Production and decay of the meson $B_c$

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Studies on the decay and production of $B_c(B_c^*)$ meson are briefly reviewed. Considering RUN-II of Tevatron and the schedule of LHC, the theoretical studies of $B_c$ meson will jump to a new stage not only for itself but also to implement the studies of the heavy quarkonia etc.

Keywords: $B_c$ meson; Decay; Production.

1. Introduction (the meson $B_c$)

The meson $B_c$ is the ground state of the heavy-flavored binding system $(c\bar{b})$, and it is the unique 'double heavy-flavored' meson in Standard Model (SM) and is stable for strong and electromagnetic interactions. The binding interaction for the system is similar to the case of heavy quarkonium $(c\bar{c})$ and $(b\bar{b})$. Its mass and the spectrum of the binding system can be computed by potential models, PNQCD, and lattice QCD, etc. The results are in the region, $m_{B_c} \simeq 6.2 \sim 6.4$GeV. Its lifetime was estimated in terms of the effective theory of weak interaction and by applying the effective Lagrangian to the inclusive processes of $B_c$ decays. According to the estimates, the lifetime $\tau_{B_c} \simeq 0.4$ps, a typical one for weak interaction via virtual $W$ boson. Hence with such a long lifetime, the vertex detection is very useful in its experimental observations. $B_c$ meson has been observed by CDF and D0 already, and so far the observations are consistent with theoretical predictions within theoretical uncertainties and experimental errors.

2. Decay

Since the system $(c\bar{b})$ carries two heavy flavors explicitly, its excited states decay to the ground state $B_c$ by electromagnetic and/or strong interaction directly or in a cascade way according to the available phase space with almost 100% possibility, while the ground state $B_c$ decays via weak interaction only. Here I shall concentrate on the weak decay of the ground state meson $B_c$.

There are two 'spectator ways' in the weak decay of $B_c$ meson: $c$-quark decays with $\bar{b}$-quark as a 'spectator' and $\bar{b}$-quark decays with $c$-quark as a 'spectator'. The
interesting aspect of them is that the rates of these two ‘ways’ are competitive in magnitude: the CKM matrix elements have $|V_{cb}| \ll |V_{cs}|$, that is in favor of the $c$-quark decay greatly, whereas the phase space factor is proportional to the fifth power of the mass of the decay fermion for a weak decay via a virtual $W$-boson to a massless three-body final state, and $m_b^5 \gg m_c^5$ for the two flavor, that compensates the CKM matrix element factor a lot. In fact, besides these two, there is one more important decay way only for the $B_c$ meson decay i.e. the annihilation of $c$ and $\bar{b}$. Here, when we talk about the three ‘ways’ individually, it means that we have ignored the interferences among the amplitudes for the three ‘ways’ in a moment. The interferences among them actually are not very great, therefore, the aspect obtained by the individual consideration is kept, so $B_c$ has very rich weak decay channels with comparable decay branching ratio. Furthermore, by measuring the decay product, one may precisely know the specific decay is caused by $c$-quark decay or by $\bar{b}$-quark decay. Hence we may study the two heavy flavors $c$ and $\bar{b}$ simultaneously just with one meson $B_c$, and may gain some advantage in comparative studies of the two flavors e.g. in estimating and measuring the ratio of CKM matrix elements $\frac{|V_{cb}|}{|V_{cs}|}$, because there is a cancellation for theoretical uncertainties and experimental systematic errors.

Of the $B_c$ decay, the rate of the decay caused by $c$-quark, in fact, is bigger than that caused by $\bar{b}$-quark. As a consequence, even though the available phase space for $c$-quark decay is comparatively small, the decay $B_c \to B_s(B_s^*) + \cdots$ still has quite great branching ratio: $Br_{B_c \to B_s + \cdots} \geq 50\%$. Therefore, ‘$B_c$ decay to $B_s$’ can be used as a $B_s$ generator (source) potentially if the $B_c$ is produced numerously. Furthermore, the $B_s$ meson generated from $B_c$ decay is ‘tagged’ explicitly by $B_c$ charge, since $B_c$ carries positive charge.

2.1. Lifetime and Inclusive decays

To estimate the lifetime of $B_c$, the most reliable way is to compute its inclusive decays with optics theorem and effective Lagrangian for weak interaction. It is because that in this way the non-spectator effects can be taken into account and the non-perturbative effects are factorized out clearly.

