B_c-meson Decays into Orbitally Excited Charmonium States

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Abstract

Factorization of hard and soft contributions into hadronic decays of B_c meson at large recoils is explored in order to evaluate the decay rates into the S, P and D-wave charmonia associated with ρ and π. The constraints of approach applicability and uncertainties of numerical estimates are discussed. The mode with the J/ψ in the final state is evaluated taking into account the cascade radiative electromagnetic decays of excited P-wave states that enlarges the branching ratio by 20-25%.

1 Introduction

After the first observation of B_c meson by the CDF Collaboration at FNAL [1] in the semileptonic mode with the J/ψ particle in the final state,

$$B_c^+ \to J/\psi l^+ \nu_l, \tag{1}$$

one expects rather a significant, of factor 20, increase of statistics with B_c in the same mode after RunII. However, the uncertainties in the mass measurements are essential in the semileptonic channel, since the neutrino momentum is not detected directly. So, the two-particle decay mode

$$B_c^+ \to J/\psi \pi^+, \tag{2}$$

is the most prospective channel for such the measurements. Therefore, we need a qualitative theoretical modeling in order to predict the basic characteristics of (2).

The feature of two-particle decays, which are studied in the present paper

$$B_c^+ \to c\bar{c}[^{2s+1}L_J]\pi^+(\rho^+), \tag{3}$$

is specified by a rather large recoil momentum of charmonium $c\bar{c}[^{2s+1}L_J]$, where s denotes the sum of quark and antiquark spins, L is the orbital quantum number running from 0 to 2, and J is the total spin of charmonium. Indeed, in the framework of potential models, the approximation of heavy-quarkonium wave function overlapping for the calculation of hadronic form factors can be explored in the region, where these wave functions are not exponentially small, i.e. if the amplitude under consideration is soft enough, and the nonperturbative modeling of the form of wave functions is reliable, while at large recoils the behavior of vertices for the quarks entering the bound states is significantly modified due to hard gluon corrections. Then, the exponential decrease of quark-meson form factors is replaced by the power-like one at large recoils. In this case, one could factorize the hard and soft amplitudes [2].

While in [3] the decays into the S and P-wave charmonia were considered, in the present paper we develop the same technique for a more accurate analysis including the D-wave states of $c\bar{c}$, too.

2 Hard-soft factorization in B_c decays

Neglecting the binding energy, in the soft amplitude we put the mass of B_c meson m_1 equal to the sum of b-quark and c-quark masses $m_b + m_c$, and the mass of $c\bar{c}$ state m_2 equal to $2m_c$. Then the heavy quark and antiquark inside the bound state move with the same 4-velocity, so that in the accepted non-relativistic approximation we can write down

$$v_1 = \frac{p_1}{m_1} = \frac{p_{\bar{b}}}{m_b} = \frac{p_c}{m_c}, \qquad v_2 = \frac{p_2}{m_2} = \frac{p_{\bar{c}}}{m_c} = \frac{p_c^{'}}{m_c}, \tag{4}$$

where $p_{1,2}$ are the momenta of decaying and recoil heavy quarkonia, respectively, and p_Q are the momenta of quarks composing the heavy quarkonia.

However, at large recoils specific for the decays $B_c^+ \to c\bar{c}[^{2s+1}L_J]\pi^+(\rho^+)$, the conditions of (4) could be valid only if we take into account the hard gluon correction with a large momentum transfer

$$|k^2| = \frac{m_2}{4m_1}((m_1 - m_2)^2 - m_3^2) \gg \Lambda^2_{QCD}, \tag{5}$$

where m_3 is the mass of π or ρ. At the tree level as well as with soft gluon corrections the prescription (4) would give zero matrix element, since a little smearing by soft gluons responsible for formation of wave function results in the exponential suppression of overlapping at large recoils. Numerically, the characteristic virtuality in the hard amplitude is equal to $1.0 - 1.2$ GeV^2 for the charmonium in the final state with $m_2 = 3.0 - 3.5$ GeV. We see that such virtualities are large enough for quite a reliable use of perturbative QCD. Moreover, a characteristic relative momentum of heavy quarks inside the bound states under consideration is about $p \sim 0.6 - 0.7$ GeV, and the ratio $p^2/k^2 \sim 0.3 - 0.4$ is quite a small parameter of the expansion. Thus, the kinematic conditions of the decays $B_c^+ \to c\bar{c}[^{2s+1}L_J]\pi^+(\rho^+)$ favor the application of hard-soft approximation with the accuracy about 30%. Another source of uncertainty is connected with neglecting the binding energy, and it is more essential. We will further test it numerically by the variation of charmed quark mass from 1.5 to 1.7 GeV.

