Observation of the B_c Meson in the Exclusive Decay $B_c \to J/\psi\pi$

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A fully reconstructed $B_c \to J/\psi\pi$ signal is observed with the D0 detector at the Fermilab Tevatron $p\bar{p}$ collider using 1.3 fb^{-1} of integrated luminosity. The signal consists of 54 ± 12 candidates with a significance that exceeds 5 standard deviations, and confirms earlier observations of this decay. The measured mass of the B_c meson is $6300 \pm 14(\text{stat}) \pm 5(\text{syst})\ \text{MeV}/c^2$.

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The quark model predicts the lowest-lying bound state of a bottom antiquark and a charm quark to be an isosinglet $J^P = 0^-$ pseudoscalar meson denoted as B_c. Its properties are of special interest due to its unique status as a bound state of two heavy but (unlike quarkonia) different flavor quarks. Measurements of its mass, production, and decay therefore allow for tests of theoretical models [1] under new approximation regimes or extended validity ranges beyond quarkonia.

This analysis uses data collected by the D0 detector between April 2002 and March 2006 at the Fermilab Tevatron $p\bar{p}$ collider operating at $\sqrt{s} = 1.96$ TeV. The data sample corresponds to approximately 1.3 fb^{-1} of integrated luminosity. At the Tevatron the most easily identified decay modes of the B_c have a J/ψ meson in the final state, such as the semileptonic mode $B_c \to J/\psi \ell \nu$ ($\ell = e, \mu$), a signal with much higher statistics and thus more suitable for lifetime measurements, or the hadronic mode $B_c \to J/\psi \pi$, more suitable for mass measurements given its fully exclusive reconstruction without the loss of an escaping neutrino.

Initial evidence for the B_c meson was reported at LEP [2] with a few candidate events and marginal statistical significance. The CDF Collaboration has published results on both semileptonic and hadronic decay modes [3,4], and has recently updated the B_c mass measurement to $M(B_c) = 6275.6 \pm 2.9(\text{stat}) \pm 2.5(\text{syst})\ \text{MeV}/c^2$ [5]. This Letter is the first report by the D0 Collaboration of a fully reconstructed hadronic decay mode of this state. The measured lifetime [4,6] is consistent with the expectation of a shorter B_c lifetime than for other B mesons due to the presence of a charm quark. The B_c mass has been predicted by various theoretical models [1] and most recently [7] with a three-flavor (unquenched) lattice QCD numerical algorithm that yielded the smallest theoretical uncertainty, with the result $M(B_c) = 6304 \pm 12^{+18}_{-0}\ \text{MeV}/c^2$, where the first error is the sum in quadrature of statistical and systematic uncertainties, and the second is due to heavy quark discretization effects.

The D0 detector is described elsewhere [8], and the elements most relevant to this analysis are the tracking detectors inside a 2 T superconducting solenoidal magnet and the muon detection chambers. For enhanced preselection efficiency, no specific trigger requirements are applied, but all events satisfy one of a suite of muon triggers, typically requiring at least one muon with transverse momentum (p_T) above 3 GeV/c. The decay under study consists of a single detached secondary three-track vertex: $B_c \to J/\psi \pi \to \mu^+ \mu^- \pi$ (charge conjugate modes, $\pi^\pm$, are always implied). Initial track selection extends to a pseudorapidity of $|\eta| < 2.0$ [where $\eta = -\ln[\tan(\theta/2)]$, and θ is the polar angle with respect to the beam line], and rejects tracks with $p_T < 1.5$ GeV/c. Selected final state tracks must satisfy quality requirements based on established minimal hit patterns and a goodness of track fit. Tracks identified as muons must have matching hits in all three layers of the muon detector.

Event selection starts with the requirement of an opposite-charge muon pair that forms a common vertex and whose mass is consistent with that of the J/ψ meson (between 2.85 and 3.35 GeV/c^2). There follows a search for a third track that, together with the muons, must form a common vertex with $\chi^2 < 16.0$ for the 3 degrees of freedom. The J/ψ candidate must have $p_T > 4$ GeV/c, and the third particle is assigned the pion mass. Thus formed, the B_c meson candidate is required to have $p_T > 5$ GeV/c.

Further B_c candidate selection places constraints on quantities that proved to be strong discriminators against combinatoric backgrounds. The impact parameter (IP) significance of any particle, reconstructed either from a single track or a combination of tracks, is $I_{\text{sig}} = \sqrt{[\epsilon_T/\sigma(\epsilon_T)]^2 + [\epsilon_L/\sigma(\epsilon_L)]^2}$, where ϵ_T (ϵ_L) is the transverse (longitudinal) projection (with respect to the beam direction) of that particle's IP relative to the $p\bar{p}$ primary interaction vertex, and σ is the associated uncertainty. The primary vertex is determined event by event using a method described in Ref. [9]. The transverse decay length significance of a decay (or secondary) vertex is $S_{xy} = L_{xy}/\sigma(L_{xy})$ where L_{xy} is the distance separating that vertex from the beam line. The pointing cosine, C_{xy}, measures the alignment between $\vec{L}_{xy}$ and the transverse momentum direction of the decaying candidate particle. The isolation $\mathcal{I}$ of a B_c candidate is defined as the ratio of two p_T sums: that from the three candidate tracks, divided by that from all tracks with p_T above 0.3 GeV/c whose momenta lie within a cone of radius $\Delta\mathcal{R} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.5$, where $\Delta\eta$ and $\Delta\phi$ are distances in pseudorapidity and azimuthal angle from the B_c momentum axis, respectively.