The two spectator components for $B_c$ decay, which are similar to that of $B$ and $D$ decay accordingly, contribute to the lifetime with the partial rates:

$$\Gamma(\bar{b} \to c) = \sum_{l=e,\mu,\tau} \Gamma^{sl}_{\bar{b} \to cl\nu} + \sum_{q=u,d,s,c} \Gamma^{nonl}_{\bar{b} \to cq\bar{q}}$$

i.e. $\bar{b}$-quark decay with $c$-quark as spectator, and

$$\Gamma(c \to s) = \sum_{l=e,\mu} \Gamma^{sl}_{c \to s\ell\nu} + \sum_{q=u,d,s} \Gamma^{nonl}_{c \to sqq}$$

i.e. $c$-quark decay with $\bar{b}$-quark as spectator. Each of them includes both of the semileptonic and nonleptonic decays.

$^a$Note that here the indirect cascade decays, such as $B_c \to B_s^* + \cdots$ and $B_s^* \to B_s + \cdots$, are taken into account too.
In $B_c$ decay, the annihilation component is another important one and its contributions are different from those in $B$ and $D$ decays. The so-called weak annihilation (via $W$ boson) component contains $\Gamma^{WA}_{\text{tree}}$, $\Gamma^{WA}_{\text{penguin}}$, and $\Gamma^{WA}(B_c \to \tau\nu\tau)$ which correspond to the non-leptonic decay induced by the ‘tree’ and ‘penguin’ parts, and the pure leptonic (PL) decay$^b$ respectively. The so-called Pauli interference components (interferences among the spectator components and annihilation component) contain the ‘tree’ part $\Gamma^{PI}_{\text{tree}}$ and the ‘penguin’ part $\Gamma^{PI}_{\text{penguin}}$ respectively. The total width of $B_c$ should be the sum of the partial widths $\Gamma = \Gamma^{c\to s} + \Gamma^{\bar{b}\to \bar{c}} + \Gamma^{WA} + \Gamma^{PI}$ with $\Gamma^{PI} = \Gamma^{PI}_{\text{tree}} + \Gamma^{PI}_{\text{penguin}}$ and $\Gamma^{WA} = \Gamma^{WA}_{\text{tree}} + \Gamma^{WA}_{\text{penguin}} + \Gamma^{WA}(B_c \to \tau\nu\tau)$.

Table 1. The lifetime and inclusive branching ratios for $B_c$ meson

| $f_{B_c}$ | $\tau_{B_c}$ | $Br(\bar{b})$ | $Br(c)$ | $Br^{WA}$ | $Br^{PI}$ | $Br(\tau\nu)$ | $Br^{\pi^0}$ |
|-----------|-------------|----------------|---------|-----------|-----------|---------------|--------------|
| .44       | .362       | 22.8           | 70.9    | 13.4      | -7.1      | 2.8           | 8.7          |
| .50       | .357       | 22.4           | 69.7    | 16.9      | -9.0      | 3.6           | 8.4          |

In Table 1, $\tau_{B_c}$ means the lifetime in unit ps; $f_{B_c}$ is the decay constant in unit GeV; $Br(\bar{b})$ is the branching ratio of the $\bar{b}$-quark inclusive decay to $c$-quark and the $c$ inside $B_c$ as the spectator; $Br(c)$ is the branching ratio of the $c$-quark decay to $s$-quark and the $\bar{b}$ inside $B_c$ as the spectator; $Br(\tau\nu)$ is that of the pure leptonic decay $B_c \to \tau\nu$ (without Pauli interference). Owing to the interference, $\Gamma^{PI}$ is negative, so the value of $Br^{PI}$. All of the branching ratios in the table are in percentage.

When determining the necessary input parameters, the authors of Ref. 7 further considered the measured lifetimes of $B$ mesons and $D$ mesons as well. As typical ones, here I quote the values of the theoretical estimate on the $B_c$ lifetime from Ref. 7 into Table 1. Due to the uncertainties in treating the non-perturbative matrix elements in the estimates, there are some disagreements in the theoretical estimates on the lifetime which can be found in Ref. 2, but at the present stage, all of them agree with the experimental measurements$^8$, within the experimental errors.

2.2. Pure leptonic decay and its escape from the chiral-suppression by radiation

The meson $B_c$ can decay by weak annihilation. Of them, the pure leptonic decay is of specially interest due to the fact that it can be used to measure the decay constant $f_{B_c}$ and there is no strong interaction in final state of the decay and the induced ‘penguin’ in the effective Lagrangian plays no role to it.

