B_c absorption cross sections by ρ mesons

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The cross sections of B_c absorption by ρ mesons are calculated using a meson-exchange model based on a hadronic Lagrangian having SU(5) symmetry. Calculated cross sections are found to be in the ranges 0.6–3 and 0.05–0.3 mb for the processes $B_c^+\rho \rightarrow D^*B$ and $B_c^+\rho \rightarrow DB^*$, respectively, when the monopole form factor is included. The total B_c absorption cross section by ρ mesons is found to be about three times smaller than the calculated total cross section by pions using the same model. 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

Recently, B_c absorption cross sections by pions were calculated using a meson-exchange model based on the hadronic Lagrangian having SU(5) symmetry [1]. Calculated cross sections are found to be in the ranges 2–7 and 0.2–2 mb for the processes $B_c^+\pi \rightarrow DB$ and $B_c^+\pi \rightarrow D^*B^*$, respectively, when the appropriate form factors of the participating particles are included. It thus seems a natural sequence to examine the similar contribution by the other light unflavored ($S = C = B = 0$) mesons, such as ρ mesons. In this paper, we accordingly present the B_c absorption cross sections by ρ mesons using the same hadronic Lagrangian [2]. The motivation for these calculations, in fact, comes from the long time suggestion of Matsue and Satz [3] for the suppression of J/ψ production due to color Debye screening in quark-gluon plasma (QGP) and the following work, which we would like to mention here briefly.

The observed suppression at CERN [4] and Brookhaven's Relativistic Heavy Ion Collider [5] could have also occurred because of the interaction of J/ψ with comoving hadrons, mainly pions, ρ mesons, and nucleons [6]. Owing to the large density of these comovers the effect of the interaction could be significant even for a relatively small value of the absorption cross section, only a few millibarns [7]. Another increase in J/ψ suppression due to absorption is expected if a $c\bar{c}$ pair exists in a color octet state for a sufficiently long time before forming the color singlet state of J/ψ [8]. However, it was also suggested in Refs. [9,10] that, at the higher collision energy accessible at LHC, large $c\bar{c}$ pair production could result in J/ψ enhancement due to a recombination effect in QGP. Recent studies of J/ψ in ALICE (A Large Ion Collider Experiment) at LHC hint at this regeneration effect [11]. Generally, one requires complete knowledge of the production mechanism in the presence of QGP and absorption cross sections by comoving hadrons to calculate the production rate for any experiment designed to study QGP. The required hadronic absorption cross sections of J/ψ cannot be determined directly in present experiments. Empirical studies of J/ψ photoproduction from nucleons and nuclei [12] and J/ψ production from nucleon-nucleus [13] interactions show that J/ψ-nucleon cross sections range from ∼1 to ∼7 mb. Theoretically, these cross sections were calculated using perturbative QCD [14], the QCD sum-rule approach [15], quark potential models [16], and meson-baryon exchange models based on the hadronic Lagrangians having flavor symmetries [17–19]. Bottomonium states analogous to charmonium are also affected in QGP due to color Debye screening. Recently, the most striking observation from the Compact Muon Solenoid (CMS) experiment is that excited states of the Υ are heavily suppressed in Pb+Pb collisions [20]. Once again, knowledge of absorption cross sections is required to interpret the observed signal. In this case the required absorption cross sections of Υ by π and ρ mesons are calculated using the meson exchange model based on the hadronic Lagrangian having SU(5) symmetry [2]. The results of Ref. [2] suggest that the effect of Υ absorption by hadronic comovers may be insignificant due to smaller values of the absorption cross sections and a higher value of the threshold energy.

Apart from the systems of quarkonia, the studies of the production of heavy mixed-flavor mesons and baryons in QGP were also proposed [21–23]. It is expected that B_c production could be enhanced in the presence of QGP [21]. Owing to color Debye screening, QGP contains many unpaired $b(\bar{b})$ and $c(\bar{c})$ quarks, which upon encounter could form B_c and probably survive in QGP due to the relatively large binding energy [24]. A similar effect is also suggested for Ξ_{bc} and Ω_{ccc} baryons in Ref. [23]. Once again, the knowledge of the absorption cross sections by hadronic comovers is required to interpret the observed signal. B_c absorption cross sections by nucleons were calculated in Refs. [24,25] using a meson-baryon exchange model. These cross sections are found to have values on the order of a few millibarns.