Throughout the background reduction process, a control procedure is used that tests the effect of each discriminator against a well-understood signal sample, either reconstructed $B^\pm \to J/\psi K^\pm$ candidates in data [10] or candidates in a $B_c^\pm \to J/\psi \pi^\pm$ simulated Monte Carlo sample. The latter is generated using EVTGEN [11] interfaced with PYTHIA [12], followed by full modeling of the detector response with GEANT [13] and event reconstruction exactly as in data.

J/ψ candidates are mass constrained; i.e., their daughter muon momenta are corrected to yield the Particle Data Group [14] mass value. When the third track is assumed to be a kaon, a clean, high-statistics $B^\pm$ signal in invariant mass is observed in the data. This decay has a topology similar to the B_c signal and is used as a reference in an initial round of selection cuts shown in Table I as stage 1. Here the $B^\pm$ signal and sideband regions are used as efficiency and rejection indicators of where to set selection thresholds. The $B^\pm$ study region extends from 4.98 to 5.58 GeV/c^2 in invariant mass, and the signal region is approximately $\pm 2\sigma$ wide from 5.20 to 5.36 GeV/c^2.

TABLE I. Discriminators and their values at the two selection stages (see text). $p_T^{\rm rel}(\pi)$ is introduced only for the second stage and represents the transverse momentum of the pion candidate with respect to the total B_c candidate momentum.

Discriminator	Condition	Stage 1	Stage 2
$I_{\rm sig}(B_c)$	$<$	3.5	3.5
$I_{\rm sig}(\pi)$	$>$	3.0	3.5
S_{xy}	$>$	3.0	4.5
C_{xy}	$>$	0.95	0.95
I	$>$	0.5	0.64
$p_T(\pi)$ (GeV/c)	$>$	1.8	2.2
$p_T^{\rm rel}(\pi)$ (GeV/c)	$>$	$\cdots$	1.5
$p_T^{\rm rel}(\pi)$ (GeV/c)	$<$	$\cdots$	2.5

Individual cuts are required to be about 95% efficient, with typical background rejection of approximately 20%. The resulting thresholds are listed in Table I.

However, there are differences between the $B^\pm$ and B_c. Because of the lower (by about 1 GeV/c^2) invariant mass and the longer (b-like versus c-like) lifetime of the $B^\pm$, background reduction undergoes a second stage, in which the B_c Monte Carlo data are used to model the signal. This second selection stage (stage 2 in Table I) aims at reoptimizing, if needed, those cuts associated with B_c specific decay properties. With the third track now assumed to be a pion, the range in invariant mass from 5.6 to 7.2 GeV/c^2 is studied. A subrange between 6.1 and 6.5 GeV/c^2 is treated as the B_c signal search window, and its invariant mass distribution in data is kept blinded throughout the analysis. This subrange is approximately $\pm 3\sigma$ (mass resolution as determined from simulation) wide, and covers both the theory expectations for the B_c mass [7] as well as the observed values quoted in [3,5]. Data in mass sidebands outside this subrange are used as a model for backgrounds and to quantify background rejection. Table I lists those selections that were reoptimized [or introduced, in the case of $p_T^{\rm rel}(\pi)$] in stage 2, and summarizes their evolution between the two selection stages. At this stage there remain no dimuon vertices with more than one candidate for the third track, and no events with more than one B_c candidate.

From B_c simulated events, the B_c mass signal is found to be well modeled by a Gaussian function with a width of 55 MeV/c^2. The mass resolution of the $B^\pm \to J/\psi K^\pm$ signal observed in the data under similar conditions, after all selections have been applied, reproduces the same width when scaled by the ratio of the $B^\pm$ and B_c masses.

The resulting $J/\psi\pi$ invariant mass is shown in Fig. 1 where a clear excess is observed near 6.3 GeV/c^2. An unbinned maximum log-likelihood (UML) fit of the $J/\psi\pi$ invariant mass distribution is performed, where the signal is modeled by a Gaussian function with width fixed to a value of 55 MeV/c^2, and combinatoric backgrounds are modeled by a first-degree polynomial. The result of the UML fit is overlaid in Fig. 1 and yields a signal of 54 ± 12 events and a B_c mass value of 6300.7 ± 13.6 MeV/c^2. To

