Abstract

The cross sections of $B_c$ absorption by nucleons are calculated in meson-baryon exchange model using hadronic Lagrangian based on SU(4)/SU(5) flavor symmetries. The values of different coupling constants used in the model are obtained from vector meson dominance model, QCD sum rule or SU(4)/SU(5) flavor symmetries. Calculated values of cross sections are found to be significantly different from the previous study in which b-flavored hadron exchange is neglected. These results could be useful in calculating production rate of $B_c$ meson in relativistic heavy ion collisions.

Keywords: Relativistic heavy ion collisions, Meson-nucleon interaction, bottom-charm meson, QGP, Meson-Meson interaction.

1 Introduction

Suppression of $J/\psi$ due to color Debye screening in Quark-Gluon plasma (QGP) was suggested by T. Matsui and H. Satz [1]. However, this suppression may also occur due to interaction of $J/\psi$ with hadronic comover mainly pions, $\rho$ mesons and nucleons [2]. Due to large density of these comovers the effect of interaction could be significant even for a relatively small values of absorption cross section, a few mb [3]. Thus, the knowledge of absorption cross sections is required to interpret the observed suppression of $J/\psi$ in NA50 experiment at CERN [4]. Extensive work has been done to calculate these cross sections using perturbative QCD [5], QCD sum-rule approach [6], quark potential models [7] and meson-baryon exchange models based on hadronic Lagrangian [8, 9, 10]. Bottomonium states are also affected in the QGP due to color Debye screening [11, 12]. In this case the related absorption cross sections are calculated using meson-exchange model in Ref. 11. Recently the suppression of ground and excited states of $\Upsilon$ is observed in Pb+Pb collisions at CMS [13]. The observed suppression is expected to be the blend of different effects including initial and final states interactions with the comovers. Thus we require the knowledge of the cross sections of these interactions in order to separate any suppression occurring due to QGP.

In the Refs. [14, 15, 16] the studies of mixed flavor heavy hadrons are also suggested to probe the properties of QGP. These studies predict an enhancement in the production rate of heavy hadrons like $B_c$, meson, $\Xi_{bc}$, and $\Omega_{ccc}$ baryons due to QGP. However, once again the knowledge of interaction cross sections are required to separate any enhancement occurring due to QGP. In this regard $B_c$ absorption cross sections by the pions and $\rho$ mesons are recently calculated

* Corresponding author
† Department of Physics, MS 1051, Texas Tech University, Lubbock TX 79409, USA

May 11, 2014
in Ref. [18, 19]. Calculated cross sections are found to be in the range 2 to 7 mb and 0.2 to 2 mb for the processes $B_c^+ \pi \rightarrow DB$ and $B_c^+ \pi \rightarrow D^* B^*$ respectively, and 0.6 to 3 mb and 0.05 to 0.3 mb for the processes $B_c^+ \rho \rightarrow D^* B$ and $B_c^+ \rho \rightarrow DB^*$ respectively, when the form factor is included. $B_c$ absorption cross sections by nucleons have been calculated in Ref. [17] using meson-baryon exchange model. These cross sections are found to have values on the order of few mb. The calculations in Ref. [17] included only c-flavored hadron and did not include b-flavored hadron exchange processes which could significantly change the values of the cross sections. In this paper, we have calculated these cross sections again in meson-baryon exchange model and included the effect of b-flavor exchange as well as anomalous parity interaction. This paper is organized as follows. In section II we define hadronic Lagrangian density and derive the interaction terms relevant for $B_c$ absorption by nucleons. In section III we produce the amplitudes of the absorption processes. In section IV we discuss the numerical values of different coupling constants used in the calculations. In section V we present results of cross sections and study the effect of uncertainty in cutoff parameter. In section V the effect of anomalous parity interaction is discussed. Finally, some concluding remarks are made in the last section. The paper include an appendix in which derivation of SU(5) invariant Lagrangian of baryons interaction with mesons is given.

2 Interaction Lagrangian

The following processes are studied in this work using meson-baryon exchange model.

$$NB_c^+ \rightarrow \Lambda_c B, \quad NB_c^+ \rightarrow \Lambda_c B^*, \quad NB_c^- \rightarrow D \Lambda_b, \quad NB_c^- \rightarrow D^* \Lambda_b$$

(1)

It is noted that $B_c$ absorption by nucleons processes also include the channels in which $\Sigma_c^{(b)}$ is produced instead of $\Lambda_c^{(b)}$. The cross sections of these processes may be related to that of Eq. (1) through isospin symmetry and are not included in this study. To calculate the cross sections of the processes of Eq. (1) we require the following effective interaction Lagrangian densities.

