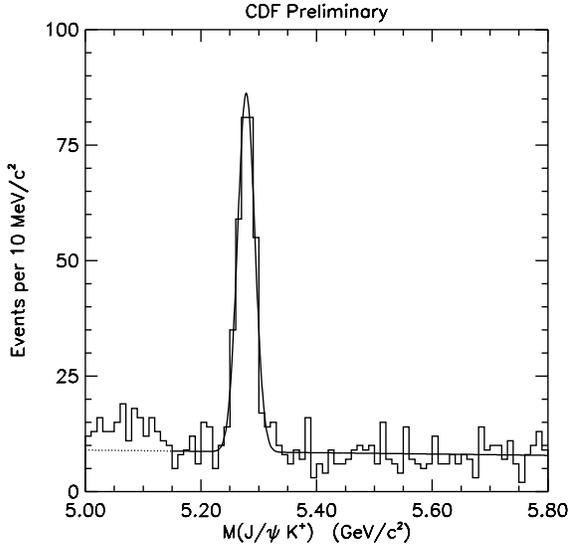


Figure 1. $B^+ \rightarrow J/\psi K^+$ candidate mass distribution with a fit to the signal and a flat background (solid line). The region below $5.15 \text{ GeV}/c^2$ (dotted line) is not included in the fit.

2.1. Signal and Background Distributions

The discovery of the B_c meson in the partially reconstructed semi-leptonic final state relies on understanding the backgrounds from lighter B mesons and fake leptons. While our J/ψ signal is very clean the associated lepton, whose kinematics hint at its possible production by a heavier B meson, can come from several sources other than B_c decay. Electron candidates can come from mis-identified hadrons that fragment predominantly in the electromagnetic compartment of the calorimeter as well as from overlaps between high momentum charged tracks and neutral pions. They can also arise from asymmetric photon conversions or Dalitz decays where we fail to reconstruct one of the e^+e^- pair. Muon candidates can be faked by the decay in flight of pions or kaons. They can also be misidentified pions or kaons that punch-through our calorimeter,

leaving no energy in the calorimeter, but a clean track in the muon chambers beyond. We account for backgrounds resulting from the association of a J/ψ meson produced by one b quark and a single lepton produced by the \bar{b} quark that must be present elsewhere in the event. In general, these backgrounds peak at lower masses than our B_c signal. The background mass shape is predicted from control samples of data. Its normalisation is allowed to float in our fit for the signal.

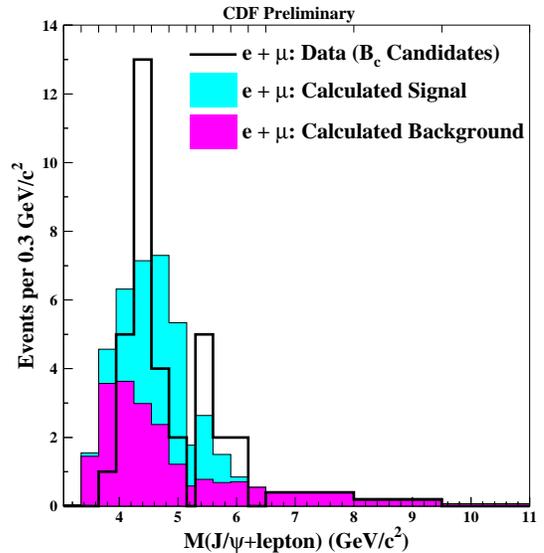


Figure 2. B_c candidate mass distribution (open) with background (dark solid) and signal (light solid) predictions from the fit.

The invariant mass distribution for our $J/\psi l \nu$ candidates is shown in Fig. 2. Superimposed on the data (open histogram) are the background, computed from control samples of the processes described above (dark solid histogram) and our best fit signal to mass templates for B_c final states (light solid histogram). A likelihood fit to these distributions yields a total of $20.4_{-5.5}^{+6.2}$ candidate B_c meson decays. We use a statistics simula-

tion to study how often the predicted background could have fluctuated to give such a signal. After generating 350,000 pseudo experiments none had fluctuated above 20.4 candidates. An extrapolation of nearby fluctuations predicts that we have a probability of less than one in 1.5 million to have observed 20.4 candidates as a result of a fluctuation. We vary the mass used to generate the B_c fitting templates and find that our data prefers a mass of $m_{B_c} = 6.4 \pm 0.4(stat.) \pm 0.1(sys.) \text{ GeV}/c^2$. The relatively poor statistical precision, relative to other mass measurements made by CDF, results from the spread in observed masses due to the partial reconstruction of the final state.