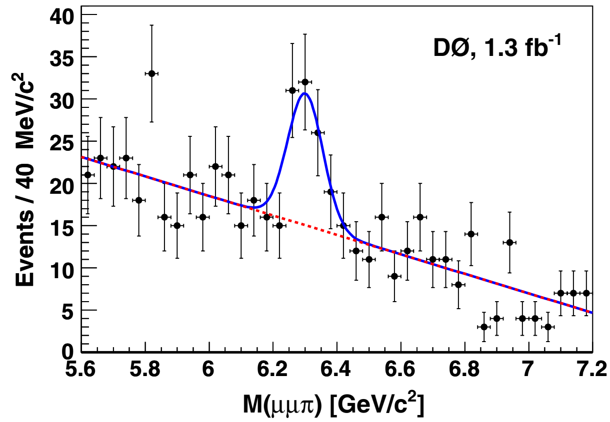

FIG. 1 (color online). $J/\psi\pi$ invariant mass distribution of B_c candidates after the final selection. A projection of the unbinned maximum likelihood fit to the distribution is shown overlaid.

estimate the signal significance, the same fit is repeated under the assumption that no signal is present. From the negative log-likelihoods of the signal plus background and background-only hypotheses, the signal significance is extracted [14] as $N_\sigma = \{2\ln[\mathcal{L}(s+b)/\mathcal{L}(b)]\}^{1/2} = 5.2$ standard deviations. For another estimate of signal significance, χ^2 fits to data (in the 40 MeV/c^2 bins of Fig. 1) under both hypotheses produce an increase in fit χ^2 of 27 units, again indicating $N_\sigma = 5.2$ standard deviations.

Possible biases and systematic uncertainties affecting the B_c mass determination are estimated using both the $B^\pm$ signal in the data and the B_c signal in either the data or the simulation. Uncertainty assessments are made as these samples are refitted under various test hypotheses. Sources of systematic uncertainties are the event selection, the fitting procedure (input mass resolution and data modeling), and the reconstructed mass scale.

The fitted mass values are examined in the simulated signal sample as the value of the $p_T(\pi)$ threshold is varied from 1.9 to 2.5 GeV/c. No systematic mass bias is observed, but statistical fluctuations of ± 4.0 MeV/c^2 are observed and assigned as a systematic uncertainty. Similarly, the $p_T^{\rm rel}$ lower threshold is varied between no cut and 2.0 GeV/c, and the resultant mass variation indicates a small upward mass bias of 0.5 MeV/c^2 for the cut value adopted with respect to the no cut case. The observed B_c mass is corrected accordingly, and a 100% uncertainty is assigned to this correction. There is no indication of a bias in mass due to the upper $p_T^{\rm rel}$ limit.

The values of the selection cuts that are not directly related to the kinematics of the third particle (the pion or kaon candidates in the B_c or $B^\pm$ cases, respectively) are varied within reasonable values. No mass biases are observed, and from the range of mass values obtained, a systematic uncertainty of ± 2.5 MeV/c^2 is assigned due to the choice of these selection cuts.

To assess the systematic uncertainty due to the uncertainty of the mass resolution, the width of the Gaussian is

TABLE II. Summary of systematic uncertainties in the B_c mass measurement.

Source	Component	Value (MeV/c^2)
Selection	π kinematics	4.0
	Other	2.5
Data modeling	Mass resolution	0.6
	Background model	0.5
	Signal shape	0.5
Mass scale		1.0
Total		4.9

allowed to float in the fit. The width input is also changed from the nominal value of 55 MeV/c^2 to other fixed values in the range from 45 to 65 MeV/c^2. From the variation of fitted mass results, a value of ± 0.6 MeV/c^2 is assigned to this uncertainty.

The background model is changed from a first-degree polynomial to a second-degree and third-degree polynomial, and to an exponential function. From the resulting change in mass observed, a systematic uncertainty of ± 0.5 MeV/c^2 is assigned due to uncertainty in the background model. The signal model is changed from a single Gaussian to a double Gaussian function, and the resulting shift of 0.5 MeV/c^2 is assigned as a systematic uncertainty.

Lastly, for an estimate of the mass scale uncertainty, a direct comparison is carried out between generated and reconstructed Monte Carlo masses, as well as between recent D0 mass measurements of well-known B states and the world averages of their measurements [14]. From the observed range of mass differences, a systematic uncertainty of ± 1.0 MeV/c^2 is assigned due to uncertainty in the D0 mass scale for the B_c decay.

A summary of all systematic uncertainties in the B_c mass measurement is shown in Table II. The overall systematic uncertainty is ± 4.9 MeV/c^2. The mass fit result of 6300.7 ± 13.6 MeV/c^2 is corrected by -0.5 MeV/c^2 for the $p_T^{\rm rel}$ bias. The final result for the B_c mass is $6300 \pm 14({\rm stat}) \pm 5({\rm sys})$ MeV/c^2.

In summary, using a data set corresponding to 1.3 fb^{-1}, a signal for $B_c \to J/\psi\pi$ has been observed with a significance higher than 5 standard deviations above background. The mass of the B_c meson has been measured and found to be consistent with the latest and most precise lattice QCD prediction [7]. Besides its relevance as confirmation of earlier observations and in the development and tuning of heavy-quark bound-state models, the B_c sample described here, with added integrated luminosity, is expected to be used in the extraction of lifetime, relative branching ratio, and production rate.

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