Hadronic absorption cross sections of B_c

M. A. K. Lodhi,[1,*] Faisal Akram,[2,†] and Shaheen Irfan[2,‡]
[1]*Department of Physics, MS 1051, Texas Tech University, Lubbock, Texas 79409, USA*
[2]*Center for High Energy Physics, Punjab University, Lahore, Pakistan*

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The cross sections of B_c absorption by π mesons are calculated using a hadronic Lagrangian based on the SU(5) flavor symmetry. Calculated cross sections are found to be in the ranges 2–7 mb and 0.2–2 mb for the processes $B_c^+\pi \to DB$ and $B_c^+\pi \to D^*B^*$, respectively, when the monopole form factor is included. These results could be useful in calculating the production rate of B_c mesons in relativistic heavy ion collisions.

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I. INTRODUCTION

Matsui and Satz [1] postulated that J/ψ would be dissociated due to color Debye screening in a deconfined phase of hadronic matter, called Quark-Gluon Plasma (QGP). Thus suppression of J/ψ could be regarded as a signal for the existence of QGP. The NA50 experiment at CERN [2] has observed an anomalously large suppression of events with moderate to large transfer energy from the Pb + Pb collision at $P_{\rm Lab} = 158$ GeV/c. However, this observed suppression may also occur due to absorption by comoving hadrons. It has been argued by many authors that this phenomenon could be significant if the absorption cross section is in the range of at least a few milibarns [3–8]. Extensive work has been done to calculate these cross sections using the perturbative QCD [9], QCD sum-rule approach [10], quark potential models [11], and the hadronic Lagrangian based on flavor symmetry [12–15].

Bottomonium states analogous to charmonium are also subjected to dissociation due color screening [1]; therefore their suppression is also expected in the QGP. Recently the most striking observation from the CMS (compact muon solenoid experiment) is that weakly bound states of the bottom quark are heavily suppressed in Pb + Pb collisions [16]. This phenomenon is important for understanding the properties of the QGP. Once again the knowledge of the absorption cross section is required to interpret the observed signal [12,17]. It has also been suggested that the production rate of heavy mixed flavor hadrons would also be affected in the presence of QGP [18,19]. In order to calculate production rates, one requires complete knowledge of the production mechanism in the presence of QGP and absorption cross sections by comoving hadrons. In this paper we have focused on the B_c meson. It is expected that B_c production could be enhanced in the presence of QGP. Due to color Debye screening, QGP contains many unpaired $b(\overline{b})$ and $c(\overline{c})$ quarks, which upon encounter could form B_c and probably survive in QGP due to the relatively large binding energy [20]. However, the observed production rate would also depend upon the absorption cross section by hadronic comovers. The B_c absorption cross section by nucleons has been calculated in [20] using the meson-baryon exchange model. This cross section is found to have a value on the order of few millibarns. In this paper, we have calculated B_c absorption cross sections by π mesons using a hadronic Lagrangian based on the SU(5) flavor symmetry.

In Sec. II, we define the hadronic Lagrangian and derive the interaction term relevant for B_c absorption of π mesons. In Sec. III, we calculate the absorption cross sections. In Sec. IV, we discuss the numerical values of different couplings used in the calculation. In Sec. V, we present numerical results of the cross sections with and without a form factor. Finally, some concluding remarks are made in Sec. VI.

II. INTERACTION LAGRANGIAN

The following processes are studied in this work using the SU(5) flavor symmetric Lagrangian:

$$B_c^+\pi \to DB,\ B_c^-\pi \to \overline{DB},\ B_c^+\pi \to D^*B^*,$$
$$B_c^-\pi \to \overline{D}^*\overline{B}^*. \tag{1}$$

The first and second processes are charge conjugations of each other and hence have the same cross sections. Similarly the third and fourth processes are also charge conjugations of each other and have the same cross sections.

To calculate the cross sections of the above processes, we use the SU(5) flavor symmetric Lagrangian density [12]. The free SU(5) Lagrangian density is given by

$$\mathcal{L}_0 = \mathrm{Tr}(\partial_\mu P^\dagger \partial^\mu P) - \tfrac{1}{2}\mathrm{Tr}(F_{\mu\nu}^\dagger F^{\mu\nu}), \tag{2}$$

where $F_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$, and P and V_μ denote pseudoscalar and vector mesons matrices respectively as given in Ref. [12].