The vector left-hand nature of the weak interaction causes the so-called chiral suppression. Indeed, due to the suppression, the decays $B_c \to l\bar{v}(l = e, \mu)$ are negligible small because $m_l$ is negligible small. Whereas, if there is additional particle such as one photon or one gluon in the final state, then the decay may escape from the chiral suppression. When there is an additional photon in final state, due to the ‘escape’, the branching ratio is enhanced by several magnitude order e.g.

$^b$Since the helicity suppression, here the pure leptonic decays $B_c \to l(e, \mu) + \nu$ are ignored.

$^c$In Ref. 7 there is a typo that the unit of $\Gamma(\tau\nu)$ should be $0.1 \cdot ps^{-1}$ instead of $ps^{-1}$. 
Fig. 1. The matrix element of the relevant current $< P'_{B_f}|J_\mu|P(A_i) >$, where the wave line represents a virtual ‘particle (W-boson)’ which brings momentum and quantum number away; the full dot represents the current which couples to the virtual W-boson; the ladder-like spring-lines in right hand diagram mean the binding interactions multi-times between the two components.

$Br(Bc \to e^+\nu_e) + Br(Bc \to e^+\nu_e\gamma) \simeq (10^4 \sim 10^5) \cdot Br(Bc \to e^+\nu_e)$, and with a hard photon the absolute branching ratio still can be sizable as $10^{-5} \sim 10^{-4}$. Detail analysis about the suppression and enhancement can be found in Ref.11.

Moreover if there is an additional gluon (which fragments to light hadrons) to the neutrino and charged lepton in the final state, the decay not only escapes from the chiral suppression but also can be used as a test of the color-octet components in the meson $B_c$. It is interesting to point out that such decay can be used to measure the color-octet components in the meson $B_c$ indeed, if the color-octet components in the meson are predicted as that by the ‘scaling-rule’ of NRQCD. When the meson is produced numerously, as long as more attention is payed to the region of the decay phase-space that is close to the end point of the charged lepton (the final state of the decay contains the charged lepton, light hadrons and missing neutrino only) in the measurements, the color-octet components can be measured. In the ‘end point’ region of the decay the contributions from the color-octet components become greater than those from the color-singlet components. The quantitative computations on the decays of $B_c$ to leptons with light hadrons (which are fragmented from one or two gluons) and the conclusion about the color-octet component measurements can be found in Ref.12.

2.3. Semileptonic and Nonleptonic decays

The essential factor which must be computed in nonleptonic decays with naive factorization$^d$ and in semileptonic decays may be attributed to a matrix element of the relevant current as $< P'(B_f)|J_\mu|P(A_i) >$ (Fig.1), where the particle $A_i$ in initial state is $B_c$, and the particle $B_f$ in final state is one of the particles $J/\psi, \eta_c, \chi_c, h_c, \cdots; B_{s}, B_{s}^*, \cdots$.

Since the $B_c$ meson is much heavier than the bound state $B_f$ in the final state, so there may be a great momentum recoil, i.e., the velocity $v$ of the produced bound state $B_f$ in C.M.S. of $B_c$ meson may be very great, e.g., $v$ even may reach to 0.7 (in unit $c$) in the semileptonic decay $B_c \to J/\psi + l + \nu$. Therefore, the recoil effects should be treated carefully in estimation of the decays.

To deal with the recoil effects in the decays, there are several ways, but I think that all of them should ‘contain’ multi-interactions between the components as

$^d$Naive factorization can be applied to nonleptonic decays only for leading-order estimates.
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Fig. 2. The two ‘Isgur-Wise’-like functions for the decays from $S$-wave state ($B_c$ meson) to a $P$-wave state (e.g. $\eta_c, J/\psi, \cdots$).

indicated in Fig.1 (the right hand diagram). In Refs.\textsuperscript{51,11,14,15} the authors consider the multi-interactions to dictate the recoil effects with Bether-Salpeter or Dyson-Schwinger equations, while in Ref.\textsuperscript{16} the authors consider them with QCD sum rule with infinite ‘Coulomb gluon’ exchanges. The results obtained by the different ways are different due to the fact that each of them has taken certain approximations and has different input parameters, although all are similar in the inspirsts.