$$\mathcal{L}_{B_cBD^*} = ig_{B_cBD^*} D^{\mu \nu} B_c^- B_c^+ \partial_\mu B - \partial_\nu B_c^+ B_c^- + hc$$

(2a)

$$\mathcal{L}_{B_cB^*D} = ig_{B_cB^*D} (B_c^+ \partial_\mu B - \partial_\mu B_c^+ B_c^-) + hc$$

(2b)

$$\mathcal{L}_{DN\Lambda_c} = ig_{DN\Lambda_c} (N^\gamma_5 \Lambda_c D + D N_{\gamma 5} N)$$

(2c)

$$\mathcal{L}_{D^*N\Lambda_c} = g_{D^*N\Lambda_c} (N^\gamma_5 \Lambda_c D^* + D^* N_{\gamma 5} N)$$

(2d)

$$\mathcal{L}_{B_{\Lambda_b}} = ig_{B_{\Lambda_b}} (\bar{N}^\gamma_5 \Lambda_b B + \bar{B}^\mu \gamma_5 \rho_{\gamma 5} N)$$

(2e)

$$\mathcal{L}_{B^*N\Lambda_b} = g_{B^*N\Lambda_b} (\bar{N}^\gamma_5 \Lambda_b B^* + \bar{B}^\mu \gamma_5 \Lambda_b N)$$

(2f)

$$\mathcal{L}_{B_{\Lambda_c}\Lambda_b} = ig_{B_{\Lambda_c}\Lambda_b} (\bar{N}^\gamma_5 \Lambda c \Lambda_b B_c^+ + \bar{B}^\mu \gamma_5 \Lambda c B_c^-)$$

(2g)

Where,

$$D = \begin{pmatrix} 0 & D^+ \\ D^0 & 0 \end{pmatrix}, \quad \bar{D} = \begin{pmatrix} D^0 & D^- \end{pmatrix}^T, \quad D^*_\mu = \begin{pmatrix} D^{*0}_\mu & D^{*+}_\mu \end{pmatrix}^T,$$

$$B = \begin{pmatrix} B^+ & B^0 \end{pmatrix}^T, \quad B^*_\mu = \begin{pmatrix} B^{*+}_\mu & B^{*0}_\mu \end{pmatrix}^T,$$

$$N = \begin{pmatrix} p & n \end{pmatrix}$$

(3)

Pseudoscalar-pseudoscalar-vector meson (PPV) couplings given in Eqs. (2a) and (2b) are obtained from the hadronic Lagrangian based on SU(5) gauge symmetry introduced in Ref. [11]. In this Lagrangian the coupling constant of different PPV, VVV and PPVV couplings are expressed in
Scattering amplitudes of these diagrams are given by,

\[ g_{\pi DD^*} = g_{\pi BB^*} = \frac{g}{4}, \quad g_{B_b B D^*} = g_{B_b B^* D} = \frac{g}{2\sqrt{2}} \]  

(4)

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 SU(5) symmetry relations given in Eq. 4 are violated.

Baryon-baryon-pseudoscalar meson (BBP) and baryon-baryon-vector meson (BBV) couplings given in Eqs. 2c to 2g can be obtained from the following SU(5) invariant Lagrangians [10, 20].

\[
\mathcal{L}_{BBP} = g_P (a\phi^{*\alpha\mu\nu}\gamma_5 P^\beta_\alpha \phi_{\beta\mu} + b\phi^{*\alpha\mu\nu}\gamma_5 P^\beta_\alpha \phi_{\beta\nu}) \\
\mathcal{L}_{BBV} = ig_V (c\phi^{*\alpha\mu\nu}\gamma V^\beta_\alpha \phi_{\beta\mu} + d\phi^{*\alpha\mu\nu}\gamma V^\beta_\alpha \phi_{\beta\nu})
\]

(5)

where all the indices run from 1 to 5. The tensors \( P^\beta_\alpha \) and \( V^\beta_\alpha \) are defined by the pseudoscalar and vector meson matrices given in Ref. [11] and the tensor \( \phi^{\alpha\mu\nu} \) defines the \( J^P = \frac{1}{2}^+ \) baryons which belongs to 40-plet states in SU(5) quark model (see the Appendix). The Lagrangian density of Eq. 5 defines all the BBP couplings in terms of universal coupling \( gp \) and the constants \( a \) and \( b \). Similarly the Lagrangian density of Eq. 6 defines all the BBV couplings in terms of universal coupling \( gV \) and the constants \( c \) and \( d \). For the coupling constants \( g_{\pi NN} \), \( g_{\rho NN} \), \( g_{K N\Lambda} \), \( g_{K^* N\Lambda} \) and given in the Eqs. 2c to 2g we obtain the following results.

