B_c and Excited B States — A Tevatron Review

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1. INTRODUCTION

In this paper recent results from the CDF and DØ experiments on heavy flavor spectroscopy are reported. Both experiments are using up to 1.1 fb\textsuperscript{-1} of data delivered by the Tevatron proton-antiproton collider at the Fermi National Accelerator Laboratory, Batavia, IL, USA. The CDF and DØ detectors are described in references [1,2].

2. PROPERTIES OF THE B_c

Although discovered in 1998 by CDF [3], the properties of the B_c remain poorly measured due to small samples of candidates available until recently. In Run II of the Tevatron, CDF and DØ experiments have accumulated enough data to study the B_c in greater detail. Being the last discovered ground state of the B meson and the only meson with two heavy quarks of different flavor, the B_c is a great laboratory for potential models, HQET, and lattice QCD. Its mass, lifetime, decay properties, and production are all of interest as many precise predictions have been made by theorists.

At the Tevatron, the B_c is reconstructed in several decay channels containing a J/\psi meson. It is seen in the semileptonic modes B_c \rightarrow J/\psi e\nu X by CDF and in B_c \rightarrow J/\psi \mu\nu X by DØ, as well as in the hadronic mode B_c \rightarrow J/\psi \pi by CDF. The signal significance in all cases is over 5\sigma. The semileptonic decays are used to determine the proper decay time of the B_c [12]:

CDF: \( \tau_{B_c} = 0.474^{+0.073}_{-0.066} \pm 0.033 \) ps

DØ: \( \tau_{B_c} = 0.448^{+0.123}_{-0.096} \pm 0.121 \) ps

Note, that only a fraction of available data is used by both experiments (CDF analyzed 360 pb\textsuperscript{-1} and DØ 210 pb\textsuperscript{-1}), so significant improvements of the measurements are expected in near future. The measured values agree well with the theoretical prediction of 0.55 \pm 0.15 ps found in [6].

The hadronic mode B_c \rightarrow J/\psi \pi using the full data sample of 1.1 fb\textsuperscript{-1} yields the best mass measurement so far [7]. The selection criteria were tuned on the control sample B \rightarrow J/\psi K to give a large signal while keeping the background low in order to improve the possibility of a significant B_c observation. The J/\psi \rightarrow \mu^+\mu^- candidates were formed using muon quality criteria and requiring the dimuon mass to be within 70 MeV/c\textsuperscript{2} of the world average J/\psi mass. The transverse momentum of the third track and of the B_c candidate is used to determine the proper decay time of the B_c [12].

The lifetime (c\tau) of the B_c candidate needs to be positively displaced and have its uncertainty determined with good precision. A good fit of the combined vertex and of the J/\psi mass constrained fit is required. The B candidate has to point to the primary vertex both in terms of a pointing angle and in terms of having a small impact parameter significance. For the third track, we require the impact parameter with respect to a secondary vertex determined by the J/\psi \rightarrow \mu^+\mu^- candidate to be small and the impact parameter significance with respect to the primary vertex to be large.
The selection criteria are tuned for a standard selection and a high-$p_T$ selection. Both samples combined yield 11300 $B \rightarrow J/\psi K$ candidates with a small background of 250 events in the region between 5.4 and 5.5 GeV/$c^2$. After fixing the selection criteria, the only change is the assignment of a $\pi$ versus $K$ mass hypothesis for the third track that is combined with the $J/\psi$. Figure 1 shows the number of $B_c$ candidates growing as a function of including additional integrated luminosity. The top of Fig. 2 depicts a binned fit using a linear background and a Gaussian signal shape for the $B_c$ data. The $J/\psi\pi$ mass distribution with the linear background subtracted is shown (bottom) along with the number of events above background, $N(B_c)$ and the background in the 60 MeV/$c^2$ region between 6.245 and 6.305 GeV/$c^2$. In both cases the signal significance exceeds 6$\sigma$, which has been confirmed by a toy Monte Carlo study.

The mass of the $B_c$ meson is determined by an unbinned log likelihood fit to a linear background and a Gaussian signal where the signal fraction, the background slope, and a scale factor for each event’s mass resolution are fit parameters in addition to the mass. The scale factor for each event’s mass resolution is fixed to 1.56 which is found from an unbinned log likelihood fit for the $B \rightarrow J/\psi K$ decay. The fit gives a mass of $m(B_c) = 6276.5 \pm 4.0 \pm 2.7$ MeV/$c^2$, which agrees well with the binned fit. The systematic error includes uncertainties from the detector calibration, the tracking, and the small statistics.
fit procedure, which is the dominant contribution. This result can be compared to the recent prediction using lattice QCD calculations: \( m(B_c) = 6304 \pm 12^{+15}_{-9} \) MeV/c\(^2\) \[^8\].

