B_c Meson Production at Hadron Colliders by Heavy Quark Fragmentation

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We present a reliable estimate on the production rate of B_c mesons in $1S$ and $2S$ states in the large transverse momentum region at hadronic colliders using heavy quark fragmentation functions derived within the framework of perturbative QCD. We also present the transverse momentum distribution for the B_c mesons. The production rate is large enough for the B_c mesons to be identified at the Fermilab Tevatron. At the Superconducting Super Collider or the CERN Large Hadron Collider the rate is so large that their properties can be studied in detail.

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Heavy flavor production and decays are very useful for measuring Cabibbo-Kobayashi-Maskawa (CKM) matrix elements of the standard model and for testing bound-state models for mesons and baryons. Ever since the first B meson was discovered, a lot of data have been coming out from, e.g., CLEO, ARGUS, LEP, SLC, and Fermilab on the B_d and B_u meson families. From the recent run at the Fermilab Tevatron the masses and other properties of the B_s have been measured and confirmed [1]. The next family of B mesons will be the B_c mesons made up of $\bar{b}c$. The B_c meson family differs from the J/ψ and Υ families and from other B mesons because it is made up of a pair of heavy quark and antiquark of *different* flavors and masses. The J/ψ and Υ families have played important roles in developing heavy quark bound-state models inspired by QCD. Being quarkonium systems of different flavors and masses $\bar{b}c$ bound states provide unique opportunities to test different bound-state models of QCD. The decays of B_c mesons also provide rich sources to test the standard model, e.g., the measurement of $|V_{bc}|$, and enable us to see the interplay between strong and weak interactions.

Since the physics of the B_c mesons is so interesting, one would like to know how many can be produced in the present colliders (e.g., Tevatron) and in future hadronic supercolliders [Superconducting Super Collider (SSC), CERN Large Hadron Collider (LHC)]. It is the purpose of this Letter to present reliable estimates in the high p_T region by using the heavy quark fragmentation functions $D_{\bar{b}\to B_c}(z)$ [2] which are based on perturbative QCD. We will summarize some features of these heavy quark fragmentation functions below, and present the production rates and the p_T distributions for the B_c mesons.

Previous estimates of B_c meson production have been based on perturbative QCD calculations for e^+e^- colliders [3] and Monte Carlo studies for both e^+e^- and hadronic colliders [4]. The Monte Carlo estimates of the ratio $\sigma(B_c^\pm)/\sigma(b\bar{b}X)$ are all of the order 10^{-3} for the CERN e^+e^- collider LEP, Tevatron, SSC, LHC, and the DESY ep collider HERA. This fact leads us to think that the production mechanisms are all of the same nature. In the region of large p_T, the major mechanism for producing B_c or any other mesons is heavy quark fragmentation [2, 5], in which a $\bar{b}$ antiquark is produced at large p_T by a hard-scattering process and it subsequently fragments into the meson. The differential cross section for direct production of the B_c meson at high p_T can be factorized at leading order in α_s as

$$d\sigma(B_c(p)) = \int_0^1 dz\, d\hat{\sigma}(\bar{b}(p/z,\,\mu))D_{\bar{b}\to B_c}(z,\,\mu)\,, \tag{1}$$

where z is the longitudinal momentum fraction carried by the B_c, and μ is a factorization scale. The physical interpretation is as follows: a heavy $\bar{b}$ antiquark is produced in a hard process with four-momentum p/z, and then it fragments into the B_c meson with a longitudinal momentum fraction z. The fragmentation function $D_{\bar{b}\to B_c}(z)$ satisfies the Altarelli-Parisi evolution equation

$$\mu\frac{\partial}{\partial\mu}D_{\bar{b}\to B_c}(z) = \int_z^1 \frac{dy}{y}P_{\bar{b}\to\bar{b}}(z/y,\mu)D_{\bar{b}\to B_c}(y,\mu)\,, \tag{2}$$

where

$$P_{\bar{b}\to\bar{b}}(z,\mu) = \frac{4\alpha_s(\mu)}{3\pi}\left(\frac{1+z^2}{1-z}\right)_+\,,$$

at leading order in α_s. The factorization for B_u, B_d, and B_s productions can be described in the same way as Eqs. (1) and (2), with the corresponding fragmentation functions. These fragmentation functions should be independent of the hard process by which the $\bar{b}$ is produced.

