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Study of the $B_c \to J/\psi + D_q^{(*)}$ decays in covariant confined quark model

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Abstract. In this work we study the $B_c \to J/\psi + D_q^{(*)}$ decays. It was defined ratios ($R_{D_s^*/D_s}$, $R_{D^*/D}$, R_{D^*/D_s^*} and R_{D/D_s}) of nonleptonic branching ratios of B_c meson, which will be hopefully tested on LHC experiments. We compare the obtained results with available experimental data and with the results from other theoretical approaches.

Introduction

Recently the ATLAS Collaboration reported on the measurement of the various branching fractions of the decays $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$ [1]. The first observations of these decays have been performed by the LHCb Collaboration [2]. In view of these developments, we decided to calculate ratios of branching fractions within the covariant confined quark model(CCQM).

The decay properties of the above processes were studied in various theoretical approaches [3–12].

Effective Hamiltonian and matrix element

The effective Hamiltonian describing the B_c nonleptonic decays into charmonium and $D(D_s)$ meson is given by (see, Ref. [13])

$$\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{cb} V_{cq}^\dagger \sum_{i=1}^{6} C_i \mathcal{O}_i,$$

$$\begin{aligned}
\mathcal{O}_1 &= (\bar{c}_{a_1} b_{a_2})_{V-A} (\bar{q}_{a_2} c_{a_1})_{V-A}, & \mathcal{O}_2 &= (\bar{c}_{a_1} b_{a_1})_{V-A}, (\bar{q}_{a_2} c_{a_2})_{V-A}, \\
\mathcal{O}_3 &= (\bar{q}_{a_1} b_{a_1})_{V-A} (\bar{c}_{a_2} c_{a_2})_{V-A}, & \mathcal{O}_4 &= (\bar{q}_{a_1} b_{a_2})_{V-A} (\bar{c}_{a_2} c_{a_1})_{V-A}, \\
\mathcal{O}_5 &= (\bar{q}_{a_1} b_{a_1})_{V-A} (\bar{c}_{a_2} c_{a_2})_{V+A}, & \mathcal{O}_6 &= (\bar{q}_{a_1} b_{a_2})_{V-A} (\bar{c}_{a_2} c_{a_1})_{V+A},
\end{aligned} \tag{1}$$

where the subscript $V-A$ refers to the usual left–chiral current $O^\mu = \gamma^\mu(1-\gamma^5)$ and $V+A$ to the usual right–chiral one $O_+^\mu = \gamma^\mu(1+\gamma^5)$. The a_i denote the color indices. The quark q stands for either s or d. The numerical values of the Wilson coefficients are taken as in Ref.[14]. They are listed in Table 1. Since in NNLO the numerical values of the C_5 and C_6 coefficients are less to the order than the C_3

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Table 1. Values of the Wilson coefficients in NNLO.

C_1	C_2	C_3	C_4	C_5	C_6
−0.2632	1.0111	−0.0055	−0.0806	0.0004	0.0009

and C_4 coefficients respectively, we drop the contribution from those operators.

By using the Fierz transformation one can check that $O_3 = O_1$ and $O_4 = O_2$. Then the calculation of the matrix elements describing the nonleptonic decays of the B_c meson into charmonium and $D(D_s)$ meson is straightforward. The combinations of the Wilson coefficients appear as $a_1 = C_2 + C_4 + \xi\,(C_1 + C_3)$ and $a_2 = C_1 + C_3 + \xi\,(C_2 + C_4)$ with $\xi = 1/N_c$. In the numerical calculations we set the color-suppressed parameter ξ to zero. Then the Wilson coefficients are equal to

$$a_1 = C_2 + C_4 = 0.93\,, \qquad \text{and} \qquad a_2 = C_1 + C_3 = -0.27 \tag{2}$$

which should be compared with the old ones $a_1 = 1.14$ and $a_2 = -0.20$ used in paper [3].

