Observation of the B_c Meson in $p\overline{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We have observed bottom-charm mesons via the decay mode $B_c^\pm \to J/\psi\, \ell^\pm \nu$ in 1.8 TeV $p\overline{p}$ collisions using the CDF detector at the Fermilab Tevatron. A fit of background and signal contributions to the $J/\psi\, \ell$ mass distribution yielded $20.4^{+6.2}_{-5.5}$ events from B_c mesons. A fit to the same distribution with background alone was rejected at the level of 4.8 standard deviations. We measured the B_c^+ mass to be $6.40 \pm 0.39(\text{stat}) \pm 0.13(\text{syst})$ GeV/c^2 and the B_c^+ lifetime to be $0.46^{+0.18}_{-0.16}(\text{stat}) \pm 0.03(\text{syst})$ ps. Our measured yield (production cross section times branching ratio) for $B_c^+ \to J/\psi\, \ell^+ \nu$ relative to that for $B^+ \to J/\psi\, K^+$ is $0.132^{+0.041}_{-0.037}(\text{stat}) \pm 0.031(\text{syst})^{+0.032}_{-0.020}(\text{lifetime})$. [S0031-9007(98)07127-0]

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The B_c^+ meson is the lowest-mass bound state of a family of quarkonium states containing a charm quark and a bottom antiquark [1]. This pseudoscalar ground state has nonzero flavor and no strong or electromagnetic decays. It is the last such meson predicted by the standard model. Its weak decay is expected to yield a large branching fraction to final states containing a J/ψ [2–5]. Nonrelativistic potential models predict the c and $\overline{b}$ to be tightly bound with a mass $M(B_c)$ in the range 6.2–6.3 GeV$/c^2$ [6,7] with a rich spectroscopy of excited states.

We expect three major contributions to B_c decay: $\overline{b} \to \overline{c}W^+$ with the c as spectator and final states like $J/\psi\,\pi$ or $J/\psi\,\ell\nu$; $c \to sW^+$, with the $\overline{b}$ as spectator and final states like $B_s\pi$ or $B_s\ell\nu$; and $c\overline{b} \to W^+$ annihilation with final states like DK, $\tau\nu_\tau$, or multiple pions. Since these processes lead to different final states, their amplitudes do not interfere. The predicted lifetime is in the range 0.4–1.4 ps [2,8–12]. Because of the wide range of predictions, a B_c lifetime measurement is a test of the assumptions made in these calculations. Several authors have also calculated the B_c partial widths to semileptonic final states [2–5,13].

The production of B_c mesons has been calculated in perturbative QCD. At transverse momenta $p_T/c \gg M(B_c)$ the $\overline{b}$ is most often produced by gluon fusion in the hard collision and fragmentation provides the c [14]. At lower p_T, based on a full α_s^4 calculation [15], both the $\overline{b}$ and c quarks are produced in the hard scattering. These calculations [14–18], which vary in specific details, predict inclusive B_c production cross sections along with distributions in p_T and other kinematic variables. The results reported here are insensitive to the choice of theoretical model.

Searches at the CERN e^+e^- collider (LEP) yielded limits on B_c production [19–21] and a few candidate events [20,21]. A prior CDF search [22] placed a limit on B_c production with $B_c^+ \to J/\psi\,\pi^+$.

We report here the observation of B_c mesons produced in 1.8 TeV $p\overline{p}$ collisions at the Fermilab Tevatron collider using a 110 pb^{-1} data sample collected with the CDF detector. In a sample of trilepton events, we found an excess over expected backgrounds consistent with $B_c^+ \to J/\psi\,\mu^+\nu$ and $B_c^+ \to J/\psi\,e^+\nu$ followed by $J/\psi \to \mu^+\mu^-$. This interpretation is reinforced by measurements of mass, lifetime, and event yield which agree with theoretical expectations for B_c mesons. Reference [23] gives a more detailed description of this work.

We have describe the CDF detector elsewhere [24,25]. Its tracking system gives a transverse momentum resolution $\delta p_T/p_T = [(0.0009 \times p_T)^2 + (0.0066)^2]^{1/2}$, where p_T is in units of GeV$/c$. The average track impact parameter resolution relative to the beam axis is $[13 + (40/p_T)]$ μm in the plane transverse to the beam [26]. Events with $B_c^+ \to J/\psi\,\ell^+\nu$ have a decay point for $J/\psi \to \mu^+\mu^-$ displaced from the primary interaction point and a third track emerging from the same point. From our data, we selected J/ψ + track events with these properties. Prior to the application of lepton identification criteria to the third track, this sample included $B_c^+ \to J/\psi\,e^+\nu$, $B_c^+ \to J/\psi\,\mu^+\nu$, $B_c^+ \to J/\psi\,K^+$, and background from various sources. We subjected the three tracks to a fit that constrained the two muons to the J/ψ mass and that constrained all three tracks to originate from a common point. A calculation of B_c production and decay to $J/\psi\,\ell\nu$ showed that, for $M(B_c) = 6.27$ GeV$/c^2$, 93% of the $J/\psi\,\ell$ decays would have trilepton masses with $4.0 < M(J/\psi\,\ell) < 6.0$ GeV$/c^2$. We call this the signal region, but we accepted events with $3.35 < M(J/\psi\,\ell) < 11$ GeV$/c^2$.