A general covariant formalism for calculating the production and decay rates of S-wave and P-wave heavy quarkonium in the non-relativistic expansion was developed in [4]. In this approach, the amplitude of the decay of bound state $(\bar{b}c)$ with the momentum p_1, total spin J_1, orbital momentum L_1 and total spin S_1 into the bound-state $(\bar{c}c)$ with the momentum p_2, total spin J_2, orbital momentum L_2 and summed spin S_2 is given by the following:

$$\begin{aligned} A(p_1,p_2) \;=\; & \int \frac{d\mathbf{q}_1}{(2\pi)^3} \sum_{L_{1z}S_{1z}} \Psi_{L_{1z}S_{1z}}(\mathbf{q}_1)\langle L_1 L_{1z}; S_1 S_{1z}|J_1 J_{1z}\rangle \times \\ & \int \frac{d\mathbf{q}_2}{(2\pi)^3} \sum_{L_{2z}S_{2z}} \Psi_{L_{2z}S_{2z}}(\mathbf{q}_2)\langle L_2 L_{2z}; S_2 S_{2z}|J_2 J_{2z}\rangle M(p_1,p_2,q_1,q_2), \end{aligned} \tag{6}$$

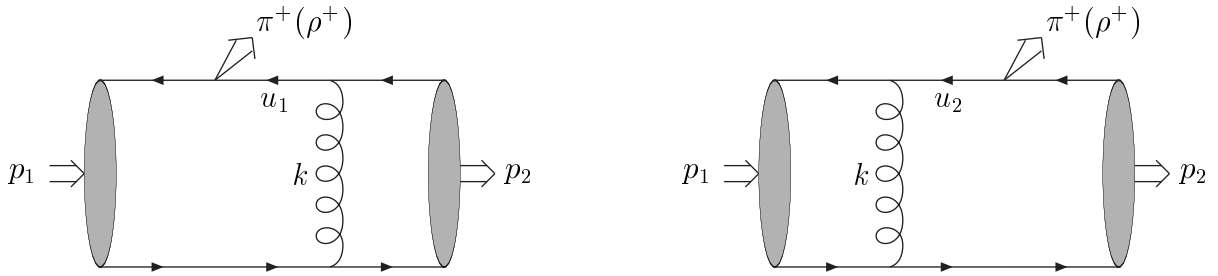

Figure 1: The diagrams with the hard gluon exchange in decays $B_c^+ \to c\bar{c}[^{2s+1}L_J]\pi^+(\rho^+)$.

where $M(p_1, p_2, q_1, q_2)$ is the hard amplitude of the process with truncated fermion legs entering the initial and final mesons as described by the diagrams in Fig. 1. Here $\Psi_{L_z S_z}(\mathbf{q})$ are the non-relativistic wave functions for the heavy quarkonia.

With the accuracy up to the second order in relative momenta q_1 and q_2, the operators $\Gamma_{SS_z}(p, q)$ projecting the quark-antiquark pairs onto the bound states with fixed quantum numbers can be written in the form

$$\Gamma_{S_1 S_{1z}}(p_1, q_1) = \frac{\sqrt{m_1}}{4 m_c m_b}\left(\frac{m_c}{m_1}\not{p}_1 - \not{q}_1 + m_c\right)\not{A}_1\left(\frac{m_b}{m_1}\not{p}_1 + \not{q}_1 - m_b\right), \tag{7}$$

where $\not{A}_1 = \gamma_5$ for the pseudoscalar initial state $S_1 = 0$ and $\not{A}_1 = \not{\varepsilon}(S_{1z})$ for the vector one $S_1 = 1$, and

$$\Gamma^\dagger_{S_2 S_{2z}}(p_2, q_2) = \frac{\sqrt{m_2}}{4 m_c^2}\left(\frac{m_c}{m_2}\not{p}_2 + \not{q}_2 - m_c\right)\not{A}_2\left(\frac{m_c}{m_2}\not{p}_2 - \not{q}_2 + m_c\right), \tag{8}$$

where $\not{A}_2 = \gamma_5$ for the total spin $S_2 = 0$ of recoil quarkonium, and $\not{A}_2 = \not{\varepsilon}(S_{2z})$ for $S_2 = 1$. Here $\varepsilon(S_{1z,2z})$ denotes polarization of vector-spin state. The color factor $\delta^{ij}/\sqrt{3}$ for the singlet states should be also introduced in the quark-meson vertices.