Table 2. Typical semileptonic and nonleptonic decay rates for $B_c$ meson in units of $10^{-15}$ GeV.

|       | $A$     | $B$     | $C$     | $D$     | $A$     | $C$     | $D$     |
|-------|---------|---------|---------|---------|---------|---------|---------|
| $B_c \to \eta_c \nu \bar{\nu}$ | 14.2    | 10.7    | 11.1    | 11 ± 1  | $B_c \to \eta_c \pi$ | 3.29    | 2.52    | ×       |
| $B_c \to J/\psi \nu \bar{\nu}$ | 34.4    | 28.2    | 30.2    | 28 ± 5 | $B_c \to J/\psi \pi$ | 3.14    | 1.94    | ×       |
| $B_c \to \chi_c^0 \nu \bar{\nu}$ | 1.69    | 2.52    | ×       | ×       | $B_c \to \eta_c \rho$ | 8.70    | 5.94    | ×       |
| $B_c \to \chi_c^1 \nu \bar{\nu}$ | 2.21    | 1.40    | ×       | ×       | $B_c \to J/\psi \rho$ | 9.45    | 5.52    | ×       |
| $B_c \to h_c \nu \bar{\nu}$ | 2.73    | 2.92    | ×       | ×       | $B_c \to B_s \pi$    | 73.3    | 25.1    | 25.1    |
| $B_c \to B_s \nu \bar{\nu}$ | 2.51    | 4.42    | ×       | ×       | $B_c \to B_s^* \pi$  | 64.7    | 19.8    | 9.84    |
| $B_c \to B_s \rho$ | 26.6    | ×       | 14.3    | 58.0    | $B_c \to B_s \rho$   | 56.1    | 62.2    | 10.6    |
| $B_c \to B_s^* \rho$ | 44.0    | ×       | 50.4    | 72.0    | $B_c \to B_s^* \rho$ | 188.2   | 271.1   | 31.8    |

In Table 2 the value of the CKM matrix element is taken as $|V_{cb}| = 0.04$ and the coefficient in the effective Lagrangian $a_3 = 1.26$, the results in $A$ column is taken from Ref.\textsuperscript{51,11} those in column $B$ from Ref.\textsuperscript{14} those in column $C$ from Ref.\textsuperscript{13} those in column $D$ from Ref.\textsuperscript{16}.

It is interesting to point out here that due to the effects of the great momentum recoil, for the decays from $S$-wave ($B_c$ meson) to a $P$-wave state (e.g. $\eta_c, J/\psi, \cdots$) there are two ‘Isgur-Wise’-like functions (see Fig.2), while for the decays from $S$-wave ($B_c$ meson) to an $S$-wave state (e.g. $\eta_c, J/\psi, \cdots$) there is only one ‘Isgur-Wise’-like function. The so-called ‘Isgur-Wise’-like function(s) means that all of the form factors for the decays may always be depicted by the function(s) with proper kinematic factors as in the cases of HQET. The dotted curve in Fig.2 represents the ‘common’ one which is similar to that for the decays from $S$-wave to the $S$-wave state and decreases slowly with the momentum recoil $t_m - T$. Whereas the solid curve is a ‘fresh’ ‘Isgur-Wise’-like function, which is zero at $t_m - t = 0$ (null recoil) and increases with the momentum recoil $t_m - t$ rapidly then goes down slowly. If the recoil effects had been ignored, then the fresh ‘Isgur-Wise’-like function would
always is zero. Typical results of the semileptonic decays are put in Table 2 and we can see that the decay rates of the channels with $B_s$ or $B_s^*$ in final state are great.

Theoretical estimates on the nonleptonic decays of $B_c$ meson with naive factorization can be found in many references such as Refs. 5, 11, 13, 14, 15 etc. It is too long to present all of the results here, so alternatively, I only choose some of them to put in Table 2. One can see the general feature of the nonleptonic decays from Table 2 that the decay rates of the channels with $B_s$ or $B_s^*$ in final state are also comparatively great.

3. Production (at Tevatron vs at LHC)

The reason why the first experimental observation of the ‘usual’ meson $B_c$ happened so late in 1998 is because the difficulty of its production i.e. smallness of its production cross-section. Only at high energy hadronic colliders can the cross-section be sizable enough for observation, so its first observation was successful at Tevatron by CDF collaboration. According to theoretical estimates and the design luminosity of various kinds of colliders, accurately experimental studies of the meson under high statistics are accessible only at Tevatron and LHC.