The following minimal substitutions,

$$\partial_\mu P \to D_\mu P = \partial_\mu P - \frac{ig}{2}[V_\mu, P], \tag{3}$$

$$F_{\mu\nu} \to F_{\mu\nu} - \frac{ig}{2}[V_\mu, V_\nu], \tag{4}$$

*a.lodhi@ttu.edu
†Corresponding author: faisal.chep@pu.edu.pk
‡shaheen.irfan@ciitlahore.edu.pk

produce the following interaction Lagrangian density

$$\mathcal{L} = \mathcal{L}_0 + ig\mathrm{Tr}(\partial^\mu p[P, V_\mu]) - \frac{g^2}{4}\mathrm{Tr}([P, V_\mu]^2) + ig\mathrm{Tr}(\partial^\mu V^\nu [V_\mu, V_\nu]) + \frac{g^2}{8}\mathrm{Tr}([V_\mu, V_\nu]^2). \quad (5)$$

All mass terms, which breaks SU(5) symmetry, are added directly in the above Lagrangian. The Lagrangian density terms relevant for B_c absorption by π mesons are given by

$$\mathcal{L}_{\pi DD^*} = ig_{\pi DD^*} D^{*\mu} \vec{\tau} \cdot (\overline{D}\partial_\mu \vec{\pi} - \partial_\mu \overline{D}\vec{\pi}) + \mathrm{H.c.}, \quad (6a)$$

$$\mathcal{L}_{\pi BB^*} = ig_{\pi BB^*} \overline{B}^{*\mu} \vec{\tau} \cdot (B\partial_\mu \vec{\pi} - \partial_\mu B\vec{\pi}) + \mathrm{H.c.}, \quad (6b)$$

$$\mathcal{L}_{B_c BD^*} = ig_{B_c BD^*} D^{*\mu}(B_c^- \partial_\mu B - \partial_\mu B_c^- B) + \mathrm{H.c.}, \quad (6c)$$

$$\mathcal{L}_{B_c B^* D} = ig_{B_c B^* D} \overline{B}^{*\mu}(B_c^+ \partial_\mu \overline{D} - \partial_\mu B_c^+ \overline{D}) + \mathrm{H.c.}, \quad (6d)$$

$$\mathcal{L}_{\pi B_c D^* B^*} = -g_{\pi B_c D^* B^*} B_c^+ \overline{B}^{*\mu} \vec{\tau} \cdot \vec{\pi} \overline{D}_\mu^* + \mathrm{H.c.}, \quad (6e)$$

where

$$D = (D^0\ D^+), \overline{D} = (\overline{D}^0\ D^-)^T, D_\mu^* = (D_\mu^{*0}\ D_\mu^{*+}),$$
$$B = (B^+\ B^0)^T, B_\mu^* = \left(B_\mu^{*+}\ B_\mu^{*0}\right)^T, \quad (7)$$
$$\vec{\pi} = (\pi_1, \pi_2, \pi_3), \pi^\pm = \frac{1}{\sqrt{2}}(\pi_1 \mp i\pi_2).$$

Here we follow the convention of representing a field by the symbol of the particle which it absorbs. The coupling constants in Eq. (6) are expressed in terms of the SU(5) universal coupling constant g as follows:

$$g_{\pi DD^*} = g_{\pi BB^*} = \frac{g}{4}, \quad g_{B_c BD^*} = g_{B_c B^* D} = \frac{g}{2\sqrt{2}}, \quad (8)$$
$$g_{\pi B_c D^* B^*} = \frac{g^2}{4\sqrt{2}}.$$

It is also noted that the SU(5) symmetry also implies the following relation between the couplings:

$$g_{\pi B_c D^* B^*} = 2g_{\pi DD^*} g_{B_c B^* D} = 2g_{\pi BB^*} g_{B_c BD^*}. \quad (9)$$

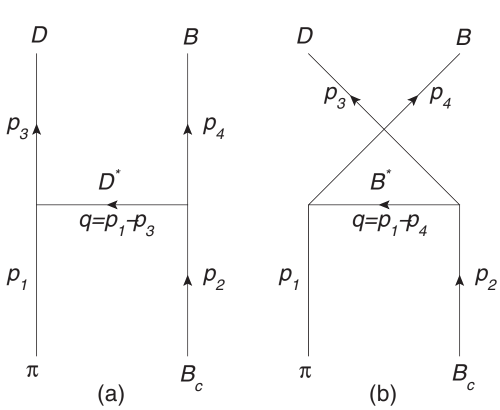

FIG. 1. Feynman diagrams for B_c absorption process $B_c^+\pi \to DB$.