The fragmentation of $\bar{b}$ into B_u, B_d, and B_s is a soft process, and can only be described by a phenomenological function [6]. However, $\bar{b}\to B_c$ requires the production of a $c\bar{c}$ pair and it is therefore a hard process which can be calculated using perturbative QCD [2, 5]. This perturbative QCD approach has been shown valid in calculating the fragmentation functions for heavy quarkonium productions [5], including the splitting of gluons and charm quarks into S-wave charmonium. The frag-

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mentation functions $D_{\bar{b}\to B_c}(z)$ derived in Ref. [2] need only the input parameters of α_s, m_b, m_c, and the radial wave function $R(0)$ of the bound state at the origin so that it has more predictive power. The initial fragmentation functions are given by

$$D_{\bar{b}\to B_c}(z,\mu_0) = \frac{2\alpha_s(2m_c)^2|R(0)|^2}{81\pi m_c^3}\frac{rz(1-z)^6}{[1-(1-r)z]^6}[6-18(1-2r)z+(21-74r+68r^2)z^2 -2(1-r)(6-19r+18r^2)z^3+3(1-r)^2(1-2r+2r^2)z^4]\,, \tag{3}$$

for the $^1S_0$ B_c state, and

$$D_{\bar{b}\to B_c^*}(z,\mu_0) = \frac{2\alpha_s(2m_c)^2|R(0)|^2}{27\pi m_c^3}\frac{rz(1-z)^6}{[1-(1-r)z]^6}[2-2(3-2r)z+3(3-2r+4r^2)z^2 -2(1-r)(4-r+2r^2)z^3+(1-r)^2(3-2r+2r^2)z^4]\,, \tag{4}$$

for the first excited state B_c^* which has the spin-orbital quantum number $^3S_1$, and $r = m_c/(m_b+m_c)$. Note that the scale in α_s is set to be $2m_c$. The perturbative QCD calculation gives directly the fragmentation function at the scale $\mu_0 = 2m_c$, which is the minimum virtuality of the gluon splitting into $c\bar{c}$. Using the heavy quark effective theory methods [7], it can be shown that the evolution up to the scale m_b is trivial, which means that higher order radiative corrections will not introduce any logarithm of m_b/m_c. A convenient choice for the initial scale is $\mu_0 = m_b + 2m_c$ [2], because the fragmentation functions for $c \to B_c$, B_c^* can then be obtained from Eqs. (3) and (4) simply by interchanging m_b and m_c.

In the factorization scheme of Eq. (1), all the dependence on the momentum p is in the hard process $\hat{\sigma}$. Large logarithm of p/μ can be avoided by choosing the factorization scale μ to be of order p. The induced large logarithm of order μ/m_b in $D(z)$ can be solved by evolving Eq. (2). To leading order in α_s only the $\bar{b} \to \bar{b}$ contributes to the evolution. The fragmentation functions $D_{\bar{b}\to B_c}(z)$ and $D_{\bar{b}\to B_c^*}(z)$ at the initial scale μ_0 and higher scales have been shown in Fig. 1 of Ref. [2].

Now we use Eq. (1) to compute the direct production rates of B_c and B_c^* in hadronic collisions. Our calculation includes

$$gg \to b\bar{b}\,, \quad g\bar{b} \to g\bar{b}\,, \quad \text{and} \quad q\bar{q} \to b\bar{b}\,, \tag{5}$$

as the hard subprocesses for the inclusive production of the $\bar{b}$. We choose the scale μ for the parton distribution functions and for α_s to be the transverse mass of the $\bar{b}$, $\sqrt{p_{T\bar{b}}^2 + m_b^2}$. We use the parametrization of HMSR (set b) [8] for parton distribution functions. The running coupling constant $\alpha_s(Q)$ is evaluated at one loop by evolving from the experimental value $\alpha_s(m_Z) = 0.12$ [9], and given by

$$\alpha_s(Q) = \frac{\alpha_s(m_Z)}{1+8\pi b_0\alpha_s(m_Z)\ln(Q/m_Z)}\,, \tag{6}$$

where $b_0 = (33-2n_f)/48\pi^2$, and n_f is the number of active flavors below the scale Q. The subprocess cross sections are convoluted with $D(z,\mu)$, as in Eq. (1). The functions $D(z,\mu_0)$ at the initial scale μ_0 are given in Eqs. (3) and (4), and are evolved to the scale μ using Eq. (2). For the initial fragmentation functions $D(z,\mu_0)$ we use the input parameters of $m_b = 4.9$ GeV, $m_c = 1.5$ GeV, and $|R(0)|^2 = (1.18\text{ GeV})^3$.