\[
g_{\pi NN} = \frac{1}{\sqrt{2}} gp(a - \frac{5}{4}b), \quad g_{B_b \Lambda_c \Lambda_b} = \frac{3}{4} gp(a - b),
\]

\[
g_{K N\Lambda} = g_{D N\Lambda_c} = g_{B N\Lambda_b} = \frac{3\sqrt{6}}{8} gp(b - a)
\]

(7)

\[
g_{\rho NN} = \frac{1}{\sqrt{2}} g_V (c - \frac{5}{4}d), \quad g_{K^* N\Lambda} = g_{D^* N\Lambda_c} = g_{B^* N\Lambda_b} = \frac{3\sqrt{6}}{8} g_V (d - c)
\]

(8)

SU(5) flavor symmetry is badly broken due to large variation in the related quark masses. Thus, these symmetry relations are also expected to be violated. It is noted that SU(4) flavor symmetry also produces the same relations as given in Eqs. 7 & 8 for couplings of the hadrons containing \( u, d, s \) and \( c \) quarks [10].

3 Amplitudes of \( B_c \) absorption processes

Shown in Fig. 1 are the Feynman diagrams of the four processes given by Eq. 1. Corresponding to each process, we have two diagrams. In all \( t \) and \( u \) channel diagrams \( c \) and \( b \) flavors are exchanged respectively.

Scattering amplitudes of these diagrams are given by,

\[
M_{1a} = -g_{D^* N\Lambda_c} g_{B_b B D^*} (-p_4 - p_2)_\mu \frac{-i}{t - m_{D^*}^2} \left( g^{\mu\nu} - \frac{(p_1 - p_3)^\mu (p_1 - p_3)^\nu}{m_{D^*}^2} \right) \times \bar{\tau}_{\Lambda_c} (p_3) \gamma_\nu u_N (p_1)
\]

\[
M_{1b} = g_{B N\Lambda_b} g_{B_b \Lambda_c \Lambda_b} \bar{\tau}_{\Lambda_c} (p_3) \gamma_5 \left( \frac{(p_1 - p_4) \gamma + m_{\Lambda_b}}{u - m_{\Lambda_b}^2} \right) \gamma_5 u_N (p_1)
\]

(9)
The required isospin factor in this case is simply 1 for all four processes. It is noted using the total amplitudes given in Eq. 13, we calculate unpolarized and isospin averaged cross sections.

\[ M_{2a} = ig_{DN\Lambda_c}g_{B^* DB}(p_4 - 2p_2)\mu \left( \frac{i}{t - m_D^2} \right) \Sigma_{\Lambda_c}(p_3)\gamma^5 u_N(p_1)\gamma^\mu(p_4) \]

\[ M_{2b} = -ig_{B^* N\Lambda_b}g_{B^* DB}\Sigma_{\Lambda_c}(p_3)\gamma^5 \left( \frac{(p_1 - p_4)\cdot \gamma + m_{\Lambda_b}}{u - m_{\Lambda_b}^2} \right) \gamma^\mu u_N(p_1)\gamma^\mu(p_4) \]

\[ M_{3a} = g_{DN\Lambda_c}g_{B^* DB}\Sigma_{\Lambda_b}(p_4)\gamma^5 \left( \frac{(p_1 - p_3)\cdot \gamma + m_{\Lambda_b}}{t - m_{\Lambda_b}^2} \right) \gamma^\mu u_N(p_1) \]

\[ M_{3b} = -g_{B^* N\Lambda_b}g_{B^* DB}(p_3 - 2p_2)\mu \frac{-i}{u - m_{B^*}^2} \left( g^{\mu\nu} - \frac{(p_1 - p_4)\mu(p_1 - p_4)\nu}{m_{B^*}^2} \right) \]

\[ \times \Sigma_{\Lambda_b}(p_4)\gamma^\nu u_N(p_1) \]

\[ M_{4a} = -ig_{DN\Lambda_c}g_{B^* DB}\Sigma_{\Lambda_b}(p_4)\gamma^5 \left( \frac{(p_1 - p_3)\cdot \gamma + m_{\Lambda_b}}{t - m_{\Lambda_b}^2} \right) \gamma^\mu u_N(p_1)\gamma^\mu(p_3) \]

\[ M_{4b} = ig_{B^* N\Lambda_b}g_{B^* DB}(p_3 - 2p_2)\mu \frac{i}{u - m_{B}^2} \Sigma_{\Lambda_b}(p_4)\gamma^5 u_N(p_1)\gamma^\mu(p_3) \]

Total amplitude of each process is given by,

\[ M_i = M_{ia} + M_{ib}, \quad \forall, \ i = 1, 2, 3, 4 \]

