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# THE LAST MESON

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We describe the observation of the $B_c$ meson through its semileptonic decays, $B_c \to J/\psi\ell\nu$, and the measurements of the $B_c$ mass, lifetime and production rate in the CDF detector at Fermilab. We also present estimates for $B_c$ production and decay into other final states in the forthcoming run of the upgraded CDF and Tevatron.

The discovery of all possible quark-antiquark combinations, i.e. the conventional mesons, occupied a time-span of a half-century. The charged $\pi$-meson and the K-meson were first observed 1947. Over the next two decades, a large number of mesonic states were added to the list until it was demonstrated[1] that the quarks proposed by Gell-Mann and Zweig[2] were real. All mesons observed until that time were ground states or excitations of the known $q\overline{q}$ combinations of $u$, $d$ and $s$. Three new quarks, the $c$, $b$ and $t$, were discovered from 1974 to 1995. The $c$ and $b$ quarks have lifetimes of order picoseconds and are able to form mesons, but the $t$ decays before it can combine with an anti-quark to form a meson. Thus, five quarks (and antiquarks) are available to form mesons, and there are just fifteen such combinations as shown in Fig. 1. The observation of the $B_c$ in 1998 provided the final entry in this chart.

The excitations of $c\overline{c}$ and $b\overline{b}$ states have been described rather successfully by potential models. Similar models, using the same quark masses,[3] have been proposed for the $B_c$ and its excited states. One example is shown in Fig. 2. These give a variety of predictions for the mass, $M(B_c)$ from 6.2 GeV/c$^2$ to 6.4 GeV/c$^2$.

It is expected that hadro-production of $B_c$ will be dominated by the gluon-gluon interaction which has 36 Feynman diagrams to order $\alpha^4$. Calculations assume the pseudoscalar decay constant in the bound-state vertex to be $f(B_c) \approx 500$ MeV.[4] The fragmentation probability for $b \to B_c$ is estimated to be $(1.3 \text{ to } 1.5)\times 10^{-5}$. The corresponding probability for $b \to B^+$ is $0.378 \pm 0.022$.

In order to compute the decay probability, we assume three main processes

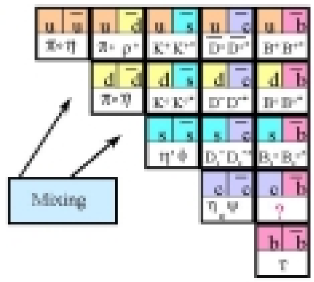


Figure 1. The fifteen possible $q\overline{q}$ states.

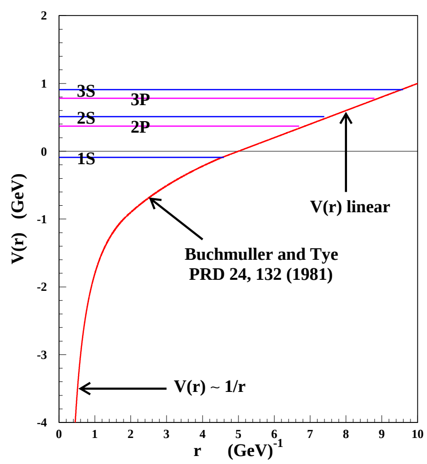


Figure 2. The potential model of Buchmuller and Tye showing the ground state and several excited states for $B_c$. This model uses $m_c = 1.48$ GeV/c$^2$ and $m_b = 4.88$ GeV/c$^2$

which do not interfere, yielding a total width: $\Gamma = \Gamma_c + \Gamma_b + \Gamma_a$, where $\Gamma_c$ represents diagrams involving $c \rightarrow sW$, $\Gamma_b$ represents $\overline{b} \rightarrow \overline{c}W$ and $\Gamma_a$ represents the annihilation process $\overline{b}c \rightarrow W$. We expect $\Gamma_c$ to dominate and this yields lifetime estimates ranging from 0.4 ps to 1.4 ps.[5,6]