Making use of projection operators in (7) and (8) we write down the hard amplitude $M(p_1, p_2, q_1, q_2)$ in the following way:

$$M(p_1, p_2, q_1, q_2) = \mathrm{Tr}\left[\Gamma^\dagger(p_2, q_2)\gamma^\mu \Gamma(p_1, q_1)\mathcal{O}_\mu\right], \tag{9}$$

where for the decay with the π meson in the final state we have

$$\mathcal{O}_\mu = \mathcal{O}_\mu^{[1]} + \mathcal{O}_\mu^{[2]}, \tag{10}$$

$$\mathcal{O}_\mu^{[1]} = \frac{G_F}{\sqrt{2}}\frac{16\pi\alpha_s}{3} V_{bc} f_\pi a_1 \not{p}_3(1-\gamma_5)\left(\frac{-\not{u}_1 + m_c}{x_1^2 - m_c^2}\right)\frac{\gamma_\mu}{k^2}, \tag{11}$$

$$\mathcal{O}_\mu^{[2]} = \frac{G_F}{\sqrt{2}}\frac{16\pi\alpha_s}{3} V_{bc} f_\pi a_1 \frac{\gamma_\mu}{k^2}\left(\frac{-\not{u}_2 + m_b}{x_2^2 - m_b^2}\right)\not{p}_3(1-\gamma_5), \tag{12}$$

with the notations

$$\not{u}_1 = \frac{m_b}{m_1}\not{p}_1 + \not{q}_1 - \not{p}_3, \quad \not{u}_2 = \frac{m_c}{m_2}\not{p}_2 + \not{q}_2 + \not{p}_3, \quad \not{k} = \frac{m_c}{m_2}\not{p}_2 - \frac{m_c}{m_1}\not{p}_1 + \not{q}_1 - \not{q}_2.$$

The factor a_1 comes from the hard gluon corrections to the four-fermion effective weak Lagrangian. Expanding $M(p_1, p_2, q_1, q_2)$ in small parameters q_1/m_1 and q_2/m_2 at $q_1 = q_2 = 0$, we get

$$\begin{aligned} M(p_1, p_2, q_1, q_2) &= M(p_1, p_2, 0, 0) + q_{1\alpha}\frac{\partial M}{\partial q_{1\alpha}}|_{q_{1,2}=0} + q_{2\alpha}\frac{\partial M}{\partial q_{2\alpha}}|_{q_{1,2}=0} + \\ &+ \frac{1}{2}q_{2\alpha}q_{2\beta}\frac{\partial^2 M}{\partial q_{2\alpha}\partial q_{2\beta}}|_{q_{1,2}=0} + \dots \end{aligned} \tag{13}$$

where the above terms correspond to various quantum numbers: the first with $L_1 = L_2 = 0$ to transition between the S-wave levels, the second and third, with $L_1 = 1$ and $L_2 = 0$, $L_1 = 0$ and $L_2 = 1$ to transitions between S and P-wave states, the fourth, with $L_1 = 0$ and $L_2 = 2$ to transition between the S-wave initial quarkonium and the D-wave recoil meson. Thus, we can easily find that for various orbital states, the soft factors in the amplitudes $A(p_1, p_2)$ are expressed in terms of quarkonium radial wave functions.

3 Results

Neglecting the π meson mass, we obtain the following analytical formulas for the widths of $B_c^+ \to c\bar{c}[^{2s+1}L_J]\pi^+(\rho^+)$:

$$\Gamma(B_c \to \psi\pi) = \frac{128}{9\pi}F\frac{|R_2(0)|^2}{m_2^3}\frac{(1+x)^3}{(1-x)^5}, \tag{14}$$

$$\Gamma(B_c \to \eta_c\pi) = \frac{32}{9\pi}F\frac{|R_2(0)|^2}{m_2^3}\frac{(1+x)^3}{(1-x)^5}(x^2-2x+3)^2, \tag{15}$$