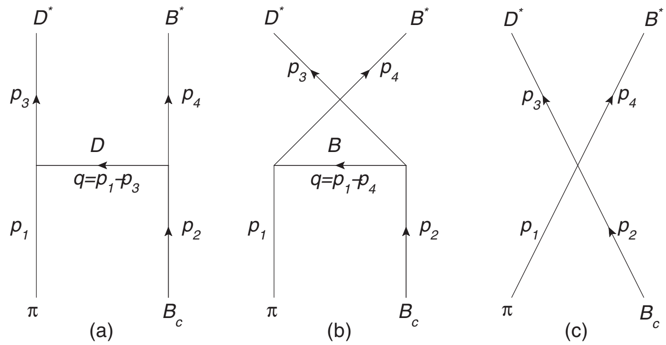

FIG. 2. Feynman diagrams for B_c absorption process $B_c^+\pi \to D^*B^*$.

III. B_c ABSORPTION CROSS SECTION

Feynman diagrams of the process $B_c^+\pi \to DB$ are shown in Fig. 1.

Scattering amplitudes of these diagrams are given by

$$M_{1a} = g_{\pi DD^*} g_{B_c BD^*}(p_1 + p_3)_\mu \frac{-i}{t - m_{D^*}^2} \times \left(g^{\mu\nu} - \frac{(p_1 - p_3)^\mu (p_1 - p_3)^\nu}{m_{D^*}^2}\right)(-p_4 - p_2)_\nu, \quad (10a)$$

$$M_{1b} = g_{\pi BB^*} g_{B_c B^* D}(p_1 + p_4)_\mu \frac{-i}{u - m_{B^*}^2} \times \left(g^{\mu\nu} - \frac{(p_1 - p_4)^\mu (p_1 - p_4)^\nu}{m_{B^*}^2}\right)(-p_3 - p_2)_\nu. \quad (10b)$$

Total amplitude is given by

$$M_1 = M_{1a} + M_{1b}. \quad (11)$$

Feynman diagrams of the process $B_c^+\pi \to D^*B^*$ are shown in Fig. 2.

Scattering amplitudes of these diagrams are given by

$$M_{2a} = -g_{\pi DD^*} g_{B_c B^* D}(2p_1 - p_3)_\mu \frac{i}{t - m_D^2} \times (p_2 - p_1 + p_3)_\nu \varepsilon_r^\mu(p_3)\varepsilon_s^\nu(p_4), \quad (12a)$$

$$M_{2b} = -g_{\pi BB^*} g_{B_c BD^*}(2p_1 - p_4)_\mu \frac{i}{u - m_B^2} \times (p_2 - p_1 + p_4)_\nu \varepsilon_r^\mu(p_3)\varepsilon_s^\nu(p_4), \quad (12b)$$

$$M_{2c} = -ig_{\pi B_c B^* D^*} g_{\mu\nu} \varepsilon_r^\mu(p_3)\varepsilon_s^\nu(p_4), \quad (12c)$$

TABLE I. Values of coupling constants used in this paper.

Coupling constant	Value	Method of derivation
$g_{\pi DD^*}$	4.4	D^* decay width
$g_{\pi BB^*}$	12.4	Heavy quark symmetries
$g_{B_c BD^*}$ and $g_{B_c B^* D}$	11.9	VMD, SU(5) symmetry
$g_{\pi B_c B^* D^*}$	105 to 295	SU(5) symmetry