The p_T spectrum for the B_c meson at Tevatron energy is shown in Fig. 1, with the acceptance cuts

$$p_T(B_c) > 10\text{ GeV} \quad \text{and} \quad |y(B_c)| < 1\,. \tag{7}$$

The corresponding spectrum for the B_c^* is also shown in the same figure. The shapes of the two spectra are very similar, because $D_{\bar{b}\to B_c}(z)$ and $D_{\bar{b}\to B_c^*}(z)$ have similar shapes and differ primarily by an overall normalization difference of about 50%. The corresponding spectra at SSC ($\sqrt{s} = 40$ TeV) and LHC ($\sqrt{s} = 14$ TeV) energies are shown in Fig. 2, but under slightly different acceptance requirements:

$$p_T(B_c) > 20\text{ GeV} \quad \text{and} \quad |y(B_c)| < 2.5\,. \tag{8}$$

The integrated cross sections versus $p_T^{\min}(B_c)$ are also

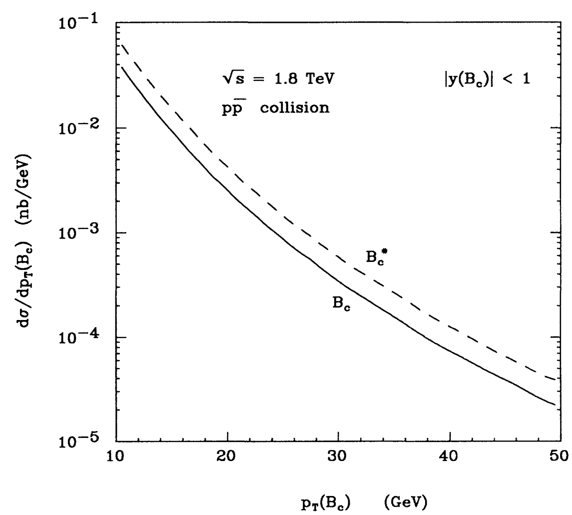

FIG. 1. The dependence of the differential cross section $d\sigma/dp_T(B_c)$ on the transverse momentum $p_T(B_c)$ for the ground state $B_c(1\,^1S_0)$ and the first excited state $B_c^*(1\,^3S_1)$ at the Tevatron.

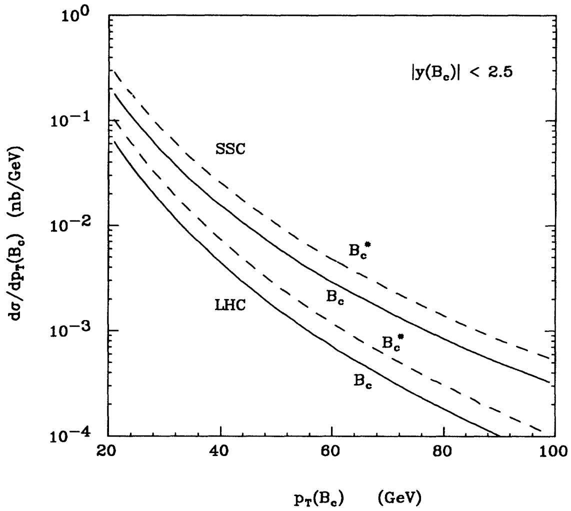

FIG. 2. The dependence of the differential cross section $d\sigma/dp_T(B_c)$ on the transverse momentum $p_T(B_c)$ for the ground state $B_c(1\,^1S_0)$ and the first excited state $B_c^*(1\,^3S_1)$ at the SSC and LHC.

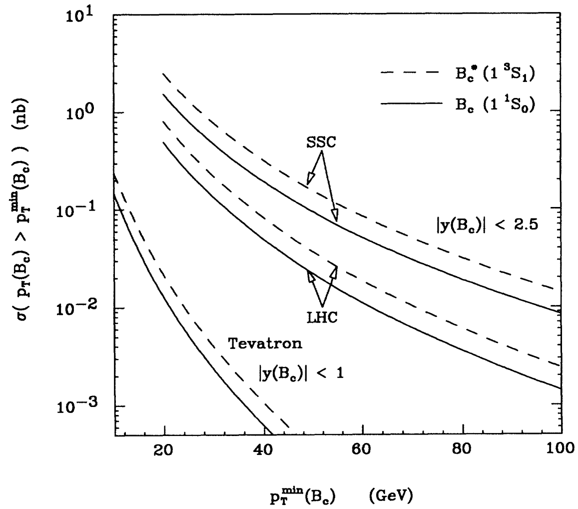

FIG. 3. The integrated cross sections $\sigma(p_T(B_c) > p_T^{\min}(B_c))$ for the ground state $B_c(1\,^1S_0)$ (solid) and the first excited state $B_c^*(1\,^3S_1)$ (dashed) versus $p_T^{\min}(B_c)$ at the Tevatron, SSC, and LHC.

shown in Fig. 3. The cross sections at the SSC are about 3 times as large as those at the LHC, and about 2 orders of magnitude larger than those at the Tevatron.