In Sec. II, we define the hadronic Lagrangian density and derive the interaction terms relevant for B_c absorption by ρ 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 the

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results of cross sections with and without 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:

$$\begin{aligned} &B_c^+\rho \to D^*B, \quad B_c^-\rho \to \overline{D}^*\overline{B}, \\ &B_c^+\rho \to DB^*, \quad B_c^-\rho \to \overline{DB}^*. \end{aligned} \tag{1}$$

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 these processes, we require the following interaction Lagrangian densities:

$$\begin{aligned} \mathcal{L}_{\rho DD} &= ig_{\rho DD}(D\vec{\tau}\partial_\mu\overline{D} - \partial_\mu D\vec{\tau}\overline{D})\cdot\vec{\rho}^{\,\mu}, \\ \mathcal{L}_{\rho BB} &= ig_{\rho BB}(\overline{B}\vec{\tau}\partial_\mu B - \partial_\mu\overline{B}\vec{\tau}B)\cdot\vec{\rho}^{\,\mu}, \\ \mathcal{L}_{\rho D^*D^*} &= ig_{\rho D^*D^*}[(\partial_\mu D^{*\nu}\vec{\tau}\overline{D}^*_\nu - D^{*\nu}\vec{\tau}\partial_\mu\overline{D}^*_\nu)\cdot\vec{\rho}^{\,\mu} \\ &\quad + (D^{*\nu}\vec{\tau}\cdot\partial_\mu\vec{\rho}_\nu - \partial_\mu D^{*\nu}\vec{\tau}\cdot\vec{\rho}_\nu)\overline{D}^{*\mu} \\ &\quad + D^{*\mu}(\vec{\tau}\cdot\vec{\rho}^{\,\nu}\partial_\mu\overline{D}^*_\nu - \vec{\tau}\cdot\partial_\mu\vec{\rho}^{\,\nu}\overline{D}^*_\nu)], \\ \mathcal{L}_{\rho B^*B^*} &= ig_{\rho B^*B^*}[(\partial_\mu\overline{B}^{*\nu}\vec{\tau}B^*_\nu - \overline{B}^{*\nu}\vec{\tau}\partial_\mu B^*_\nu)\cdot\vec{\rho}^{\,\mu} \\ &\quad + (\overline{B}^{*\nu}\vec{\tau}\cdot\partial_\mu\vec{\rho}_\nu - \partial_\mu\overline{B}^{*\nu}\vec{\tau}\cdot\vec{\rho}_\nu)B^{*\mu} \\ &\quad + \overline{B}^{*\mu}(\vec{\tau}\cdot\vec{\rho}^{\,\nu}\partial_\mu B^*_\nu - \vec{\tau}\cdot\partial_\mu\vec{\rho}^{\,\nu}B^*_\nu)], \\ \mathcal{L}_{B_cBD^*} &= ig_{B_cBD^*}D^{*\mu}(B_c^-\partial_\mu B - \partial_\mu B_c^- B) + \text{H.c.}, \\ \mathcal{L}_{B_cB^*D} &= ig_{B_cB^*D}\overline{B}^{*\mu}(B_c^+\partial_\mu\overline{D} - \partial_\mu B_c^+\overline{D}) + \text{H.c.}, \\ \mathcal{L}_{\rho B_cD^*B} &= g_{\rho B_cD^*B}B_c^+\overline{B}\vec{\tau}\cdot\vec{\rho}_\mu\overline{D}^{*\mu} + \text{H.c.}, \\ \mathcal{L}_{\rho B_cDB^*} &= g_{\rho B_cDB^*}B_c^+\overline{B}^{*\mu}\vec{\tau}\cdot\vec{\rho}_\mu\overline{D} + \text{H.c.}, \end{aligned} \tag{2}$$

where

$$\begin{aligned} &D = \left(D^0\ D^+\right), \quad \overline{D} = (\overline{D}^0\ D^-)^T, \quad D^*_\mu = (D^{*0}_\mu\ D^{*+}_\mu), \\ &B = (B^+\ B^0)^T, \quad B^*_\mu = \left(B^{*+}_\mu\ B^{*0}_\mu\right)^T, \\ &\vec{\rho} = (\rho_1, \rho_2, \rho_3), \quad \rho^\pm = \frac{1}{\sqrt{2}}(\rho_1 \mp i\rho_2). \end{aligned} \tag{3}$$