A measure of the time between production and decay of a B_c is

$$ct^* \equiv \frac{M(J/\psi\,\ell) \cdot L_{xy}(J/\psi\,\ell)}{|p_T(J/\psi\,\ell)|}, \qquad (1)$$

where L_{xy} is the distance between the beam centroid and the decay point of the B_c candidate in the transverse plane and projected along the $J/\psi\,\ell$ direction, and $p_T(J/\psi\,\ell)$ is the trilepton transverse momentum. The average uncertainty in ct^* is 25 μm. To reduce backgrounds from prompt J/ψ production, we required $ct^* > 60$ μm.

$B^+ \to J/\psi\,K^+$ candidates were identified by a peak in the $\mu^+\mu^-K^+$ mass distribution centered at $M(B^+) = 5.279$ GeV$/c^2$ with a root mean square width of 14 MeV$/c^2$. (See Fig. 2 of Ref. [23].) The peak contained 290 ± 19 events after correction for background. Events within 50 MeV of $M(B^+)$ were eliminated as $B_c^+ \to J/\psi\,\ell^+\nu$ candidates.

Muons from J/ψ decay were identified by matching a charged-particle track with $p_T > 2$ GeV$/c$ to a track segment in drift chambers outside the calorimeter (5 to 9 interaction lengths thick depending on angle). The third muon was required to have $p_T > 3$ GeV$/c$ and to pass through an additional three interaction lengths of steel. Electrons were identified by a charged-particle track with $p_T > 2$ GeV$/c$ and matched with a shower in the electromagnetic calorimeter. We found 14 $B_c^+ \to J/\psi\,\mu^+\nu$ candidates of which 12 were in the signal region and 23 $B_c^+ \to J/\psi\,e^+\nu$ candidates of which 19 were in the signal region.

Significant backgrounds in the B_c candidates come from false leptons: hadrons that reach the muon detectors without being absorbed, hadrons that decay in flight into a muon in advance of entering the muon detectors, and hadrons that are falsely identified as electrons. A "conversion background" arises from e^+e^- pairs when a member of the pair remains undetected and the other accidentally intersects the J/ψ decay point. A "$B\overline{B}$" background arises when a J/ψ from B decay and a lepton from semileptonic $\overline{B}$ decay accidentally appear to originate from a common decay point. Other backgrounds [23] were found to be negligible.

As a check on the number of events and the trilepton mass distribution for the backgrounds, we verified that we

TABLE I. B_c signal and background summary.

	$3.35 < M(J/\psi\,\ell) < 11.0$ 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 $N(B_c \rightarrow J/\psi\, e\nu)/N(B_c \rightarrow J/\psi\,\ell\nu)$	0.58 ± 0.04	
e and μ signal (derived from fit)	$12.0^{+3.8}_{-3.2}$	$8.4^{+2.7}_{-2.4}$
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]	0.63×10^{-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.

are able to predict the number of events and mass distribution in an independent, background-rich sample of same-charge, low-mass lepton pairs. (See Fig. 27 in Ref. [23].) As a further check, we applied all selection criteria except the requirement that the third track intersect the J/ψ vertex. The resulting impact parameter distribution has a prominent peak at zero, demonstrating that, for most candidate events, the three tracks arise from a common vertex. (See Fig. 28 in Ref. [23].)

Table I summarizes the results of the background calculation and of a simultaneous fit for the muon and electron channels to the mass spectrum over the region between 3.35 and 11 GeV/c^2 [23]. Figure 1 shows the mass spectra for the combined $J/\psi\,e$ and $J/\psi\,\mu$ candidate samples, the combined backgrounds, and the fitted contributions from $B_c^+ \rightarrow J/\psi\,\ell^+\nu$ decay. The fitted number of B_c events is $20.4^{+6.2}_{-5.5}$.