2.2. The B_c Meson Lifetime

We also study the lifetime associated with the signal we observe. We fit the observed flight distance distribution (shown in Fig. 3) for two components. The first, shown by the dashed line, is a prediction for our sample background. This has two components, a prompt piece from J/ψ mesons associated with fake extra leptons and a long lived tail, associated with the light B meson background. The shaded distribution is the result of an exponential decay length distribution smeared by our flight distance resolution. The proper decay length returned from the fit to this distribution is $c\tau = 137_{-49}^{+53} \mu\text{m}$. From this we infer a B_c meson lifetime of $0.46 \pm 0.16(stat.) \pm 0.03(sys.) \text{ ps}$, thus favouring the hypothesis that the c quark decays first and quasi-independently of the b quark.

2.3. Summary of B_c Results

To quantify the production rate of B_c mesons we compute the ratio: $\frac{\mathcal{R} = \sigma(B_c) \cdot \mathcal{B}(B_c \rightarrow J/\psi l\nu)}{\sigma(B) \cdot \mathcal{B}(B \rightarrow J/\psi K)}$. In measuring this ratio our J/ψ trigger and reconstruction efficiency as well as our luminosity determination cancel. Similarly, in predicting this ratio the theoretical uncertainty on the b quark production cross-section at the Tevatron also cancels. Figure 4 shows a prediction for \mathcal{R} as a function of the B_c meson lifetime. Our data, represented by the point and cross, is in reasonable agreement with a relatively simple theory [3].

We also compare our measurement of \mathcal{R} with previous limits. Table 1 shows these comparisons.

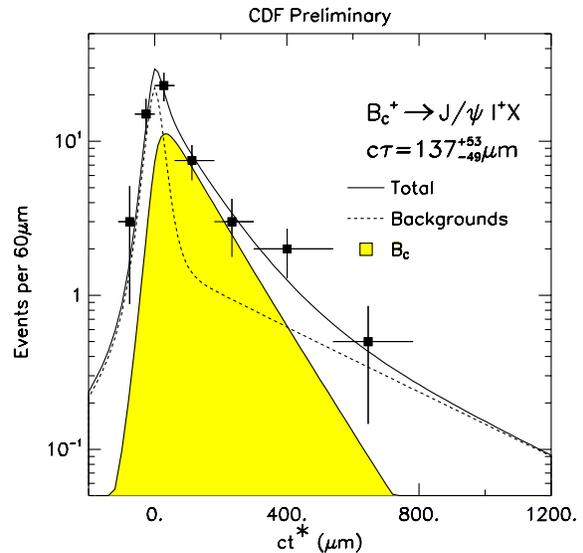


Figure 3. Pseudo decay length distribution for our B_c candidate sample. The dashed curve shows our two-component background distribution and the solid area represents the exponential decay length distribution of the B_c signal. The solid line is the sum of the two representing our best fit to the data.

We see that our observation is consistent with previous limits. However we also see how close the LEP experiments were to actually observing these decays before they stopped collecting data at the Z^0 resonance.

3. B Meson Decays to $\psi(2S)$

The huge production cross section for b quarks has also allowed us to accumulate sizeable samples of less exotic, but no less rare, B meson decays. In particular we have studied B meson final states involving $\psi(2S)$ mesons. We reconstruct the $\psi(2S)$ mesons that decay directly into $\mu^+ \mu^-$ as well as those that cascade into $J/\psi \pi^+ \pi^-$. In this way we accumulate a sample of 10,000 inclu-

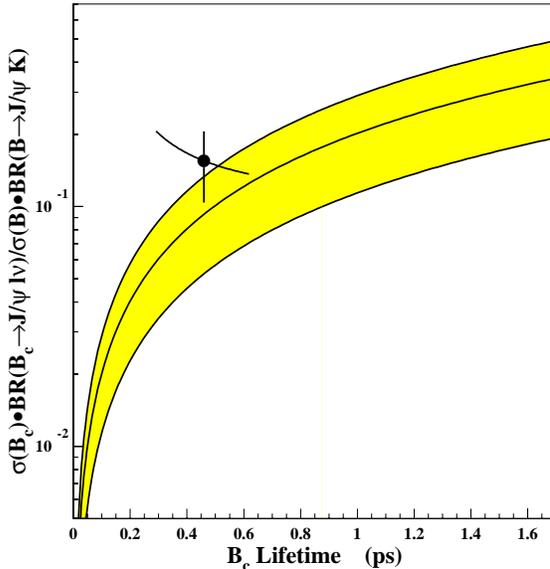


Figure 4. Comparison of CDF result with prediction of simple fragmentation theory [3]. The band represents uncertainties in the prediction of the model, while the dot with error bars shows the CDF measurement.

sive $\psi(2S)$ candidates. To these we associate either a K^+ or K^{*0} candidate and fully reconstruct 158 B meson candidates in four different modes. Our signals (see [4] for details) have S/\sqrt{B} in excess of 2 in all cases and statistical significances in excess of 4σ in all but one channel. By measuring the rate of these rare final states, relative to normalisation samples of $J/\psi K^+$ and $J/\psi K^{*0}$ we make the world’s most precise determinations of the branching fractions of B mesons into final states containing a $\psi(2S)$ meson (see Fig. 5).