We used data from the Collider Detector at Fermilab (CDF) to look for $B_c$ production in 1.8 TeV $p\overline{p}$ collisions in 110 pb$^{-1}$ of data collected during the runs of 1991-1996. Detailed results of our successful search for the $B_c$ have been published,[7] and we give a summary here. We directed our efforts toward the decay processes $B_c \to J\psi\mu\nu$ and $B_c \to J\psi e\nu$, and we searched for events containing a secondary vertex formed by $J\psi\mu$ or $J\psi e$ with $J\psi \to \mu^+\mu^-$, i.e. three leptons. A Monte Carlo calculation of $B_c$ production and decay to $J/\psi\ell\nu$ showed that, for an assumed $B_c$ mass of 6.27 GeV/$c^2$, 93% of the $J/\psi\ell$ final state particles would have $J/\psi\ell$ masses with $4.0 < M(J/\psi\ell) < 6.0$ GeV/$c^2$. This was our "signal region", but we accepted candidates with $M(J/\psi\ell)$ between 3.35 and 11 GeV/$c^2$.

These events have a very simple topology: a decay point for $J/\psi \to \mu^+\mu^-$ displaced from the primary interaction point (Fig. 3) and a third track emerging from the same decay point. This $J/\psi+$ track sample included $B_c \to J\psi\mu\nu$,

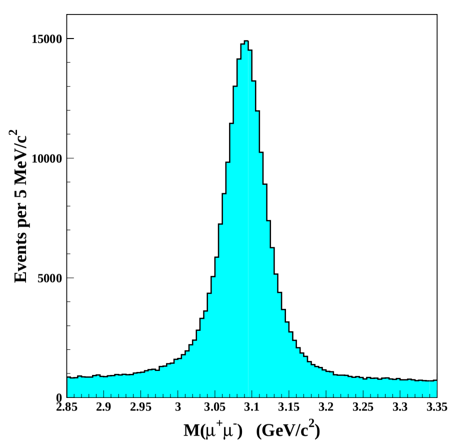


Figure 3. The mass spectrum for $\mu^+\mu^-$. Such events with a vertex displaced from the primary interaction position were the starting point in the search for $B_c$.

$B_c \to J\psi e\nu$ and background from various sources. One background process, $B^\pm \to J\psi K^\pm$, was easily reconstructed (Fig. 4), cut from the candidate sample and used for normalization. For the remaining $B_c$ candidates, we subjected the three tracks to a fit that constrained the two muons to the $J/\psi$ mass and that constrained all three tracks to originate from a common point.

Electrons were identified by the association of a charged-particle track with $p_T > 2$ GeV/c and an electromagnetic shower in the calorimeter. Muons from $J/\psi$ decay were identified by matching a charged-particle track with $p_T > 2$ GeV/c to a track segment in muon drift chambers outside the calorime-

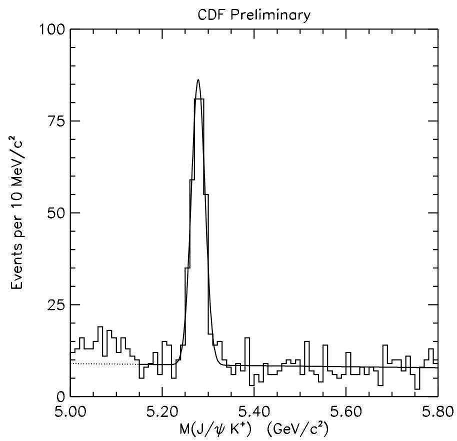


Figure 4. The mass spectrum for $J/\psi K^{\pm}$ which were cut from the data in the search for the $B_c$, and used to normalize the $B_c$ production rate. The fitted peak contains $290 \pm 19$ events and is centered at 5.279 GeV/c$^2$ with an r.m.s. width of 14 MeV/$c^2$. Events within 50 MeV of this peak were eliminated from the search for $B_c$.

ters. The third muon was required to have $p_T > 3$ GeV/c and pass through additional absorber. We found 23 $B_c \to J\psi e\nu$ candidates, of which 19 were in the signal region, and 14 $B_c \to J\psi\mu\nu$ candidates, of which 12 were in the signal region.

Significant contributions to backgrounds come from misidentification of hadron tracks as leptons and from random combinations of real leptons with $J/\psi$. These are discussed in detail in Ref. 7 The procedure for determining the amount of each source of background was checked by applying it to an independent data sample where the background could be determined experimentally.

Table 1 summarizes the results of the background calculation and of a simultaneous fit for the mass spectrum over the region between 3.35 and 11 GeV/c$^2$. Figure 5 presents the mass spectra for the combined $J/\psi e$ and $J/\psi\mu$ candidate samples, the combined backgrounds and the fitted contribution from $B_c \to J\psi\ell\nu$. The fitted number of $B_c$ events is $20.4^{+6.2}_{-5.5}$.