Using the total amplitudes given in Eq. 13, we calculate unpolarized and isospin averaged cross sections. The required isospin factor in this case is simply 1 for all four processes. It is noted
that in the study of the processes of the Eq. (1) we do not include any diagram in which $\Sigma_c$ or $\Sigma_b$ particle is exchanged. These diagram require $B_c\Sigma_b\Lambda_c$ and $B_c\Sigma_c\Lambda_b$ couplings in addition to $DN\Sigma_c$, $B\Sigma_b\Lambda_c\Sigma_c$, $D^*\Sigma_b\Sigma_c$ and $B^*\Sigma_b\Sigma_c$ couplings. These couplings of $B_c$ meson violate isospin (I) and also not produced by the SU(5) invariant Lagrangian given in Eq. (5). Therefore, It is a good approximation to neglect $\Sigma_c$ or $\Sigma_b$ exchange diagrams for the processes given in Eq. (1).

4 Numerical values of coupling constants

The values of the couplings $g_{B_cBD^*}$ and $g_{B_cB^*D}$ are fixed by using $g_{YBB} = 13.3$, which is obtained using vector meson dominance (VMD) model in ref. [11] and SU(5) symmetry result $g_{B_cBD^*} = g_{B_cB^*D} = \frac{2}{\sqrt{2}}g_{YBB}$ [17]. In this way we obtain $g_{B_cBD^*} = g_{B_cB^*D} = 11.9$. The couplings $g_{D^\Lambda\Lambda_c}$ and $g_{D^\Lambda\Lambda_c}$ can be fixed by using SU(5)/SU(4) symmetry relations $g_{K^\Lambda\Lambda_c} = g_{D^\Lambda\Lambda_c}$ and $g_{K^\Lambda\Lambda_c} = g_{D^\Lambda\Lambda_c}$ given in Eqs. (7) & (8) and the empirical values of the couplings $g_{K^\Lambda\Lambda_c}$ and $g_{K^\Lambda\Lambda_c}$ given in ref. [21]. In this way we obtain the following results,

$$g_{D^\Lambda\Lambda_c} = 13.1, \quad g_{D^\Lambda\Lambda_c} = 4.3$$

(14)

Whereas, the QCD sum-rule approach gives the following values of these couplings [22].

$$|g_{D^\Lambda\Lambda_c}| = 7.9, \quad |g_{D^\Lambda\Lambda_c}| = 7.5$$

(15)

Due to significant difference between the values given in Eqs. (14) & (15) we use both of them separately to study their effect on the calculated cross sections. However, It is noted that the values given in Eq. (14) are less reliable due to the effect of breaking of SU(5)/SU(4) flavor symmetries. There are no empirically fitted values available for the couplings $g_{B_c\Lambda_c\Lambda_b}$, $g_{B_b\Lambda_b}$ and $g_{B^*B\Lambda_b}$, thus we use SU(5) symmetry relations given in Eqs. (7) & (8) which implies,

$$g_{B_c\Lambda_c\Lambda_b} = \frac{2}{\sqrt{6}}g_{D^\Lambda\Lambda_c}, \quad g_{B_b\Lambda_b} = g_{D^\Lambda\Lambda_c}, \quad g_{B^*B\Lambda_b} = g_{D^\Lambda\Lambda_c}$$

(16)

The values of $g_{D^\Lambda\Lambda_c}$ & $g_{D^\Lambda\Lambda_c}$ in Eq. (14) give $g_{B_c\Lambda_c\Lambda_b} = -10.7$, $g_{B_b\Lambda_b} = 13.1$ & $g_{B^*B\Lambda_b} = 4.3$, whereas the values in Eq. (15) give $g_{B_c\Lambda_c\Lambda_b} = -6.5$, $g_{B_b\Lambda_b} = 7.9$ & $g_{B^*B\Lambda_b} = 7.5$. Where, we choose the sign of the couplings $g_{D^\Lambda\Lambda_c}$ & $g_{D^\Lambda\Lambda_c}$ in accordance with the Eq. (14). Two sets of the values of the coupling constants used in this paper and methods of obtaining them are summarized in Table 1.

5 Results and Discussion

Shown in Fig. 2 are the $B_c$ absorption cross sections by nucleons for the four processes given in Eq. (1) as function of total center of mass (c.m) energy. These cross sections are obtained using
Figure 2: $B_c$ absorption cross sections of the four processes using the values of the couplings given in set 1. Solid and dashed curves represent cross sections without and with form factor respectively. Lower and upper dashed curves are with cutoff parameter $\Lambda = 1$ and $\Lambda = 2$ GeV respectively.

the values of couplings given in set 1. Solid and dashed curves in these figures represent cross sections without and with form factors. Form factors are required to include the effect of finite size of interacting hadrons. In the present work we use the following monopole form factor.

$$f_3 = \frac{\Lambda^2}{\Lambda^2 + \mathbf{q}^2},$$

where $\Lambda$ is cutoff parameter and $\mathbf{q}^2$ is squared three momentum transfer in c.m frame. In Ref. [18], it is found that for charm and bottom mesons $\Lambda$ could be in the range $1.2 - 1.8$ GeV. However, we adopt a more conservative view and vary it from 1 to 2 GeV to study the uncertainty in the cross sections due to cutoff parameter.