Here we follow the convention of representing a field by the symbol of the particle that it absorbs. Pseudoscalar-pseudoscalar-vector meson (PPV), VVV, and PPVV couplings given in Eqs. (2) are obtained from the hadronic Lagrangian density based on SU(5) flavor symmetry [2]. In Ref. [2] the interaction Lagrangian of pseudoscalar and vector mesons is obtained by imposing the SU(5) gauge symmetry and treating all the vector mesons as the gauge particles. The coupling constants of the resultant PPV, VVV, and PPVV couplings are expressed in terms of the universal coupling constant g of SU(5) symmetry. The coupling constants of Eqs. (2) are given as follows:

$$\begin{aligned} g_{\rho DD} &= g_{\rho BB} = g_{\rho D^*D^*} = g_{\rho B^*B^*} = \frac{g}{4}, \\ g_{B_cBD^*} &= g_{B_cB^*D} = \frac{g}{2\sqrt{2}}, \\ g_{\rho B_cBD^*} &= g_{\rho B_cB^*D} = \frac{g^2}{8\sqrt{2}}. \end{aligned} \tag{4}$$

The following relation based on SU(5) symmetry is also noted for later use:

$$g_{\rho B_cBD^*} = g_{\rho B_cB^*D} = g_{\rho DD}g_{B_cB^*D} = g_{\rho BB}g_{\rho B_cBD^*}. \tag{5}$$

All the mass terms of vector mesons, which break the SU(5) symmetry, are added directly in the Lagrangian density. Thus, it is expected that the SU(5) symmetry relations given in the above equation are violated.

III. B_c ABSORPTION CROSS SECTIONS

Shown in Fig. 1 are the Feynman diagrams of the processes $B_c^+\rho \to D^*B$ and $B_c^+\rho \to DB^*$.

Scattering amplitudes of the diagrams of the first process are given by

$$M_{1a} = g_{\rho DD}g_{B_cBD^*}(2p_3 - p_1)_\mu\frac{i}{t - m_B^2}(p_4 - 2p_2)_\nu\,\varepsilon_r^\mu(p_1)\varepsilon_s^\nu(p_4), \tag{6a}$$

$$\begin{aligned} M_{1b} &= g_{\rho D^*D^*}g_{B_cBD^*}[(2p_4 - p_1)_\mu\,g_{\beta\nu} + (2p_1 - p_4)_\nu\,g_{\mu\beta} + (-p_4 - p_1)_\beta\,g_{\mu\nu}] \\ &\quad \times\frac{-i}{u - m_{D^*}}\left(g^{\alpha\beta} - \frac{(p_1 - p_4)^\alpha(p_1 - p_4)^\beta}{m_{D^*}^2}\right)(-p_3 - p_2)_\alpha\,\varepsilon_r^\mu(p_1)\varepsilon_s^\nu(p_4), \end{aligned} \tag{6b}$$

$$M_{1c} = ig_{\rho B_cBD^*}g_{\mu\nu}\varepsilon_r^\mu(p_1)\varepsilon_s^\nu(p_4). \tag{6c}$$