To test the significance of this result, we generated Monte Carlo trials with the statistical properties of the backgrounds, but with no contribution from B_c mesons. These were fit to determine the apparent signal size arising solely from background fluctuations. The probability of obtaining a yield of 20.4 events or more is 0.63×10^{-6}, equivalent to a 4.8 standard-deviation effect.

To check the B_c signal stability, we varied the assumed B_c mass from 5.52 to 7.52 GeV/c^2. The signal template for each value of $M(B_c)$ and the background mass distributions were fit to the data. The magnitude of the B_c signal is stable over the range of theoretical predictions for $M(B_c)$, and the minimum in the log-likelihood function vs mass yielded $M(B_c) = 6.40 \pm 0.39(\text{stat}) \pm 0.13(\text{syst})$ GeV/c^2.

We obtained the mean proper decay length $c\tau$ and hence the lifetime τ of the B_c meson from the distribution of ct^*. We used only events with $4.0 < M(J/\psi\,\ell) < 6.0$ GeV/c^2, and we changed the decay-length requirement from $ct^* > 60$ μm to $ct^* > -100$ μm for this lifetime measurement. This yielded a sample of 71 events, 42 $J/\psi\,e$ and 29 $J/\psi\,\mu$. We fit functional forms to the shapes in ct^* for each of the backgrounds. To the sum of these we added a resolution-smeared exponential B_c-decay contribution, dependent on $c\tau$. Because of the missing neutrino, the proper decay length ct for each event differs from ct^* of Eq. (1). We convoluted the exponential in ct with the distribution of ct^*/ct derived from Monte Carlo studies. Finally, we incorporated the data from each of the candidate events in an

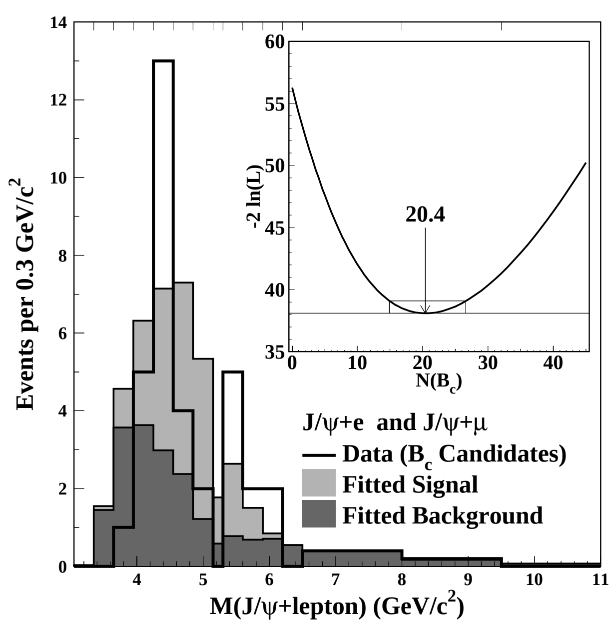

FIG. 1. Histogram of the $J/\psi\,\ell$ mass that compares the signal and background contributions determined in the likelihood fits to the combined data for $J/\psi\,e$ and $J/\psi\,\mu$. Note that the mass bins, indicated by tick marks at the top, vary in width. The total B_c contribution is $20.4^{+6.2}_{-5.5}$ events. The inset shows the behavior of the log-likelihood function $-2\ln(L)$ vs the number of B_c mesons.

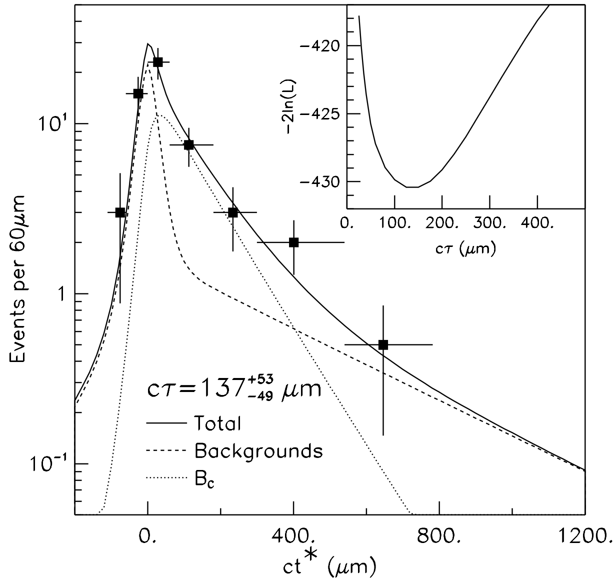

FIG. 2. The distribution in ct^* for the combined $J/\psi\,\mu$ and $J/\psi\,e$ data along with the fitted curve and contributions to it from signal and background. The inset shows the log-likelihood function vs $c\tau$ for the B_c.