Fig. 2 shows that, for the processes (i) $NB_c^+ \rightarrow \Lambda_c B$, (ii) $NB_c^+ \rightarrow \Lambda_c B^*$, (iii) $NB_c^- \rightarrow D\Lambda_b$, (iv) $NB_c^- \rightarrow D^\ast \Lambda_b$ the cross sections roughly vary $2 - 5$ mb, $0.05 - 0.3$ mb, $0.1 - 2$ mb, and $0.1 - 1$ mb respectively in the most part of the energy scalewhen the cutoff parameter $\Lambda$ is between $1 - 2$ GeV. Relatively high suppression due to cutoff in the processes 2 and 4 is due to higher values of the masses of vector mesons $D^*$ and $B^*$. In Fig. 3, we present the plots of cross sections using the values of couplings given in the set 2. Again the solid and dashed curves in these figures represent cross sections without and with form factors respectively. These cross sections roughly vary $5 - 15$ mb, $0.05 - 0.2$ mb, $0.1 - 1$ mb and $0.1 - 0.6$ mb in the most part of energy scale, for the processes (i) to (iv), when the cutoff $\Lambda$ is between $1 - 2$ GeV. In Table 2, we present the comparison of peak values of the cross sections for two sets of the coupling

\footnote{These approximate variations are defined for $\sqrt{s} \geq 9$ GeV}
values. These results show that the values of set 2 increase the peak values of the cross sections of the process 1 by the factor of ∼1.5 and decrease of the process 3 by the factor ∼4, whereas the peak values of the processes 2 and 4 almost remain unchanged. In order to study the effect of b-flavored hadron exchange, we also present in the table 2, the comparison of the peak values with and without b-flavor exchange diagrams. The results show that the b-flavor exchange between interacting hadrons significantly increases the peak values of the cross sections of the first three processes for the coupling set 1 and processes (ii) and (iii) for the set 2. Generally, the contribution of a diagram at tree level depend upon the mass of the exchange particle, coupling product and the form of amplitude. Higher value of the mass of the exchange particle tends to decrease the contribution of a diagram. However, in some case the other factors like the higher value of the coupling product or the form of amplitude may significantly increase the contribution even when mass of the exchange particle is increased. In our case two contributing amplitudes for each process have different form and contain different coupling product. Thus, the mere fact that the mass of bottom-hadron is higher than charm-hadron does not imply that contribution of the bottom-exchange diagrams is lesser than charm-exchange diagrams.

6 Effect of anomalous parity interaction

The diagrams of the Fig. 1 are produced using PPV, BBP and BBV couplings defined in Eqs. 2. However, if the PVV coupling of $B_c$ meson due to anomalous parity interaction is also included then two additional diagrams shown in Fig. 4 are introduced for the processes (ii) and (iv).
| Process | Set 1 | Set 2 |
|---------|-------|-------|
| $NB^+_c \rightarrow \Lambda_c B$ | \begin{align*} \text{with b-exchange} & : \Lambda = 1 \text{ GeV} \quad 6 \text{ mb} \\
& : \Lambda = 2 \text{ GeV} \quad 19 \text{ mb} \\
\text{without b-exchange} & : \Lambda = 1 \text{ GeV} \quad 3 \text{ mb} \\
& : \Lambda = 2 \text{ GeV} \quad 7 \text{ mb} \end{align*} | \begin{align*} \text{with b-exchange} & : \Lambda = 1 \text{ GeV} \quad 0.25 \text{ mb} \\
& : \Lambda = 2 \text{ GeV} \quad 0.8 \text{ mb} \\
\text{without b-exchange} & : \Lambda = 1 \text{ GeV} \quad 0.08 \text{ mb} \\
& : \Lambda = 2 \text{ GeV} \quad 0.6 \text{ mb} \end{align*} |
| $NB^+_c \rightarrow \Lambda_c B^*$ | \begin{align*} \text{with b-exchange} & : \Lambda = 1 \text{ GeV} \quad 0.08 \text{ mb} \\
& : \Lambda = 2 \text{ GeV} \quad 0.6 \text{ mb} \\
\text{without b-exchange} & : \Lambda = 1 \text{ GeV} \quad 0.03 \text{ mb} \\
& : \Lambda = 2 \text{ GeV} \quad 0.22 \text{ mb} \end{align*} | \begin{align*} \text{with b-exchange} & : \Lambda = 1 \text{ GeV} \quad 10 \text{ mb} \\
& : \Lambda = 2 \text{ GeV} \quad 28 \text{ mb} \\
\text{without b-exchange} & : \Lambda = 1 \text{ GeV} \quad 9 \text{ mb} \\
& : \Lambda = 2 \text{ GeV} \quad 23 \text{ mb} \end{align*} |
| $NB^-_c \rightarrow \overline{D} \Lambda_b \ast$ | \begin{align*} \text{with b-exchange} & : \Lambda = 1 \text{ GeV} \quad 0.6 \text{ mb} \\
& : \Lambda = 2 \text{ GeV} \quad 2 \text{ mb} \\
\text{without b-exchange} & : \Lambda = 1 \text{ GeV} \quad 0.7 \text{ mb} \\
& : \Lambda = 2 \text{ GeV} \quad 2.1 \text{ mb} \end{align*} | \begin{align*} \text{with b-exchange} & : \Lambda = 1 \text{ GeV} \quad 6 \text{ mb} \\
& : \Lambda = 2 \text{ GeV} \quad 14 \text{ mb} \\
\text{without b-exchange} & : \Lambda = 1 \text{ GeV} \quad 1.5 \text{ mb} \\
& : \Lambda = 2 \text{ GeV} \quad 4.2 \text{ mb} \end{align*} |