So far we have only estimated the B_c meson productions in $1\,^1S_0$ and $1\,^3S_1$ states. Since the annihilation channel for the decay of the excited B_c meson states is suppressed relative to the electromagnetic and hadronic transitions, all the excited states ($1\,^3S_1$, $2S$, $1P$, $2P$, $1D$) below the BD threshold will decay to the ground state $1\,^1S_0$ by emitting photons or pions. Therefore they all contribute to the inclusive production of B_c mesons. A simple modification can be made to estimate the productions in $2\,^1S_0$ and $2\,^3S_1$ states, by multiplying with the factor $|R_{2S}(0)/R_{1S}(0)|^2 \simeq 0.6$ [10]. Therefore, the curves in Figs. 1, 2, and 3 can be multiplied by 0.6 to get the productions for $2S$ states. To get the total inclusive production rate, however, we need to include P-wave and possibly D-wave contributions, which have not been calculated. Therefore, the cross sections presented here are rather conservative in comparison to the actual production rates. Table I shows the number of B_c mesons that can be produced inclusively at Tevatron, SSC, and LHC, including the contributions from $1S$ and $2S$ states, with integrated luminosities of 0.025, 10, and 100 fb^{-1}, respectively. It is also informative to give the ratio $\sigma(B_c)/\sigma(\bar{b}X)$, which is simply the fragmentation probability $\int_0^1 dz\, D_{\bar{b}\to B_c}(z)$. Adding the contributions from $1S$ and $2S$ states, the ratio $\sigma(B_c)/\sigma(\bar{b}X)$ is about 1.5×10^{-3}, which is consistent with Monte Carlo studies [4].

The factorization in Eq. (1) is correct up to the order $(m_b/p_T)^2$, which explains why we impose a rather high p_T cut on the B_c mesons. In the low p_T region, mechanisms other than heavy quark fragmentation have to be taken into account. For example, production of pairs of $b\bar{b}$ and $c\bar{c}$ followed by recombination of $\bar{b}$ and c to form a B_c meson contributes at low p_T region, whereas heavy quark fragmentation dominates at high p_T. Similar conclusions can be found in the production of J/ψ by heavy quark fragmentation [11], which is dominant over the process $gg\to\psi g$ in the large p_T region. There are other uncertainties arising from higher order QCD corrections, relativistic corrections of the bound-state model, and the values of α_s and $R(0)$ used. But the largest source of uncertainties comes from the values of m_b and m_c employed because of the factor $1/m_c^3$ in the initial fragmentation functions as in Eqs. (3) and (4).

We have used heavy quark fragmentation functions derived from perturbative QCD to calculate the production rates and the p_T distributions for S-wave B_c mesons

TABLE I. The number of B_c mesons that can be produced at Tevatron, SSC, and LHC, including the contributions from $1S$ and $2S$ states, and under different $p_T^{\min}(B_c)$ cuts. Another acceptance cut is $|y(B_c)| < 1$ (2.5) at Tevatron (SSC, LHC). The integrated luminosities are 0.025, 10, and 100 fb^{-1} for the Tevatron, SSC, and LHC, respectively.

$p_T^{\min}(B_c)$ (GeV)	Tevatron	SSC	LHC
10	16 000	...	...
15	4100	...	...
20	1400	6.4×10^7	2.1×10^8
30	250	2.0×10^7	5.7×10^7
40	67	8.3×10^6	2.1×10^7
50	22	4.0×10^6	9.4×10^7

at Tevatron, SSC, and LHC energies. Imposing cuts of $p_T(B_c) > 10$ GeV and $|y(B_c)| < 1$ at the Tevatron, and including the contributions from $1S$ and $2S$ states, about 16 000 B_c^+ and 16 000 B_c^- mesons should be produced for 25 pb^{-1} integrated luminosities. The corresponding numbers for SSC and LHC with $p_T(B_c) > 20$ GeV and $|y(B_c)| < 2.5$ are 6.4×10^7 and 2.1×10^8 with integrated luminosities of 10 and 100 fb^{-1}, respectively. These B_c mesons can be detected via the decays of the form $J/\psi + X$, and, in particular, via

$$B_c^\pm \to \psi \ell^\pm \nu_\ell \quad \text{and} \quad B_c^\pm \to \psi \pi^\pm, \tag{9}$$

with $\psi \to \ell'^+ \ell'^-$. The first one has a distinct signature of three charged leptons coming off from the same secondary vertex and has a combined branching ratio of about 1%. The second decay channel has a smaller branching ratio of order (0.2–0.4)%, but it has the advantage that the B_c can be fully reconstructed. The production rate of B_c mesons given above is large enough that it should be possible to use these decay modes to identify the B_c mesons at the Tevatron, and to study its properties in detail at the SSC and LHC.

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