Since the meson $B_c$ carries two heavy flavors explicitly, so to produce it in the most favorable manner is to produce two pairs of heavy quarks: $c, \bar{c}, b, \bar{b}$ first, and then the two heavy quarks $c, \bar{b}$ of them combine into the meson by certain possibility. Two pairs of the quarks $c, \bar{c}, b, \bar{b}$ are so heavy that their production always in the perturbative region of QCD, while the ‘possibility’ to combine the two heavy quarks $c, \bar{b}$ into the meson, being nonperturbative nature, relates to a relevant matrix element in NRQCD framework (for color-singlet production it can be related to the wave function of $B_c$ at origin in potential model framework) directly [17]. Therefore the production of $B_c$ meson may be always estimated by perturbative QCD (pQCD) with proper factorization formulation [2, 17, 18, 19, 20, 21].

Table 3. Total cross-sections (LO QCD estimate and in unit of nb) for the hadronic production of $B_c[1^1S_0]$ and $B_c^*[1^3S_1]$ at TEVATRON and at LHC.

|                  | CTEQ6L | GRV08L | MRST2001L | CTEQ6L | GRV08L | MRST2001L |
|------------------|--------|--------|------------|--------|--------|------------|
| $\sigma_{B_c}(1^1S_0)$ | 3.79   | 3.27   | 3.49       | 5.50   | 4.54   | 4.86       |
| $\sigma_{B_c^*}(1^3S_1)$ | 9.07   | 7.88   | 8.16       | 13.4   | 11.1   | 11.9       |
|                  |        |        |            |        |        |            |
| $\sigma_{B_c}(1^1S_0)$ |        |        |            |        |        |            |
| $\sigma_{B_c^*}(1^3S_1)$ |        |        |            |        |        |            |

In Table 3, the characteristic energy scale $Q$ is taken as $Q^2 = \sqrt{s}/4$ and $\sqrt{s}$ is the C.M. energy of the active subprocess or $Q^2 = p_T^2 + m_{B_c}^2$ and $p_T$ is the transverse momentum of $B_c$ meson; the values are taken from Ref. 20.

There are two theoretical approaches of pQCD to the estimate of its production: the so-called fragmentation approach [18] and the so-called complete calculation approach of the lowest-order perturbative QCD [17, 19, 20, 21]. Since the second one may
keep more useful information of the production for experiments, it is highlighted in literature. There are several mechanisms for the hadronic production of $B_c$ meson, in most $P_T$ (transverse momentum of the produced $B_c$ meson) region, the so-called ‘gluon-gluon fusion’ mechanism is dominant\cite{19,20}. Since only LO estimates of $B_c$ production are available up-to now, so several important theoretical uncertainties for LO estimate are investigated in Ref.\cite{20}. Recently the $P$-wave excited $B_c$ production not only via its color-singlet component but also via its color-octet components is estimated, and it is pointed out that the $P$-wave production can be sizable\cite{21}. The general feature of the production is the cross sections increase slowly with the center mass energy of the collision $\sqrt{S}$. The total production cross-sections\cite{20} at Tevatron and LHC are put in Table. 3 and the precise $p_T$ distributions for the production can be found in Refs.\cite{20,21}. From Table. 3, one still can see that the cross-sections at LHC are greater than those at Tevatron by one order of magnitude, therefore, the studies at LHC can have much higher statistics than that at Tevatron.

It is remarkable that to meet various experimental needs of event simulation for feasibility studies of the meson $B_c$ at Tevatron and LHC, a computer program (the event generator for $B_c$) named BCVEGPY that is in compliment to the PYTHIA environment has been completed\cite{22}. It is powerful enough for most purposes, i.e., with it one can enhance the event generating efficiency greatly in contrast to PYTHIA itself. With the latest version BCVEGPY2.0, not only the ground state of $B_c$ meson can be generated, but can also its $P$-wave excited states.

4. Outlook

In prospects of the cross sections of $B_c$ production, available detectors, collision luminosity at Tevatron (Run-II) and at LHC, accurately and thoroughly experimental studies of it is accessible very soon. $B_c$ physics is compelling. With very high statistics we will have various tests of the theoretical estimates (predictions) etc. and might have better measurements on CKM matrix elements. The self-tagged $B_s$ mesons via $B_c$ decays as a tagged $B_s$ source might be achieved. The future copious data require more accurate theoretical predictions in the environments at Tevatron and at LHC respectively since now on etc. The studies of $B_c$ meson will jump to a new stage not only for itself but also to implement the studies of the heavy quarkonia etc.

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