Invariant and helicity amplitudes

The invariant form factors for the semileptonic B_c decay into the hadron with spin $S = 0, 1$ are defined by

$$\mathcal{M}^{\mu}_{S=0} = P^{\mu}\, F_+(q^2) + q^{\mu}\, F_-(q^2), \tag{3}$$

$$\begin{aligned} \mathcal{M}^{\mu}_{S=1} &= \frac{1}{m_1 + m_2}\,\epsilon^{\dagger}_{\nu}\,\Big\{ -g^{\mu\nu}\, Pq\, A_0(q^2) + P^{\mu}\, P^{\nu}\, A_+(q^2) + q^{\mu}\, P^{\nu}\, A_-(q^2) \\ &\qquad + i\,\varepsilon^{\mu\nu\alpha\beta}\, P_{\alpha}\, q_{\beta}\, V(q^2)\Big\}, \end{aligned} \tag{4}$$

where $P = p_1 + p_2$ and $q = p_1 - p_2$. Here p_1 is the momentum of the ingoing meson with a mass m_1 (B_c) and p_2 is the momentum of the outgoing meson with a mass m_2. It is convenient to express all physical observables through the helicity form factors H_m. The helicity form factors H_m can be written in terms of the invariant form factors in the following way [15]:
Spin S=0:

$$H_t = \frac{1}{\sqrt{q^2}}\Big\{(m_1^2 - m_2^2)\, F_+ + q^2\, F_-\Big\}\,, \qquad H_{\pm} = 0\,, \qquad H_0 = \frac{2\, m_1\, |\mathbf{p_2}|}{\sqrt{q^2}}\, F_+\,. \tag{5}$$

Spin S=1:

$$\begin{aligned} H_t &= \frac{1}{m_1 + m_2}\,\frac{m_1\,|\mathbf{p_2}|}{m_2\,\sqrt{q^2}}\Big\{(m_1^2 - m_2^2)\,(A_+ - A_0) + q^2 A_-\Big\}, \\ H_{\pm} &= \frac{1}{m_1 + m_2}\Big\{-(m_1^2 - m_2^2)\, A_0 \pm 2\, m_1\, |\mathbf{p_2}|\, V\Big\}, \\ H_0 &= \frac{1}{m_1 + m_2}\,\frac{1}{2\, m_2\,\sqrt{q^2}}\Big\{-(m_1^2 - m_2^2)\,(m_1^2 - m_2^2 - q^2)\, A_0 + 4\, m_1^2\, |\mathbf{p_2}|^2\, A_+\Big\}. \end{aligned} \tag{6}$$

Here $|\mathbf{p_2}| = \lambda^{1/2}(m_1^2, m_2^2, q^2)/(2\, m_1)$ is the momentum of the outgoing meson in the B_c rest frame.

The nonleptonic B_c decay widths in terms of the helicity amplitudes are given by

$$\begin{aligned}
\Gamma(B_c^+ \to J/\psi D_q^+) &= N_W \left\{ -a_1 f_{D_q} m_{D_q} H_t^{B_c\to J/\psi}(m_{D_q}^2) + a_2 f_{J/\psi} m_{J/\psi} H_0^{B_c\to D_q}(m_{J/\psi}^2) \right\}^2 , \\
\Gamma(B_c^+ \to J/\psi D_q^{*+}) &= N_W \sum_{i=0,\pm} \left\{ a_1 f_{D^*} m_{D_q^*} H_i^{B_c\to J/\psi}(m_{D_q^*}^2) + a_2 f_{J/\psi} m_{J/\psi} H_i^{B_c\to D_q^*}(m_{J/\psi}^2) \right\}^2 ,
\end{aligned}$$

where we use the short notation

$$N_W \equiv \frac{G_F^2}{16\pi} \frac{|\mathbf{p}_2|}{m_1^2} |V_{cb} V_{cq}^\dagger|^2 \,.$$

Numerical results

All necessary details and values of the calculations of the leptonic decay constants and hadronic form factors may be found in recent publications [14, 16]. In Table 2 we show widths of the B_c meson for general values of the Wilson coefficients a_1 and a_2 obtained in this work and in other works.

Table 2. Exclusive nonleptonic decay widths of the B_c meson in units of 10^{-15} GeV for general values of the Wilson coefficients a_1 and a_2.