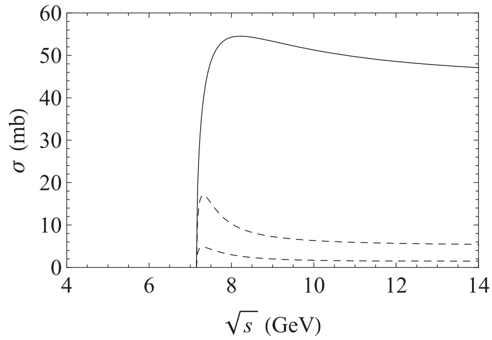

FIG. 3. B_c absorption cross sections for the process $B_c^+\pi \to DB$. Solid and dashed curves represent cross sections without and with form factors, respectively. Lower and upper dashed curves are with cutoff parameters $\Lambda = 1$ and 2 GeV, respectively. Threshold energy is 7.15 GeV.

and total amplitude is given by

$$M_2 = M_{2a} + M_{2b} + M_{2c}. \tag{13}$$

Using the total amplitudes given in Eqs. (11) and (13), we calculate the unpolarized but not the isospin averaged cross sections. The isospin factor in this case is simply 2 for the both processes.

IV. NUMERICAL VALUES OF INPUT PARAMETERS

Numerical values of all the masses are taken from the Particle Data Group [21]. The coupling constant $g_{\pi DD^*} = 4.4$ is determined from the D^* decay width [22,23]. The coupling $g_{\pi BB^*}$ can be fixed by two methods. Heavy quark symmetries [23–25] imply that $g_{\pi BB^*} \approx g_{\pi DD^*}\frac{m_B}{m_D} = 12.4$, and from the light-cone QCD sum rule [23], we obtain $g_{\pi BB^*} = 10.3$. In this paper, we use the value obtained from the former method.

The values of the couplings $g_{B_cBD^*}$ and $g_{B_cB^*D}$ are fixed by using $g_{\Upsilon BB} = 13.3$, which is obtained using the vector meson dominance (VMD) model in Ref. [12] and the SU(5) symmetry result $g_{B_cBD^*} = g_{B_cB^*D} = \frac{2}{\sqrt{5}}g_{\Upsilon BB}$ [20]. In this way we obtain $g_{B_cBD^*} = g_{B_cB^*D} = 11.9$.

There is no empirically fitted value available for the four-point coupling $g_{\pi B_cB^*D^*}$; thus we use the SU(5) symmetry, which implies $g_{\pi B_cD^*B^*} = 2g_{\pi DD^*}g_{B_cB^*D} = 2g_{\pi BB^*}g_{B_cBD^*}$. These two identities give two values of 105 and 295, whereas their mean values in 200. The values of the coupling constants used in this paper and methods for obtaining them are summarized in Table I.

V. RESULTS AND DISCUSSION

Figure 3 shows the B_c absorption cross sections of the process $B_c^+\pi \to DB$ as a function of the total c.m. energy $\sqrt{s}$. The solid and dashed curves in this figure represent cross sections without and with form factors, respectively. Form factors are included to account for the finite size of the interacting hadrons. We use the following monopole form factor at three-point vertices:

$$f_3 = \frac{\Lambda^2}{\Lambda^2 + \overline{q}^2}, \tag{14}$$

where Λ is the cutoff parameter, and $\overline{q}^2$ is the squared three-momentum transfer in the c.m. frame. At the four-point vertex, we use the following form factor:

$$f_4 = \left(\frac{\Lambda^2}{\Lambda^2 + \overline{q}^2}\right)^2, \tag{15}$$

where $\overline{q}^2 = \frac{1}{2}[(\overline{p}_1 - \overline{p}_3)^2 + (\overline{p}_1 - \overline{p}_4)^2]_{\text{c.m.}}$.

In general, the value of the cutoff parameter used in the form factor could have different values at different vertices. There is no direct way to calculate the values of these parameters. In some cases cutoff parameters can be fixed empirically by studying hadronic scattering data in meson or baryon exchange models. Such empirical fits put the cutoff parameters on the scale of 1 to 2 GeV for the vertices connecting light hadrons (π, K, ρ, N, etc.) [26]. However, due to limited information about the scattering data of charmed and bottom hadrons, no empirical values of the related cutoff parameters are known. In this case we can estimate cutoff parameters by relating them with the inverse (rms) size of hadrons. The cutoff parameter for the meson-meson vertex is determined by the ratio of the