4. Limits on Rare B Meson Decay Modes

Our sample is also the ideal place to search for ultra-rare B meson final states. Fully reconstructed final states such as $\mu^+\mu^-$ are forbidden, at tree level, in the standard model. Radiative correction calculations predict that these

Table 1

Comparison of CDF result for B_c production rate and limits from other experiments.

Experiment	Mode	\mathcal{R}
DELPHI	$J/\psi \pi$	≤ 0.9 to 0.7
	$J/\psi l$	≤ 0.5 to 0.4
	$J/\psi \pi \pi \pi$	≤ 1.5
OPAL	$J/\psi \pi$	≤ 0.6
	$J/\psi a_1$	≤ 0.3
	$J/\psi l$	≤ 0.4
ALEPH	$J/\psi \pi$	≤ 0.2
	$J/\psi l$	≤ 0.3
CDF (old)	$J/\psi \pi$	≤ 0.15 to 0.04
CDF (new)	$J/\psi l \nu$	0.14 ± 0.04

final states should have branching fractions of less than 10^{-10} . Similarly, states such as $\mu^+\mu^-K$ are only expected, within the confines of the standard model, at branching fractions of $O(10^{-6})$. Finally, B meson final states containing combinations such as $e^+\mu^-$ are forbidden altogether by a standard model with massless neutrinos. A significant rate for these last decays could indicate new physics beyond the standard model such as Pati-Salam leptoquarks that couple the first and second families of leptons. Although we are not currently sensitive to any of these decays we expect to see decays of the type $\mu^+\mu^-K^{(*)}$ during the next run of CDF. Table 2 summarises the limits we set on the branching fractions of the various decay modes. While the first two are published [5] the rest are in the process of publication.

5. Summary

The CDF experiment at the Tevatron collider has searched through a large sample of B meson decays. We have found evidence for the existence of the B_c meson and have made a first

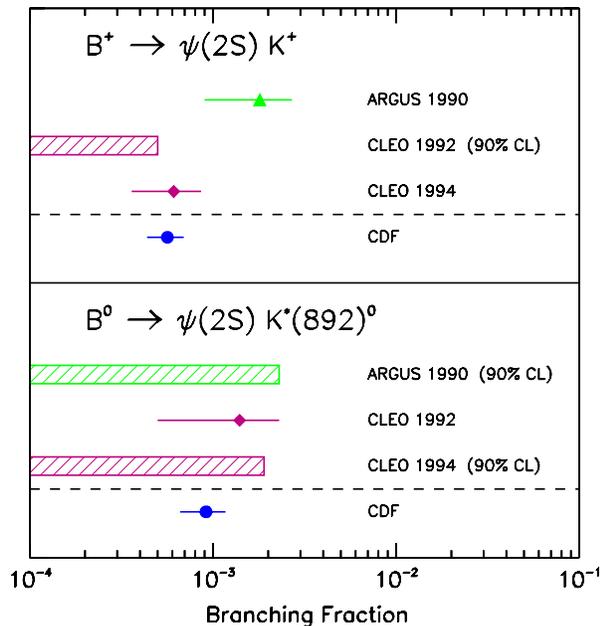


Figure 5. A summary of the B meson branching fractions to $\psi(2S)$ final states with a comparison to other measurements.

determination of its mass and lifetime. We have studied several other decay modes with branching fractions below 10^{-3} , including those involving $\psi(2S)$ mesons in the final state. We have searched for ultra-rare processes involving only pairs of charged leptons in the final state and have set limits below 10^{-5} for several modes. In the upcoming run CDF-II will collect 20 times more data (see [6]) which will allow us to pursue all of these channels further and to observe some of the ultra-rare decays.

Table 2

Limits on rare B meson decay final states. Those with an asterisk (*) are still preliminary.

Channel	B	limit
$B^0 \rightarrow \mu^+ \mu^-$	8.6×10^{-7}	95% CL
$B_s^0 \rightarrow \mu^+ \mu^-$	2.6×10^{-6}	95% CL
$B^0 \rightarrow e^+ \mu^-$ or $\mu^+ e^-$	4.4×10^{-6}	95% CL*
$B_s^0 \rightarrow e^+ \mu^-$ or $\mu^+ e^-$	2.3×10^{-5}	95% CL*
$B^+ \rightarrow K^+ \mu^+ \mu^-$	5.4×10^{-6}	90% CL*
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$	4.1×10^{-6}	90% CL*

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