3. EXCITED \( B \) STATES

The spectroscopy of the \( \bar{b}q \) system, where \( q \) is either a \( u \) or \( d \) quark, is well understood theoretically. The HQET describes a heavy-light state and predicts that there are four P-wave states, collectively called \( B^{**} \) or \( B_J \). It is expected that two of them, \( B_0^* \) and \( B_1^* \), are wide states as they decay via S-wave. The other two states, \( B_1 \) and \( B_2^* \), are narrow because they decay via D-wave. The quantitative understanding is not nearly as good. Few experimental data are available on \( B^{**} \) properties. However, since recently we are starting to see progress in this area. Both CDF and DO seek to observe and measure the two of the \( B^{**} \) that have a narrow width, expected to be of the order of 10 MeV/c\(^2\). The other two P-wave states are ignored, as they are so wide that distinguishing them from combinatorial background is nearly impossible with the available data. \( B_1 \) decays only to \( B^+\pi^-\), while \( B_2^* \) can decay to either \( B^{++}\pi^- \) or the ground state \( B^+\pi^- \).

The DO experiment searches for all three decays of the narrow states mentioned above \[^9\]. The final state \( B^+\pi^- \) is reconstructed from \( B^+ \to J/\psi K^+ \) where the \( J/\psi \) is found in the muon channel. The photon coming from the decay of the excited state \( B^{++} \to B^+\gamma \) is ignored. This leads to a shifted position of the mass peak for \( B_1 \to B^{++}\pi^- \) and \( B_2^* \to B^{++}\pi^- \). The mass difference \( m(B\pi) - m(B) \) for the \( B^+\pi^- \) candidates is shown in Fig. 3 \[^3\]. This is the first observation of separate peaks for the narrow \( B^{**} \) states.

DO proceeds to fit this mass spectrum, assuming that the widths of the two narrow resonances are the same and fixing the mass difference between the \( B^+ \) and \( B^{++} \) to 45.78 MeV/c\(^2\) \[^10\]. The fit returns the masses and the width of these states:

\[
m(B_1) = 5720.8 \pm 2.5 \pm 5.3 \text{ MeV/c}^2
\]

\[
m(B_2^*) - m(B_1) = 25.2 \pm 3.0 \pm 1.1 \text{ MeV/c}^2
\]

\[
\Gamma(B_1) = \Gamma(B_2^*) = 6.6 \pm 5.3 \pm 4.2 \text{ MeV/c}^2
\]

DO also reports the production rates for these resonances:

\[
\frac{\mathcal{B}(B_2^* \to B^{+}\pi)}{\mathcal{B}(B_2^* \to B^{*(0)}\pi)} = 0.513 \pm 0.092 \pm 0.115
\]

\[
\frac{\mathcal{B}(B_1 \to B^{++}\pi)}{\mathcal{B}(B^{**} \to B^{*(0)}\pi)} = 0.545 \pm 0.064 \pm 0.071
\]

\[
\frac{\mathcal{B}(b \to B^{**} \to B\pi)}{\mathcal{B}(b \to B^+)} = 0.165 \pm 0.024 \pm 0.028
\]

The CDF experiment performs a similar analysis \[^11\]. The same three decays of the \( B_1 \) and \( B_2^* \) are the subject of the measurement. The CDF sample of \( B^+ \) contains two signatures: \( B^+ \to J/\psi K^+ \) and \( B^+ \to D^0\pi^+ \). The combined yield on 374 pb\(^{-1}\) of data is about 4000 signal candidates. The mass difference \( m(B\pi) - m(B) - m(\pi) \) for the reconstructed \( B^{**} \) candidates is shown in Fig. 3 \[^4\]. The fit of the mass spectrum is performed with the widths of both \( B_1 \) and \( B_2^* \) fixed to the theoretical expectation \( \Gamma = 16 \pm 6 \) MeV/c\(^2\) \[^12\], and the ratio \( \mathcal{B}(B_2^* \to B\pi)/\mathcal{B}(B_2^* \to B^{**}\pi) \) is assumed to be \( 1.1 \pm 0.3 \) \[^13\]. The result of the fit yields two mass measurements for \( B_1 \) and \( B_2^* \).
which are not separated as in the case of DØ:

\[
m(B_1) = 5734 \pm 3 \pm 2 \text{ MeV}/c^2
\]
\[
m(B_2) = 5738 \pm 5 \pm 1 \text{ MeV}/c^2
\]

4. EXCITED $B_s^0$ STATES

The heavy-light system $\bar{b}s$ is similar in its behavior to the $\bar{b}d$ systems. As well, the HQET predicts two narrow and two wide $B_{s}^{*+}$ states. These are even more difficult to study because of the lower production rates of $B_{s}^{0}$ mesons in comparison to the more common $B^0$ and $B^+$. Due to the isospin conservation, the decay of $B_{s}^{**} \rightarrow B_{s}^{0}\pi^-$ is highly suppressed. Thus the decay $B_{s}^{**} \rightarrow B^{+}K^-$ is used.