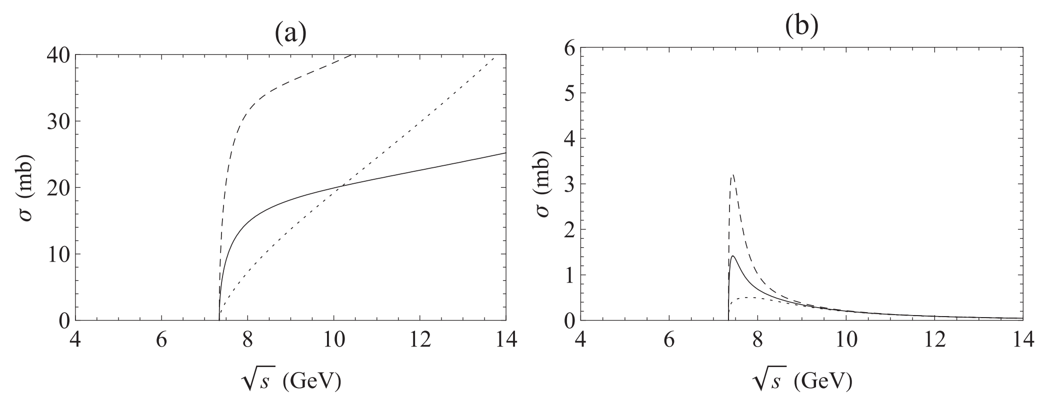

FIG. 4. B_c absorption cross sections of the process $B_c^+\pi \to D^*B^*$ for three different values of the four-point coupling $g_{\pi B_cB^*D^*} =$ 105, 200, 295 for dotted, solid, and dashed curves, respectively (a) without and (b) with the form factor. Cutoff parameter is taken at 1.5 GeV.

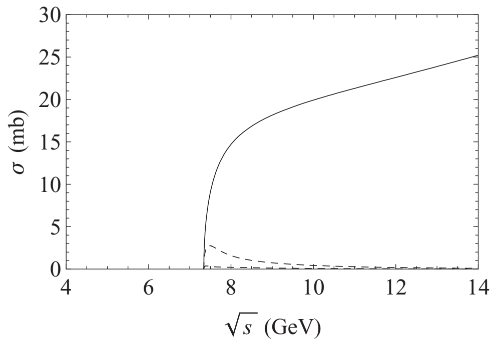

FIG. 5. B_c absorption cross sections for the process $B_c^+\pi \to D^*B^*$. Solid and dashed curves represent cross sections without and with the form factor, respectively. Lower and upper dashed curves are with cuttoff parameters $\Lambda = 1$ and 2 GeV, respectively, and $g_{\pi B_c B^* D^*} = 200$. Threshold energy is 7.34 GeV.

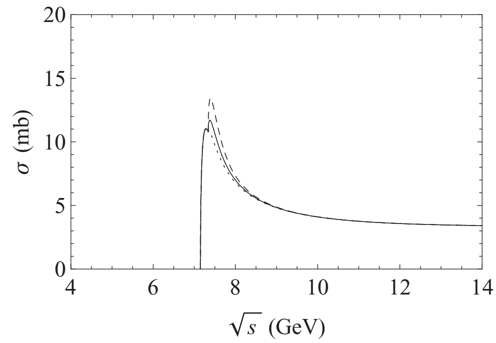

FIG. 6. Total B_c absorption cross sections by pions for three different values of the four-point coupling $g_{\pi B_c B^* D^*} = 105, 200, 295$ for dotted, solid, and dashed curves, respectively. Cutoff parameter is taken 1.5 GeV.

size of the nucleon to the pseudoscalar meson in Ref. [27]:

$$\Lambda_D = \frac{r_N}{r_D}\Lambda_N, \qquad \Lambda_B = \frac{r_N}{r_B}\Lambda_N. \tag{16}$$

The values of the ratios $r_N/r_D = 1.35$ and $r_N/r_B = 1.29$ are determined by the quark potential model for D and B mesons, respectively [27]. The cutoff parameter Λ_N for the nucleon-meson vertex can be determined from the empirical data of the nucleon-nucleon system. In Ref. [27] $\Lambda_N = 0.94$ GeV is fixed from the empirical value of the binding energy of deuterium, whereas nucleon-nucleon scattering data give $\Lambda_{\pi NN} = 1.3$ GeV and $\Lambda_{\rho NN} = 1.4$ GeV [28]. A variation of 0.9 to 1.4 GeV in Λ_N produces a variation of 1.2 to 1.8 GeV in Λ_D and Λ_B. Based on these results we take all the cutoff parameters to be the same for simplicity and vary them on the scale 1 to 2 GeV to study the uncertainties in cross sections due to the cutoff parameter.