$$\Gamma(B_c \to h_c\pi) = \frac{128}{3\pi}F\frac{|R_2'(0)|^2}{m_2^5}\frac{(1+x)^3}{(1-x)^7}(x^3-2x^2+3x+4)^2, \tag{16}$$

$$\Gamma(B_c \to \chi_{c0}\pi) = \frac{128}{\pi}F\frac{|R_2'(0)|^2}{m_2^5}\frac{(1+x)^3}{(1-x)^7}(x^2-2x+3)^2, \tag{17}$$

$$\Gamma(B_c \to \chi_{c1}\pi) = \frac{256}{3\pi}F\frac{|R_2'(0)|^2}{m_2^5}\frac{(1+x)^3}{(1-x)^3}, \tag{18}$$

$$\Gamma(B_c \to \chi_{c2}\pi) = \frac{256}{\pi}F\frac{|R_2'(0)|^2}{m_2^5}\frac{(1+x)^5}{(1-x)^7}, \tag{19}$$

$$\Gamma(B_c \to {}^1D_2\pi) = \frac{2560}{9\pi}F\frac{|R_2''(0)|^2}{m_2^7}\frac{(1+x)^5}{(1-x)^9}(x^3-3x+5x+5)^2, \tag{20}$$

$$\Gamma(B_c \to {}^3D_1\pi) = \frac{256}{9\pi}F\frac{|R_2''(0)|^2}{m_2^7}\frac{(1+x)^3}{(1-x)^9}(5x^3-22x^2+41x+8)^2, \tag{21}$$

$$\Gamma(B_c \to {}^3D_2\pi) = \frac{5120}{3\pi}F\frac{|R_2''(0)|^2}{m_2^7}\frac{(1+x)^5}{(1-x)^5}, \tag{22}$$

$$\Gamma(B_c \to {}^3D_3\pi) = \frac{8192}{3\pi}F\frac{|R_2''(0)|^2}{m_2^7}\frac{(1+x)^7}{(1-x)^9}, \tag{23}$$

where

$$x = \frac{m_2}{m_1}, \text{ and } F = \alpha_s^2 G_F^2 V_{bc}^2 f_\pi^2 |R_1(0)|^2 a_1^2.$$

In numerical estimations we use the following set of parameters:

$$\begin{array}{llllll} |R_1(0)|^2 = 1.27\ \text{GeV}^3, & m_c = 1.5\ \text{GeV}, & m_\pi = 0.14\ \text{GeV}, \\ |R_2(0)|^2 = 0.94\ \text{GeV}^3, & m_b = 4.8\ \text{GeV}, & f_\pi = 0.13\ \text{GeV}, \\ |R'_2(0)|^2 = 0.08\ \text{GeV}^5, & m_1 = 6.3\ \text{GeV}, & V_{bc} = 0.04, \\ |R''_2(0)|^2 = 0.015\ \text{GeV}^7. & m_2 = 3.0\ \text{GeV}, & \alpha_s = 0.33. \end{array}$$

The values of the wave function parameters are taken from [5]. Then we get the estimate of direct J/ψ yield associated with the pion

$$\Gamma(B_c^+ \to J/\psi\pi^+) = 6.455 \times 10^{-15} a_1^2\ \text{GeV}. \tag{24}$$

The decay widths as the fractions of decay width for $B_c^+ \to J/\psi\pi^+$ into different charmonium states and π meson are presented in Table 1, while the absolute values depending on the choice of a_1 are given in Table 2.

Table 1: The yields of charmonium states in hadronic two-particle decays of B_c meson represented as the ratios.

$c\bar{c}$	$^{2S+1}L_J$	$\dfrac{\Gamma(B_c \to c\bar{c}[^{2S+1}L_J]\pi)}{\Gamma(B_c \to J/\psi\pi)}$	$\dfrac{\Gamma(B_c \to c\bar{c}[^{2S+1}L_J]\rho)}{\Gamma(B_c \to c\bar{c}[^{2S+1}L_J]\pi)}$
J/ψ	$^3S_1$	1.0	3.9
η_c	$^1S_0$	1.3	3.2
h_c	$^1P_1$	2.7	3.4
χ_{c0}	$^3P_0$	1.6	3.5
χ_{c1}	$^3P_1$	0.016	51
χ_{c2}	$^3P_2$	1.4	4.0
	$^1D_2$	5.4	3.6
	$^3D_1$	2.8	3.8
	$^3D_2$	0.053	31
	$^3D_3$	2.4	4.2