Table 2: The peak values of the cross sections of the four processes with and without b-flavor exchange, using coupling values of set 1 and 2.

respectively. The effective Lagrangian density defining the anomalous interaction of mesons is discussed in [26]. Here, we report the relevant interaction term of the Lagrangian density as following.

\[
\mathcal{L}_{B_c B^* D^*} = g_{B_c B^* D^*} \varepsilon_{\alpha \beta \mu \nu} \left[ (\partial^\mu D^\nu) \left( \partial^\alpha B^{*\beta} \right) B_c^- + B_c^+ \left( \partial^\nu \overline{B}^{*\beta} \right) \left( \partial^\mu D^\nu \right) \right]
\]  

Figure 4: Additional Feynman diagrams for $B_c$ absorption processes: (2) $NB^+_c \rightarrow \Lambda_c B^*$ and (4) $NB^-_c \rightarrow \overline{D}^* \Lambda_b$, due to anomalous parity interaction.

The coupling constant $g_{B_c B^* D^*}$, which has the dimension of GeV$^{-1}$, can be approximated by $g_{B_c B^* D^*}/\overline{M}_D$ in heavy quark mass limit [27]. Where, $\overline{M}_D$ is the average mass of $D$ and $D^*$ mesons. The scattering amplitudes of the diagrams of Fig. 4 are given by,

\[
M_{2c} = g_{D^* N \Lambda_c} g_{B_c B^* D^*} \varepsilon^{\alpha \beta \gamma \delta} (p_4)_{\alpha} (p_3 - p_1)_{\beta} \frac{-i}{t - m_D^2} \left( g_{\nu \lambda} - \frac{(p_3 - p_1)_{\nu}(p_3 - p_1)_{\lambda}}{m_D^2} \right) \\
\times \overline{u}_{\Lambda_c} (p_3) \gamma^\lambda u_N (p_1) \varepsilon^{\mu}_{D^*} (p_4),
\]

\[
M_{4c} = -g_{D^* N \Lambda_c} g_{B_c B^* D^*} \varepsilon^{\alpha \beta \gamma \delta} (p_3)_{\beta} (p_1 - p_4)_{\gamma} \frac{-i}{u - m_B^2} \left( g_{\nu \lambda} - \frac{(p_1 - p_4)_{\nu}(p_1 - p_4)_{\lambda}}{m_B^2} \right) \\
\times \overline{u}_{\Lambda_c} (p_4) \gamma^\lambda u_N (p_1) \varepsilon^{\mu}_{D^*} (p_3),
\]

(19) 

(20)

Shown in Fig. 5 are the cross sections of the processes (ii) and (iv) with anomalous interaction for the both coupling sets. The results show that the cross section of the process (ii) is increased
by $\sim 0.2$ mb and $\sim 0.5$ mb for the coupling sets 1 and 2 respectively, in most part of the energy range. Fig. 5 also shows that the effect of anomalous interaction on cross section of the process (iv) is negligible for both coupling sets. Although the anomalous interaction significantly increases the cross section of the process (ii), this effect is marginal on the total cross section (i.e., the sum of four processes) due to relatively small value of the cross section of the process (ii).