Figure 3 shows that for the $B_c^+\pi \to DB$ process the cross section roughly varies from 2 to 7 mb, when the cutoff parameter is between 1 to 2 GeV. The suppressions due to form factor at cutoff values $\Lambda = 1$ and 2 GeV is roughly by factors of 11 and 3, respectively.

The B_c absorption cross section of the process $B_c^+\pi \to D^*B^*$ depends upon the four-point contact coupling $g_{\pi B_c B^* D^*}$, whose value is fixed through the SU(5) symmetry. It is noted in the previous section that although SU(5) symmetry uniquely fixes it, the difference in the values of the couplings $g_{\pi DD^*}$ and $g_{\pi BB^*}$ produces two values 105 and 295 of the four-point contact coupling. In this paper, we treat this variation as an uncertainty in the coupling and study its effect on the cross section of the process. Figure 4(a), shows how the value of the four-point coupling could affect the values of B_c absorption cross sections through the process $B_c^+\pi \to D^*B^*$ without the form factor. Both of the cross sections increase very rapidly for the values 105 and 295, which are not realistic. However, if we use the value of 200, the average to two extreme values, the variation in the cross section, denoted by the solid line is some what of a compromise. Figure 4(b), shows the effect of the uncertainty in the four-point contact coupling on the cross section with the form factor. This figure indicates that the value of the contact coupling significantly affects the cross section only near the threshold energy (7.34 GeV). It will be discussed later that this effect is further marginalized in the total absorption cross section.

Figure 5 shows the B_c absorption cross sections of the process $B_c^+\pi \to D^*B^*$ as a function of total c.m. energy $\sqrt{s}$. The cross section of the process roughly varies from 0.2 to 2 mb, when the cutoff parameter is between 1 to 2 GeV and $g_{\pi B_c B^* D^*} = 200$. The suppressions due to form factor at cutoff values $\Lambda = 1$ and 2 GeV is roughly by factors of 45 and 7, respectively. Relatively high suppressions in this process are mainly due to the large values of mass of the final particles D^* and B^*. It is noted that these estimates of the cross sections are highly dependent on the choice of the form factor and the value of the cutoff, as well as on the values of the coupling constants. However, it is observed that the effect of the uncertainty in the four-point contact coupling $g_{\pi B_c B^* D^*}$ is marginal on the total cross section due to the relatively small value of the cross section of the second process. This is shown in the Fig. 6, in which total absorption cross section for $B_c + \pi$ is plotted for three different values of $g_{\pi B_c B^* D^*} = 105$, 200, 295.

VI. CONCLUDING REMARKS

In this paper, we have calculated the B_c absorption cross section by π mesons using the hadronic Lagrangian based on the SU(5) flavor symmetry. This approach has already been used for calculating absorption cross sections of J/ψ and Υ mesons by hadrons. In our study, all the coupling constants are preferably determined empirically using the vector meson dominance model, heavy quark symmetries, or QCD sum rules instead of using the SU(5) symmetry. The hadronic Lagrangian based on the SU(5) flavor symmetry is developed by imposing the gauge symmetry, but this symmetry is broken when the mass terms are added in the Lagrangian. Thus SU(5) gauge symmetry exists only in the limit of zero hadronic masses. Broken SU(5) symmetry does not necessarily imply that the coupling constants of three- or four-point vertices should be related through the SU(5) universal coupling constant. It is, therefore, justified to empirically fix the couplings. It can also be seen that the empirical values of the couplings also violate SU(5) symmetry relations given in Eqs. (8) and (9). It is also noted that the four-point coupling constant $g_{\pi B_c B^* D^*}$ cannot be fixed empirically. Thus in this case we have no choice except to make a reasonable estimate using the SU(5) symmetry as discussed above. Calculated cross sections are found to be in the ranges 2–7 mb and 0.2–2 mb for the processes $B_c^+\pi \to DB$ and $B_c^+\pi \to D^*B^*$, respectively, when the form factor is included. These results could be useful in calculating the production rate of the B_c meson in relativistic heavy ion collisions.

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