unbinned likelihood fit to $c\tau$. Figure 2 shows the data and the signal and background distributions with $c\tau = 137^{+53}_{-49}(\text{stat}) \pm 9(\text{syst})\ \mu\text{m}$ and

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

From the 20.4 B_c events and the 290 $B^+ \to J/\psi\,K^+$ events, we calculated the B_c production cross section times the $B_c^+ \to J/\psi\,\ell^+\nu$ branching fraction $\sigma \times \mathcal{B}(B_c^+ \to J/\psi\,\ell^+\nu)$ relative to that for the topologically similar decay $B^+ \to J/\psi\,K^+$. Many systematic uncertainties cancel in the ratio. A combination of measurements and Monte Carlo calculations yielded the efficiencies that do not cancel. The efficiency for $B_c^+ \to J/\psi\,\ell^+\nu$ depends on $c\tau$ because of the requirement $ct^* > 60\ \mu$m, and we quote a separate systematic uncertainty due to the lifetime uncertainty. We assumed that the branching fraction is the same for $B_c^+ \to J/\psi\,e^+\nu$ and $B_c^+ \to J/\psi\,\mu^+\nu$. We multiply the 20.4 events by a factor of 0.85 ± 0.15 to correct for contributions from other B_c decay channels such as $B_c \to \psi(2S)\,\ell\nu$ [23]. We find

$$\mathcal{R}(J/\psi\,\ell\nu) \equiv \frac{\sigma(B_c) \times \mathcal{B}(B_c \to J/\psi\,\ell\nu)}{\sigma(B) \times \mathcal{B}(B \to J/\psi\,K)} = 0.132^{+0.041}_{-0.037}(\text{stat}) \pm 0.031(\text{syst})^{+0.032}_{-0.020}(\text{lifetime}), \qquad (3)$$

for B_c^+ and B^+ with transverse momenta $p_T > 6.0$ GeV/c and rapidities $|y| < 1.0$. This is consistent with previous searches [19–21]. Figure 3 compares phenomenological predictions with our measurements of $c\tau$ and $\mathcal{R}(J/\psi\,\ell\nu)$, which are consistent within experimental and theoretical uncertainties.

In conclusion, we report the observation of B_c mesons through their semileptonic decay modes, $B_c \to J/\psi\,\ell\nu$,

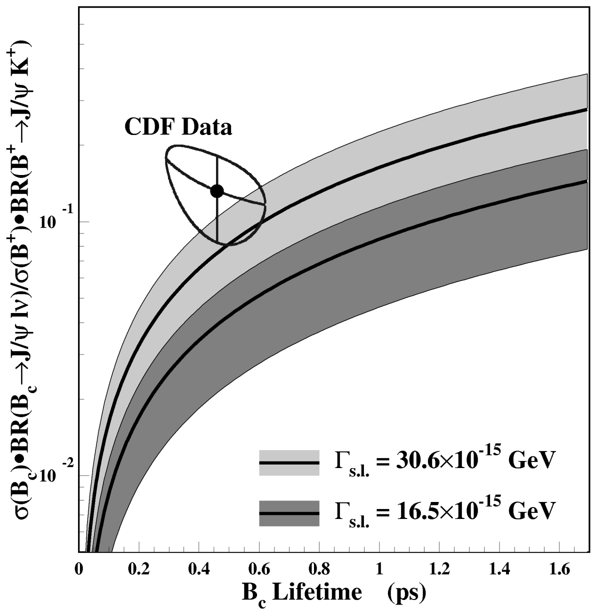

FIG. 3. The point with 1-standard-deviation contour shows our measured value of the $\sigma \times \mathcal{B}$ ratio plotted at the value we measure for the B_c lifetime. The shaded region represents theoretical predictions and their uncertainty corridors for two different values of the semileptonic width $\Gamma_{s.l.} = \Gamma(B_c \to J/\psi\,\ell\nu)$ based on Refs. [2] and [4]. The other numbers assumed in the theoretical predictions are $V_{cb} = 0.041 \pm 0.005$ [27], $\sigma(B_c^+)/\sigma(\bar{b}) = 1.3 \times 10^{-3}$ [16], $\sigma(B^+)/\sigma(\bar{b}) = 0.378 \pm 0.022$ [27], $\mathcal{B}(B^+ \to J/\psi\,K^+) = (1.01 \pm 0.14) \times 10^{-3}$ [27].

where ℓ is either an electron or a muon. We measured the B_c mass and the product of its production cross section and semileptonic branching fraction, which confirm phenomenological expectations. We measured a B_c lifetime consistent with calculations in which the decay width is dominated by the decay of the charm quark.

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*Visitor.

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