An additional source of J/ψ mesons is the two-particle decay of B_c meson with ρ in the final state: $B_c^+ \to c\bar{c}[^{2S+1}L_J]\rho^+$. Calculation of the decay widths $\Gamma(B_c^+ \to c\bar{c}[^{2S+1}L_J]\rho^+)$ can be done in the same way as for the widths $\Gamma(B_c^+ \to c\bar{c}[^{2S+1}L_J]\pi^+)$. Indeed, we use the factorization of light meson current, so that in decays with ρ we substitute $f_\pi p_3^\mu \to m_\rho f_\rho \varepsilon_3^\mu$, where ε_3^μ is the ρ meson polarization. Taking into account the numerical values of $f_\rho = 0.22$ GeV and $m_\rho = 0.77$ GeV, we get the decay widths $\Gamma(B_c^+ \to c\bar{c}[^{2S+1}L_J]\rho^+)$, which are presented in Tables 1, 2.

For the sake of comparison with the results obtained in the ordinary technique with the wave function overlapping, in Table 2 we show also the estimates which were recently evaluated in [6, 7]. The analysis of two-particle hadronic B_c decays with the charmed S-wave recoil-mesons in the final state was also done in [8], where the estimates are similar

Table 2: The widths of B_c meson with the charmonium states in hadronic two-particle decays calculated in the hard-soft factorization in comparison with the results of wave-function overlapping technique [6, 7].

$c\bar{c}$	$^{2S+1}L_J$	$\Gamma(B_c \to c\bar{c}[^{2S+1}L_J]\pi)$, 10^{-15} GeV		$\Gamma(B_c \to c\bar{c}[^{2S+1}L_J]\rho)$, 10^{-15} GeV	
η_c	$^1S_0$	8.4 a_1^2	2.1 a_1^2 [7]	27 a_1^2	5.5 a_1^2 [7]
J/ψ	$^3S_1$	6.5 a_1^2	2.0 a_1^2 [7]	26 a_1^2	6.0 a_1^2 [7]
h_c	$^1P_1$	18 a_1^2	0.57 a_1^2 [6]	60 a_1^2	1.4 a_1^2 [6]
χ_{c0}	$^3P_0$	11 a_1^2	0.32 a_1^2 [6]	37 a_1^2	0.81 a_1^2 [6]
χ_{c1}	$^3P_1$	0.10 a_1^2	0.082 a_1^2 [6]	5.2 a_1^2	0.33 a_1^2 [6]
χ_{c2}	$^3P_2$	8.9 a_1^2	0.28 a_1^2 [6]	36 a_1^2	0.58 a_1^2 [6]
	$^1D_2$	35 a_1^2		124 a_1^2	
	$^3D_1$	19 a_1^2		70 a_1^2	
	$^3D_2$	0.34 a_1^2		11 a_1^2	
	$^3D_3$	16 a_1^2		65 a_1^2	

to those of [7], but slightly smaller. Then, we see that our estimates with the charmed quark mass fixed at $m_c = 1.5$ GeV are significantly greater than the values calculated in [6, 7]. Indeed, for the S-wave charmonium the increase due to the non-exponential fall of the wave functions is about the factor 4 in the matrix element squared, while for the P-waves this factor reaches one order of magnitude. The reason for such an increase is quite transparent. So, following the Coulomb analogy, we can expect that the velocity of heavy quark motion in the P-wave quarkonium is less than the velocity in the S-wave state (remember, $v_n \sim \alpha/n$, where n is the principal quantum number). Then, the wave functions of P-wave levels have softer behavior than in the S-wave states, i.e. the relative momentum of heavy quarks is softer in the P-wave states, while the overlapping of quarkonia wave functions at large recoils is displaced into the region of high virtualities, and suppression is stronger for the P-wave levels. Thus, we would expect a significant enhancement of the P-wave level yield in the hard-soft factorization approach.