The total amplitude is given by

$$M_1 = M_{1a} + M_{1b} + M_{1c}. \tag{7}$$

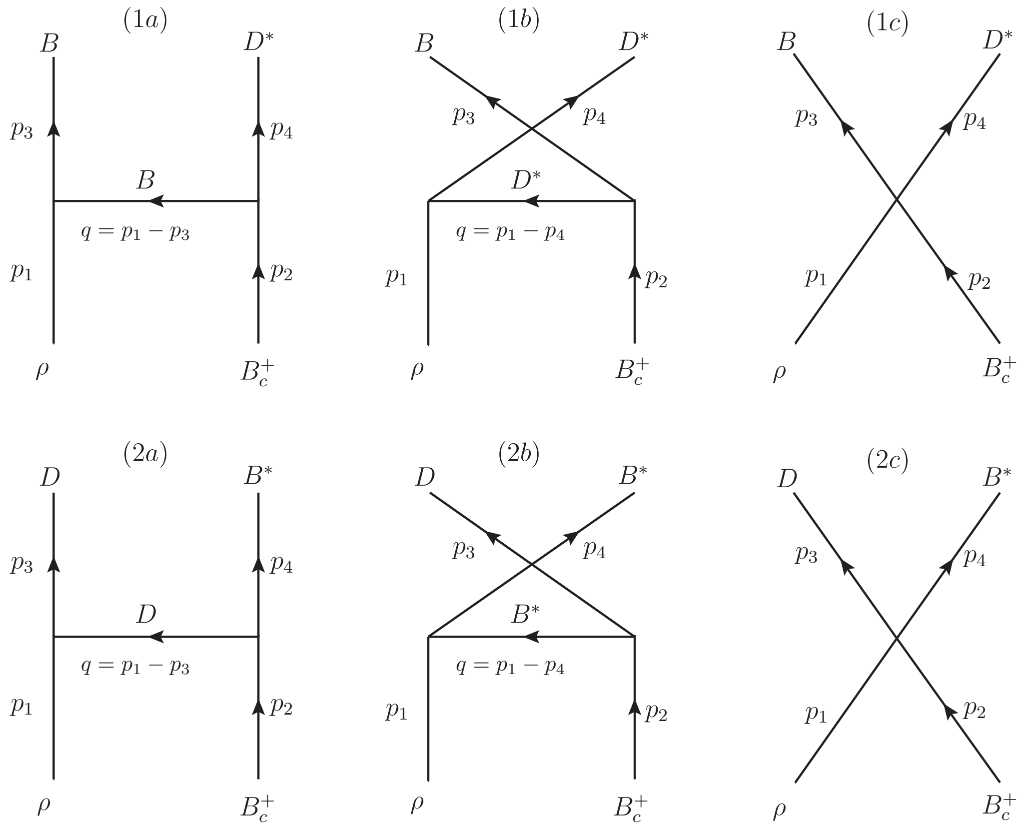

FIG. 1. Feynman diagrams of processes (a) $B_c^+\rho \to D^*B$ and (b) $B_c^+\rho \to DB^*$.

Scattering amplitudes of diagrams of the second process are given by

$$M_{2a} = g_{\rho DD}\, g_{B_cB^*D}\,(2p_3 - p_1)_\mu \frac{i}{t - m_D^2}(p_4 - 2p_2)_\nu\, \varepsilon_r^\mu(p_1)\varepsilon_s^\nu(p_4), \tag{8a}$$

$$\begin{aligned} M_{2b} = {} & g_{\rho B^*B^*}\, g_{B_cB^*D}[(2p_4 - p_1)_\mu\, g_{\beta\nu} + (2p_1 - p_4)_\nu\, g_{\mu\beta} + (-p_4 - p_1)_\beta\, g_{\mu\nu}] \\ & \times \frac{-i}{u - m_{B^*}}\left(g^{\alpha\beta} - \frac{(p_1 - p_4)^\alpha (p_1 - p_4)^\beta}{m_{B^*}^2}\right)(-p_3 - p_2)_\alpha\, \varepsilon_r^\mu(p_1)\varepsilon_s^\nu(p_4), \end{aligned} \tag{8b}$$

$$M_{2c} = i g_{\rho B_cB^*D}\, g_{\mu\nu}\varepsilon_r^\mu(p_1)\varepsilon_s^\nu(p_4). \tag{8c}$$

The total amplitude is given by

$$M_2 = M_{2a} + M_{2b} + M_{2c}. \tag{9}$$

Using the total amplitudes given in Eqs. (7) and (9), we calculate the unpolarized but not the isospin averaged cross sections as in Ref. [1]. The required isospin factor to calculate the isospin averaged cross section is 2 for both processes.

IV. NUMERICAL VALUES OF INPUT PARAMETERS

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. [2] and the SU(5) symmetry relation $g_{B_cBD^*} = g_{B_cB^*D} = \frac{2}{\sqrt{5}} g_{\Upsilon BB}$ [24]. In this way we obtain $g_{B_cBD^*} = g_{B_cB^*D} = 11.9$. In Refs. [2,18], the couplings $g_{\rho DD}$, $g_{\rho BB}$, $g_{\rho D^*D^*}$, and $g_{\rho B^*B^*}$ are also calculated using the VMD model. The results are given by

$$g_{\rho DD} = g_{\rho BB} = g_{\rho D^*D^*} = g_{\rho B^*B^*} = 2.52. \tag{10}$$

It is interesting to see that these VMD results are consistent with the SU(5) symmetry relations given in Eq. (4). There are no empirically fitted values available for the four-point contact couplings $g_{\rho B_cBD^*}$ and $g_{\rho B_cB^*D}$; thus, we use the SU(5) symmetry relations of Eq. (5), which imply

$$g_{\rho B_cBD^*} = g_{\rho B_cB^*D} = 30. \tag{11}$$

The values of the coupling constants used in this paper and the methods for obtaining them are summarized in Table I.