To test the stability of the result, we generated Monte Carlo signal templates for various assumed $B_c$ masses. The size of the signal was stable over the range of theoretical predictions, and this gave us measurement of the mass, $M(B_c) = 6.40 \pm 0.39(\text{stat.}) \pm 0.13(\text{syst.})$ GeV/c$^2$.

Table 1. $B_c$ Signal and Background Summary

| | $3.25 < M(J/\psi\ell) < 11.0$ GeV/c$^2$ | |
|---|---|---|
| | $J/\psi e$ Events | $J/\psi\mu$ Events |
| False Electrons | 4.2±0.4 | |
| Undetected Conversions | 2.1±1.7 | |
| False Muons | | 11.4±2.4 |
| $B\overline{B}$ Background | 2.3±0.9 | 1.44±0.25 |
| Total Background (predicted) | 8.6±2.0 | 12.8±2.4 |
| (from fit) | 9.2±2.0 | 10.6±2.3 |
| Predicted $\frac{N(B_c\to J/\psi e\nu)}{N(B_c\to J/\psi\mu\nu)}$ | $0.58 \pm 0.04$ | |
| $e$ and $\mu$ Signal (derived from fit) | $12.0\pm^{+3.8}_{-3.2}$ | $8.4\pm^{+2.7}_{-2.4}$ |
| Total Signal (fitted parameter) | $20.4^{+6.2}_{-5.5}$ | |
| Signal + Background[a] | 21.2±4.3 | 19.0±3.5 |
| Candidates | 23 | 14 |
| P(null)[b] | $0.63 \times 10^{-6}$ | |

[a] The total number of fitted events was not constrained to be equal to the number of candidates.

[b] Probability that background alone can fluctuate to produce an apparent signal of 20.4 events or more, based on simulation of statistical fluctuations.

Figure 6 shows distribution in $ct^*$, which is related to the proper time for $B_c$. For this study, we relaxed the cut of flight path to include events around the primary production vertex. Through a procedure described in detail in Ref. 7 we were able to determine the $B_c$ lifetime to be

$$c\tau = 137^{+53}_{-49}(\text{stat.}) \pm 9(\text{syst.})\mu m \quad (1)$$

$$\tau = 0.46^{+0.18}_{-0.16}(\text{stat.}) \pm 0.03(\text{syst.})ps \quad (2)$$

$$(3)$$

From the 20.4 $B_c$ events and the 290 $B^{\pm} \to J\psi K^{\pm}$ events, we calculated the ratio for production cross section times branching fraction for these two processes. We find

$$\frac{\sigma(B_c)\dot{B}R(B_c \to J/\psi\ell\nu)}{\sigma(B)\dot{B}R(B \to J/\psi K)} = 0.132^{+0.041}_{-0.037}(\text{stat.}) \pm 0.031(\text{syst.})^{+0.032}_{0.020}(\text{lifetime}), \quad (4)$$

for $B_c$ and $B^{\pm}$ with transverse momenta $p_T > 6.0$ GeV/c and rapidities $|y| < 1.0$. This result is consistent with previous searches.[8] Figure 7 compares

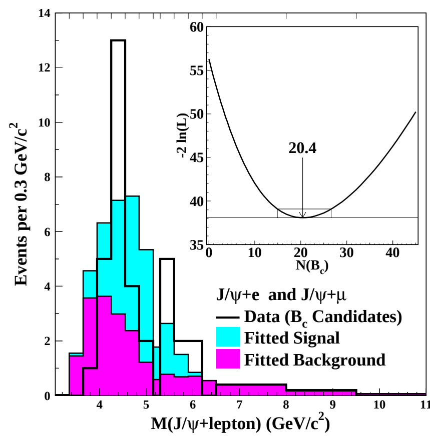


Figure 5. Histogram of the $J/\psi\ell$ mass that compares the signal and background contributions determined in the likelihood fit to the combined data for $J/\psi\mu$ and $J\psi e$. Note that the mass bins vary in width. The total $B_c$ contribution is $20.4^{+6.2}_{-5.5}$ events. The inset shows the behavior of the log-likelihood function vs. the number of $B_c$ mesons.

phenomenological predictions with our measurements of $c\tau$ and this branching fraction. Within experimental and theoretical uncertainties,[5,9] they are consistent.