Another problem concerning the factorization applicability is related to inherent uncertainties due to neglecting the binding energy in the charmonium states. Indeed, putting $m_c = m_{J/\psi}/2$ leads to zero binding energy for the S-wave states, while for the excitations under study it is about 500 MeV, i.e. it could be quite essential in the numerical estimates. We test this dependence on the binding energy by the variation of charmed quark mass in the range of $1.5 - 1.7$ GeV. We find that this variation brings significant uncertainties into the absolute values of widths under consideration, so that the variations are about 30-50% for the P-wave charmonia and greater than 100% for the D-waves. Nevertheless, we observe that the ratios of widths presented in Table 1 are quite stable under such variation of the charmed quark mass. The corresponding uncertainties are limited by $5 - 10\%$. This fact implies that the theoretical predictions for the ratios of two-particle widths in the B_c decays are quite reliable. Moreover, these ratios are close to the values

obtained in [6, 7].

Since the J/ψ meson in the decays of B_c,is experimentally detected with a good efficiency, we compare the direct J/ψ yield ($B_c^+ \to J/\psi\pi^+(\rho^+)$) with the cascade one in decays with the radiative electromagnetic transitions of excited P-wave states into J/ψ. The corresponding branching ratios of radiative decays are known experimentally [9]. So,

$$\mathrm{Br}(\chi_{c0} \to J/\psi\gamma) = 0.007,\ \mathrm{Br}(\chi_{c1} \to J/\psi\gamma) = 0.27,\ \mathrm{Br}(\chi_{c2} \to J/\psi\gamma) = 0.14.$$

Then we obtain

$$\frac{\Gamma(B_c^+ \to \chi_{c0,c1,c2}\pi^+ \to J/\psi\pi^+\gamma)}{\Gamma(B_c^+ \to J/\psi\pi^+)} = 0.21, \tag{25}$$

and

$$\frac{\Gamma(B_c^+ \to \chi_{c0,c1,c2}\rho^+ \to J/\psi\rho^+\gamma)}{\Gamma(B_c^+ \to J/\psi\rho^+)} = 0.26. \tag{26}$$

Thus, we see that the correction to the J/ψ yield in the hadronic two-particle decays of B_c due to the indirect mechanism with the P-wave charmonium is about 20-25%. In contrast, analogous contribution to the semileptonic decays of B_c is significantly smaller, and the corresponding fraction due to the P-wave charmonium is about 5% [10].

Supposing $a_1 = 1.1$, we get

$$\mathrm{Br}(B_c^+ \to J/\psi\pi^+) + \mathrm{Br}(B_c^+ \to J/\psi\rho^+) \approx 2.8\%, \tag{27}$$

and in the B_c decays to J/ψ with radiative transitions of $\chi_{c0,c1,c2}$ the correction is equal to

$$\mathrm{Br}(B_c^+ \to J/\psi\pi^+\gamma) + \mathrm{Br}(B_c^+ \to J/\psi\rho^+\gamma) = 0.64\%. \tag{28}$$

4 Conclusion

In this paper we have considered the hadronic two-particle decays of B_c meson with large recoils in the technique of hard-soft factorization for the matrix elements. This factorization is based on the physical separation of hard rescattering of the constituents composing the heavy quarkonia (the scale of virtualities $\sim 1 - 1.5$ GeV^2) from the soft binding of heavy quarks (the scale of virtualities $\sim 0.3 - 0.45$ GeV^2). Hard factors can be calculated in the perturbative QCD, while the soft ones are expressed in terms of wave functions and their derivatives at the origin for S, P and D-wave levels of heavy quarkonia. We have calculated the widths of $B_c^+ \to c\bar{c}[^{2S+1}L_J]\pi^+(\rho^+)$ decays for the charmonium in the final states (see Tables 1, 2). We have found that the results for the ratios of widths are quite stable under the variation of model parameters, while the absolute values have rather large uncertainties, especially because of variation of charmed quark mass, that reflects the main systematic uncertainty due to the approximation of zero binding energy in the charmonium. We have compared our results with the potential model [6, 7] operating with the wave function overlapping. The relative momentum of charmed quarks inside the charmonium states (especially inside the excited P and D-waves, where the relative velocity of heavy quarks becomes less than for the S-levels) is rather small in comparison with the recoil momentum, so that the overlapping is displaced into the exponentially

suppressed region, where the wave function formalism is not reliable. In this region the hard gluon corrections replacing the exponential behavior of the quark-meson form factors by the power one are significant. Thus, we expect significant yields of excited charmonium states in the two-particle decays of B_c. This increase results in the additional 20-25% fraction of $J/\psi\pi$ inclusive branching ratio due to the contribution caused by the radiative electromagnetic transitions of P-wave charmonium states.

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