	$B_c^+ \to J/\psi D_s^+$	$B_c^+ \to J/\psi D_s^{*+}$	$B_c^+ \to J/\psi D^+$	$B_c^+ \to J/\psi D^{*+}$
CCQM	$(-1.84\,a_1 + 2.47\,a_2)^2$	$(3.26\,a_1 + 2.74\,a_2)^2$	$(-0.34\,a_1 + 0.36\,a_2)^2$	$(0.66\,a_1 + 0.51\,a_2)^2$
[3]	$(2.19\,a_1 + 1.32\,a_2)^2$	$(3.69\,a_1 + 2.35\,a_2)^2$	$(0.462\,a_1 + 0.277\,a_2)^2$	$(0.785\,a_1 + 0.460\,a_2)^2$
[4]	$(1.02\,a_1 + 1.95\,a_2)^2$		$(0.177\,a_1 + 0.442\,a_2)^2$	
[5]	$(0.67\,a_1 + 0.23\,a_2)^2$	$(1.1\,a_1 + 1.04\,a_2)^2$	$(0.13\,a_1 + 0.047\,a_2)^2$	$(0.20\,a_1 + 0.23\,a_2)^2$
[17]	$(1.65\,a_1 + 2.92\,a_2)^2$	$(3.31\,a_1 + 3.89\,a_2)^2$	$(0.30\,a_1 + 0.44\,a_2)^2$	$(0.48\,a_1 + 0.80\,a_2)^2$
[18]	$(1.62\,a_1 + 1.72\,a_2)^2$	$(3.13\,a_1 + 3.67\,a_2)^2$	$(0.372\,a_1 + 0.338\,a_2)^2$	$(0.686\,a_1 + 0.732\,a_2)^2$

In Table 3 we show the values of branching fractions obtained in this work for two different set of the Wilson coefficients ($a_1 = 0.93$, $a_2 = -0.27$ and $a_1 = 1.14$, $a_2 = -0.20$) and compare them with other theoretical approaches.

Table 3. Branching ratios (in %) of nonleptonic B_c decays obtained in this work for two different set of the Wilson coefficients.

Mode	$a_1 = +0.93$ $a_2 = -0.27$	$a_1 = +1.14$ $a_2 = -0.20$	[3]	[5]	[6]	[9]	[10]	[17]	[18]
$B_c \to J/\psi D_s^+$	0.10	0.22	0.34	0.34	0.17	0.14	0.81	0.12	0.15
$B_c \to J/\psi D_s^{*+}$	0.41	0.78	0.75	0.59	0.67	0.41	2.05	0.55	0.62
$B_c \to J/\psi D^+$	0.0035	0.0074	0.013	0.013	0.009	0.0055	0.028	0.0044	0.009
$B_c \to J/\psi D^{*+}$	0.017	0.031	0.023	0.019	0.028	0.018	0.067	0.010	0.028

Table 4. Comparison of the results for the ratios of nonleptonic branching fractions of B_c meson

$R_{D_s^*/D_s}$	$R_{D^*/D}$	R_{D^*/D_s^*}	R_{D/D_s}	Ref.
$2.8^{+1.2}_{-0.9}$				ATLAS [1]
2.37 ± 0.57				LHCb [2]
4.1 ± 0.80	4.86 ± 0.97	0.041 ± 0.008	0.035 ± 0.007	CCQM
2.9	1.77	0.031	0.038	RCQM [3]
1.7	1.46	0.032	0.038	QCD PM [5]
3.9	3.11	0.042	0.053	QCD SR [6]
3.01 ± 1.23	3.27	0.044	0.039	LFQM [9]
$2.54^{+0.07}_{-0.21}$	2.39	0.033	0.035	pQCD [10]

Finally, we compare our results for ratios of nonleptonic branching fractions of B_c meson with available experimental data and the results obtained in other approaches in Table 4, where

$$R_{D^{(*)}_{1q}/D^{(*)}_{2q}} = \frac{B(B_c^+ \to J/\psi D^{(*)\,+}_{1q})}{B(B_c^+ \to J/\psi D^{(*)\,+}_{2q})}\,. \tag{7}$$

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