Figure 5: $B_c$ absorption cross sections of the processes (ii) and (iv) using the values of the couplings given in set 1 and set 2. Solid and dashed curves represent the cross sections with and without anomalous diagrams respectively, and dotted curves represent the contribution from anomalous diagrams alone, i.e., without including the contribution from the interference terms. Cutoff parameter $\Lambda$ is taken 1.5 GeV.

7 Concluding Remarks

In this paper, we have calculated $B_c$ absorption cross sections by nucleons in meson-baryon exchange model using hadronic Lagrangian based on SU(4)/SU(5) flavor symmetries. This approach has already been used for calculating absorption cross sections of $J/\psi$ and $\Upsilon$ mesons by pions, $\rho$ mesons and nucleons. In order to calculate $B_c$ absorption cross sections, we use PPV, BBP and BBV couplings given in Eq. 2. Related coupling constants $g_{DN\Lambda_c}$ and $g_{DN\Lambda_b}$ can either be fixed by SU(4)/SU(5) flavor symmetries or empirically using QCD-sum rules. We have calculated absorption cross sections using both set of values for comparison. Whereas, for the coupling constants $g_{B\Lambda_c}$, $g_{B\Lambda_b}$ and $g_{B_c\Lambda_c\Lambda_b}$ no empirical values are available, so we use SU(5) symmetry relations. These estimates are less reliable as the SU(5) flavor symmetry is broken due to large variation in the quark masses. It is noted that for the processes (i) and (ii) only the b-flavor exchange diagrams depend upon these three couplings. Thus the effect
of these couplings on the cross sections of the first two processes is less significant when the contribution of b-flavor exchange diagram is small or negligible as in the case of process (i) for coupling values of the set 2. However, for the processes (iii) and (iv), the amplitudes of both c and b-flavor exchange diagrams depends upon these couplings. Thus, any change in the values of these couplings could significantly change the cross sections of these processes irrespective of the relative contribution of the two diagrams. We conclude that a more rigorous study on these couplings could further improve our results. The anomalous parity interaction is found to be significant only for the process (ii). The effect, however, itself marginal in total value of the cross section due to lesser contribution from the process (ii).

A Appendix

In SU(5) quark model, \( J^P = \frac{1}{2}^+ \) baryons (anibaryons) are 40 (\( \overline{40} \))-plets of 1100 (0011) representation and mesons are 24-plets of 1001 representation of SU(5) group, whereas SU(5) invariant Lagrangian defining BBP or BBV couplings must be a singlet. Since \( 40 \otimes 24 = 450 \oplus 210 \oplus 175 \oplus 40 \oplus 40 \oplus 35 \oplus 10 \), there are two possible BBP and BBV couplings as in case of SU(3) and SU(4). These SU(5) invariant couplings are expressed in terms of irreducible tensors \( P^\beta_\alpha, V^\beta_\alpha \) and \( \phi_{\mu\nu\lambda} \) in Eqs. 5 and 6. The tensor \( \phi_{\mu\nu\lambda} \), which define \( J^P = \frac{1}{2}^+ \) baryons, satisfies the conditions

\[
\phi_{\mu\nu\lambda} + \phi_{\lambda\mu\nu} + \phi_{\nu\lambda\mu} = 0 \quad \text{and} \quad \phi_{\mu\nu\lambda} = \phi_{\nu\mu\lambda}.
\]

The relations defining \( J^P = \frac{1}{2}^+ \) baryons in terms of the elements of \( \phi_{\mu\nu\lambda} \) for \( u,d,s \) and \( c \) quarks are given in ref. [20]. Here, we present the relations defining the baryons with bottom quark(s).

\[
\begin{align*}
\Sigma_b^+ &= \phi_{115}, & \Sigma_b^0 &= \sqrt{2}\phi_{125}, & \Sigma_b^- &= \phi_{225}, \\
\Xi_b^0 &= \sqrt{2}\phi_{135}, & \Xi_b^- &= \sqrt{2}\phi_{235}, \\
\Xi_b^0 &= \sqrt{2}(\phi_{513} - \phi_{531}), & \Xi_b^- &= \sqrt{2}(\phi_{523} - \phi_{532}), \\
\Lambda_b^0 &= \sqrt{2}(\phi_{521} - \phi_{512}), & \Omega_b^- &= \phi_{335}, & \Omega_{cb}^+ &= \phi_{445}, \\
\Xi_bb &= \phi_{155}, & \Xi_b^- &= \phi_{552}, \\
\Omega_{bb} &= \phi_{553}, & \Omega_{cb} &= \phi_{554}, \\
\Xi_{cb}^0 &= \sqrt{2}\phi_{145}, & \Xi_{cb}^- &= \sqrt{2}\phi_{245}, \\
\Xi_{cb}^+ &= \sqrt{2}(\phi_{514} - \phi_{541}), & \Xi_{cb}^0 &= \sqrt{2}(\phi_{524} - \phi_{542}), \\
\Omega_{cb}^0 &= \phi_{345}, & \Omega_{cb}^0 &= \sqrt{2}(\phi_{543} - \phi_{534}).
\end{align*}
\]  

(21)

References

[1] T. Matsui & H. Satz, Phys. Lett. B 178, (1986) 416.