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

Coupling constant	Value	Method of derivation
$g_{\rho DD}$, $g_{\rho BB}$, $g_{\rho D^* D^*}$, $g_{\rho B^* B^*}$	2.52	VMD
$g_{B_c BD^*}$ and $g_{B_c B^* D}$	11.9	VMD, SU(5) symmetry
$g_{\rho B_c D^* B}$, $g_{\rho B_c DB^*}$	30	SU(5) symmetry

V. RESULTS AND DISCUSSION

Shown in Figs. 2(a) and 2(b) are the B_c absorption cross sections of the processes $B_c^+\rho \to D^*B$ and $B_c^+\rho \to DB^*$, respectively, as a function of the total center-of-mass (c.m.) energy $\sqrt{s}$. The solid and dashed curves in these figures represent cross sections without and with form factors, respectively. Form factors are included to account for the finite size of interacting hadrons. We use the following monopole form factor at three point vertices:

$$f_3 = \frac{\Lambda^2}{\Lambda^2 + \overline{q}^2}, \tag{12}$$

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:

$$f_4 = \left(\frac{\Lambda^2}{\Lambda^2 + \overline{q}^2}\right)^2, \tag{13}$$

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 cutoff parameter used in the form factor could have different values at different vertices. It is noted that the form factors and the related cutoff parameters can be determined by the theories of the interaction of the quark constituents of the participating hadrons [26]. Alternatively, the effect of the form factor can also be studied in the hadronic Lagrangian by the loop corrections to the tree level diagrams. To avoid the difficulties in applying these methods, we assume the form factor in the conventional monopole form as given in Eq. (12). The related 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 1–2 GeV for the vertices connecting light hadrons (π, K, ρ, N, etc.) [27]. However, because information about the scattering data of charmed and bottom hadrons is limited, 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 size of the nucleon to the pseudoscalar meson in Ref. [28]:

$$\Lambda_D = \frac{r_N}{r_D}\Lambda_N, \quad \Lambda_B = \frac{r_N}{r_B}\Lambda_N, \tag{14}$$

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 [28]. The cutoff parameter Λ_N for the nucleon-meson vertex can be determined from the empirical data of the nucleon-nucleon system. In Ref. [28], $\Lambda_N = 0.94$ 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 [29]. A variation of 0.9–1.4 GeV in Λ_N produces a variation of 1.2–1.8 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 a scale of 1 to 2 GeV to study the uncertainties in cross sections due to the cutoff parameter.

Figure 2(a) shows that for the process $B_c^+\rho \to D^*B$ the cross section roughly varies from 0.6 to 3 mb in most of the energy scale,[1] when the cutoff parameter is between 1 and 2 GeV. The reduction in the cross section due to the form factor at $\Lambda = 1$ and 2 GeV is roughly by factors of 6.5 and 1.6, respectively. However, Fig. 2(b) shows that for the process $B_c^+\rho \to DB^*$ the cross section roughly varies from 0.05 to 0.3 mb in most of the energy scale, when the cutoff parameter is between 1 and 2 GeV. The reduction in the cross section due to the form factor at $\Lambda = 1$ and 2 GeV is roughly by factors of 10 and 2.5, respectively. Thus, the total absorption cross section by ρ mesons varies from 0.65 to 3.3 mb. The scale of this variation is about three times smaller than the calculated variation of the total absorption cross section by pions in Ref. [1], using the same model.

[1]These approximate variations are defined for $\sqrt{s} \geqslant 8$ GeV.