What are the prospects for further studies of the $B_c$ in Run 2 of CDF which is scheduled to start in March, 2001? This has been studied by my collaborators, Vaia Papadimitriou and Wei Hao. Run 2 will have a factor of twenty higher luminosity, 3-dimensional micro-vertex tracking covering the full interaction region ( $\times 1.4$ acceptance), and lower energy thresholds yielding another factor of 1.4 in acceptance. Overall, we expect a factor of 40 greater acceptance for $B_c$ and enhanced ability to reject backgrounds. In Ref. [10] there are estimates of a variety of decay branching fractions for $B_c$, including the semileptonic modes measured above and a variety of fully hadronic modes with all charged particles in the final state. Any of the latter would allow a precise measurement of the $B_c$ mass.

One of the most promising decay modes is $B_c^{\pm} \to J/\psi\pi^{\pm}$ which is estimated to have a decay rate about a factor of ten lower than either of the two modes discussed above. Monte Carlo calculations for the CDF detector suggest that the mass peak for this process would have an r.m.s. width of

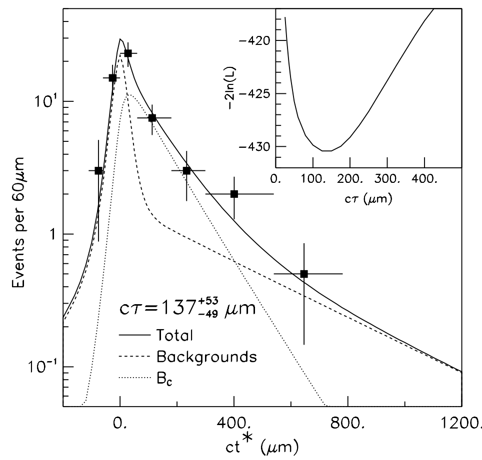


Figure 6. The distribution in $ct*$ for the combined $J/\psi\mu$ and $J\psi e$ data along with the fitted curve and contributions to it from signal and background. The inset shows the log-likelihood function vs. $c\tau$ for the $B_c$.

about 17 MeV with the Run 1 detector. We searched for a $B_c$ signal in this and other decay channels in the Run 1 data, but were unable to extract a definitive result above backgrounds. The higher luminosity of Run 2 should produce a much higher yield of such events, and the 3-D tracking should reduce backgrounds. We expect to be able to obtain a measurement of the $B_c$ mass to an accuracy at least an order of magnitude better than that reported above for the semileptonic decays. In addition, we should have hundreds of semileptonic decays with more precise tracking which should yield greatly improved measurements of the $B_c$ lifetime.

A number of you who have worked with potential model calculations of the excited states of $B_c$ have asked me about the possibility of measuring the masses of $B_c^*$ states such as those shown if Fig. 2. I am not optimistic about our ability to do this because decays such as $B_c^* \to B_c\pi^+\pi^-$ happen at the primary interaction vertex where large numbers of other pions are produced. These yield a large combinatoric background, which make it difficult to isolate a signal. Nevertheless, I suspect that we will search for such states, and if we are succesful it will certainly place strong constraints on the various potential models.

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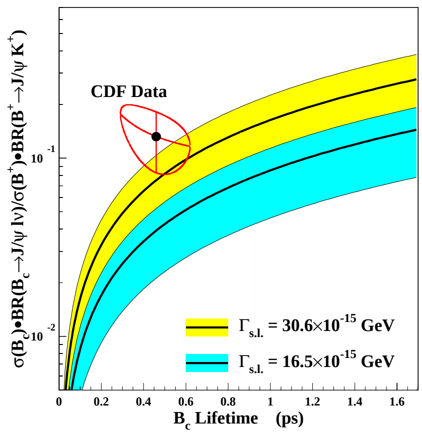


Figure 7. The point with 1-standard-deviation contour shows our measured value of the $\sigma BR$ ratio plotted at the value we measured for the $B_c$ lifetime. The shaded region represents theoretical predictions and their uncertainty corridors for two diferent values of the semileptonic width $\Gamma_{s.l.} = \Gamma(B_c \to J/\psi \ell \nu)$ based on Refs. 4 and 9.

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