[2] S. Gavin, M. Gyulassy and A. Jackson, Phys. Lett. B 207B (1988) 257; R. Vogt et. al., ibid, 207B (1988) 263.

[3] W. Cassing and C. M. Ko, Phys. Lett. B 396 (1996) 39; W. Cassing and E. L. Bratkovskaya, Nucl. Phys. A623 (1997) 570; N. Armesto and A. Capella, Phys. Lett. B 430 (1998) 23; D. E. Kahana and S. H. Kahana, Phys. Rev. C 59 (1999) 1651; C. Gale, S. Jeon and J.
Kapusta, Phys. Lett. B 459 (1999) 455; C. Spieles, R. Vogt, L. Gerland, S. A. Bass, M. Bleicher, H. Stocker and W. Greiner, Phys. Rev. C 60 (1999) 054901; Ben-Hao Sa, An Tai, Hui Wang and Geng-He Liu, Phys. Rev. C 59 (1999) 2728.

[4] M. C. Areu et. Al., NA50 Collaboration, Phys. Lett. B 450 (1999) 456.

[5] D. Kharzeev and H. Satz, Phys. Lett. B 334, (1994) 155.

[6] D. Kharzeev, H. Satz, A. Syamtomov, and G. Zinovjev Phys. Lett. B 389 (1996) 595.

[7] C. Y. Wong, E. S. Swanson and T. Barnes, Phys. Rev. C 62 (2000) 045201; M. A. Ivanov, J. G. Korner, and P. Santorelli, Phys. Rev. D 70 (2004) 014005.

[8] K. Haglin, Phys. Rev. C 61 (2000) 031902.

[9] Z. Lin and C. M. Ko, Phys. Rev. C 62 (2000) 034903.

[10] W. Liu, C. M. Ko, and Z. W. Lin, Phys. Rev. C 65 (2001) 015203.

[11] Z. Lin and C. M. Ko, Phys. Lett. B 503 (2001) 104.

[12] R. Vogt, Phys. Rept. 310 (1999) 197.

[13] CMS Collaboration, Phys. Rev. Lett. 109, 222301 (2012); CMS Collaboration, ibid. 107, 052302 (2011).

[14] Martin Schroedter, Robert L. Thews and Johann Rafelski, Phys. Rev. C 62 (2000) 024905.

[15] J. Letessier and J. Rafelski, Hadrons and Quark-Gluon Plasma (CUP, 2002).

[16] F. Becattini, Phys. Rev. Lett. 92 (2005) 022301.

[17] M. A. K. Lodhi and R. Marshall, Nucl. Phys. A 790 (2007) 323c-327c.

[18] M. A. K. Lodhi, Faisal Akram and Shaheen Irfan, Phys. Rev. C 84 (2011) 034901.

[19] Faisal Akram and M. A. K. Lodhi, Phys. Rev. C 84, (2011) 064912.

[20] S. Okubo, Phys. Rev. D 11 (1975) 3261.

[21] V.G.J. Stoks and Th. A. Rijken, Phys. Rev. C 59 (1999) 3009.

[22] F.O. Duraes, F.S. Navarra, and M. Nielsen, Phys. Lett. B 498 (2001) 169.

[23] R. Machleid, K. Holinde and C. Elster, Phys. Rev. 149 , 1 (1987); R. Machleid, Adv. Nucl. Phys. 19, 189 (1989); D. Lohse, J. W. Durso, K. Holinde, and J. Speth, Nucl. Phys. A516, 513 (1990).

[24] S. Yasui and K. Sudoh, Phys. Rev. D 80, 034008 (2009).

[25] B. Holzenkamp, K. Holinde and J. Speth, Nucl. Phys. A500, 485 (1989); G. Janssen, J. W. Durso, K. Holinde, B. C. Pearce, and J. Speth, Phys. Rev. Lett. 71, 1978 (1993).

[26] Yongseok Oh, Taesoo Song, and Su Houng Lee, Phys. Rev. C 63, 034901 (2001).

[27] M. B. Wise, Phys. Rev. D 45, 2188 (1992); Tung-Mow Yan, Hai-Yang Cheng, Chi-Yee Cheung, Guey-Lin Lin, Y. C. Lin, and Hoi-Lai Yu, Phys. Rev. D 46, 1148 (1992); 55, 5851(E) (1997); Lai-Him Chan, Phys. Rev. D 55, 5362 (1997).