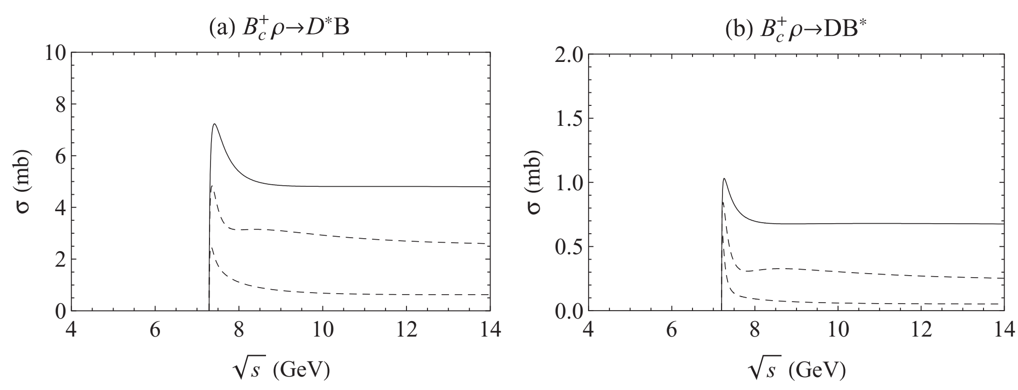

FIG. 2. B_c absorption cross sections of the processes (a) $B_c^+\rho \to D^*B$ and (b) $B_c^+\rho \to DB^*$. Solid and dashed curves represent cross sections without and with the form factor, respectively. Lower and upper dashed curves use cutoff parameter $\Lambda = 1$ and 2 GeV, respectively. Threshold energies are (a) 7.29 GeV and (b) 7.2 GeV.

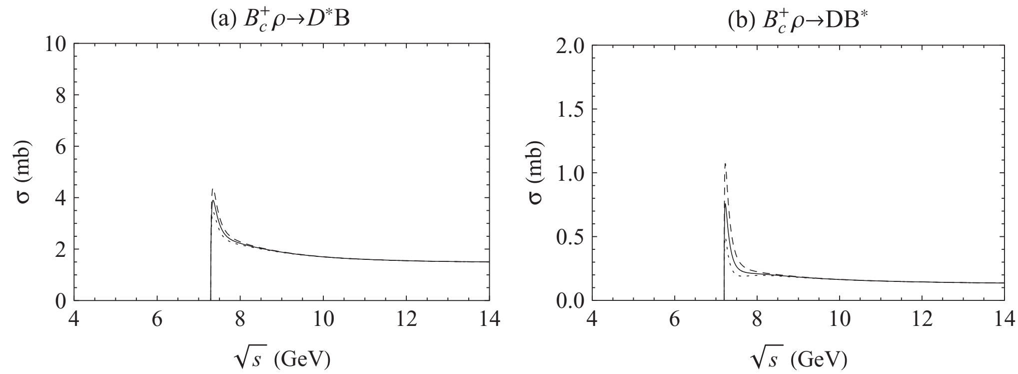

FIG. 3. B_c absorption cross sections of the processes (a) $B_c^+\rho \to D^*B$ and (b) $B_c^+\rho \to DB^*$ for three different values of the four-point couplings $g_{\rho B_c B D^*}$ and $g_{\rho B_c B^* D} = 15$, 30, and 45 for dotted, solid, and dashed curves, respectively. The cutoff parameter is taken as 1.5 GeV.

It is noted that the B_c absorption cross sections by ρ mesons depend upon the four-point contact couplings $g_{\rho B_c B D^*}$ and $g_{\rho B_c B^* D}$, whose values are fixed through the SU(5) symmetry. This symmetry is broken by the mass terms of the vector mesons in the Lagrangian. Thus, it is expected that estimated values of these couplings are less reliable. To study the role of these couplings in fixing the values of the cross sections, we calculate the absorption cross sections of the processes $B_c^+\rho \to D^*B$ and $B_c^+\rho \to DB^*$ for three different values of four-point couplings $g_{\rho B_c B D^*}$ and $g_{\rho B_c B^* D} = 15$, 30, and 45. The results given in Figs. 3(a) and 3(b) show that for both of the processes the effect of uncertainty in the four-point couplings is marginal. Thus, any change in the values of these four-point couplings cannot significantly affect the results reported in this paper.

VI. CONCLUDING REMARKS

In this paper, we have calculated B_c absorption cross sections by ρ 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 light hadrons and recently of the mixed-flavor B_c meson absorption by nucleons and pions. In our study, all the coupling constants are preferably determined empirically using the vector meson dominance model, 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 is also noted that the four-point coupling constants $g_{\rho B_c B D^*}$ and $g_{\rho B_c B^* D}$ cannot be fixed empirically. Thus, in this case we have no choice except to make an estimate using the SU(5) symmetry. The calculated total absorption cross section by ρ mesons is found to be in the range 0.65–3.3 mb, when the form factor is included. The scale of this variation is about three times smaller than the calculated variation of the total absorption cross section by pions using the same model. These results could be useful in calculating the production rate of the B_c meson in relativistic heavy-ion collisions.

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