DØ uses the same $B^+$ data sample as for the $B^{**}$ measurement. The invariant mass difference $m(BK) - m(B) - m(K)$ is shown in Fig. 5. A clear peak is observed with a significance in excess of 6σ. This peak is attributed to the process $B_{s2}^{*} \rightarrow B^+K^-$. Thus, the mass of $B_{s2}^{*}$ is $m(B_{s2}^{*}) = 5839.1 \pm 1.4 \pm 1.5 \text{ MeV}/c^2$.

CDF looks at the decays $B^+ \rightarrow J/\psi K^+$ and $B^+ \bar{D}^0\pi^+$ in 1.0 fb$^{-1}$ of data. A total of 58k signal candidates are reconstructed using the decays $J/\psi \rightarrow \mu^+\mu^-$ and $\bar{D}^0 \rightarrow K^+\pi^-$. The invariant mass difference $m(BK) - m(B) - m(K)$ shown in Fig. 6 has 2 distinct peaks. Both peaks have a significance in excess of 6σ. Assigning the two peaks to the decays $B_{s1} \rightarrow B^{*+}K^-$ and $B_{s2}^{*} \rightarrow B^{+}K^-$, one finds:

\[
m(B_{s1}) = 5829.4 \pm 0.2 \pm 0.6 \text{ MeV}/c^2
\]
\[
m(B_{s2}^{*}) = 5839.6 \pm 0.4 \pm 0.5 \text{ MeV}/c^2
\]

This corresponds to a mass difference $m(B_{s2}^{*}) - m(B_{s1}) = 10.20 \pm 0.44 \pm 0.35 \text{ MeV}/c^2$.

It is interesting to note that the masses for $B_1$ and $B_{s2}^{*}$ found by CDF and DØ agree. The mass difference in the $\bar{b}d$ and $\bar{b}s$ systems is expected to be very similar. This is indeed the case for the measurements done by CDF, albeit with large uncertainties. However, the mass difference $\Delta m \equiv m(B_{s2}^{*}) - m(B_1) = 25.2 \pm 3.0 \pm 1.1 \text{ MeV}/c^2$ as measured by DØ is significantly different from the ones found by CDF. Assuming the $\Delta m$ together with the $B_{s2}^{*}$ mass measured by DØ, the $B_{s1}$ mass would be around 5814 MeV/c$^2$. Thus, the mass would be too low for the decay $B_{s1} \rightarrow B^{*+}K^-$, which would explain the absence of the second peak in the invariant mass difference $m(BK) - m(B) - m(K)$ (Fig. 5). This puzzle will hopefully be resolved in the future when analyses using higher statistics become available.

5. CONCLUSIONS

With over 1 fb$^{-1}$ of data, many exciting results on heavy flavor physics are presently coming from the Tevatron experiments. In this paper we have seen interesting results on heavy flavor spectroscopy. The $B_c$ mass and lifetime is measured and agrees with the theoretical predictions. The excited states $B^{**}$ and $B_{s}^{*+}$ offer an interesting laboratory to experimentally verify our understanding of quark interaction in bound states and to foster further development of non-perturbative QCD. Overall, it is good time for flavor physics at the Tevatron as we are on the way to collecting multi-fb$^{-1}$ of data.
Figure 4. Invariant mass difference for the $B^{**}$ candidates in the analysis from CDF. The fit shows the result of the simultaneous unbinned likelihood fit to the $B^{**}$ mass difference of the two samples $B^+ \rightarrow J/\psi K^+$ and $B^+ \rightarrow D^0 \pi^+$. 

Figure 6. The mass difference $m(BK) - m(B) - m(K)$ as measured by CDF. The line correspond to the projection of the unbinned maximum likelihood fit using both channels $B^+ \rightarrow J/\psi K^+$ and $B^+ \rightarrow D^0 \pi^+$ added together.

REFERENCES

1. F. Abe et al., CDF collaboration, Nucl. Instr. and Meth. A271 (1988) 387.
2. V. M. Abazov et al., DØ collaboration, Nucl. Instr. and Meth. A565 (2006) 463.
3. F. Abe et al., CDF collaboration, Phys. Rev. Lett. 81 (1998) 2432.
4. A. Abulencia et al., DØ collaboration, Phys. Rev. Lett. 97 (2006) 012002.
5. DØ collaboration, DØ public note 4539-CONF (2004).
6. V. V. Kiselev, hep-ph/0308214 (2003).
7. CDF collaboration, CDF public note 8004 (2006).
8. I. F. Allison et al., Phys. Rev. Lett. 94 (2005) 172001.
9. DØ collaboration (2006), DØ public note 5026-CONF.
10. S. Eidelman et al., Phys. Lett. B592 (2004) 1.
11. CDF collaboration, CDF public note 7938 (2005).
12. A. F. Falk and T. Mehen, Phys. Rev. D53 (1996) 231.
13. DELPHI collaboration, DELPHI 2004-025 CONF 700 (2004).
14. DØ collaboration, DØ public note 5027-CONF (2006).