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Finding $B_c(3S)$ states via their strong decays

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ABSTRACT

The experimentally known B_c states are all below open bottom-charm threshold, which experience three main decay modes, and all induced by weak interaction. In this work, we investigate the mass spectrum and strong decays of the $B_c(3S)$ states, which just above the threshold, in the Bethe-Salpeter formalism and $^3P_0$ model. The numerical estimation gives $M(B_c(3^1S_0)) = 7273$ MeV, $M(B_c^*(3^3S_1)) = 7304$ MeV, $\Gamma\left(B_c(3^1S_0) \to B^*D\right) = 26.02^{+2.33}_{-2.21}$ MeV, $\Gamma\left(B_c^*(3^3S_1) \to BD\right) = 3.39^{+0.27}_{-0.26}$ MeV, $\Gamma\left(B_c^*(3^3S_1) \to B^*D\right) = 14.77^{+1.40}_{-1.33}$ MeV and $\Gamma\left(B_c^*(3^3S_1) \to BD^*\right) = 6.14^{+0.58}_{-0.54}$ MeV. Compared with previous studies in non-relativistic approximation, our results indicate that the relativistic effects are notable in $B_c(3S)$ exclusive strong decays. According to the results, we suggest to find the $B_c(3S)$ states in their hadronic decays to B and D mesons in experiment, like the LHCb.

The B_c meson family is unique in quark model as its states are composed of heavy quarks with different flavors. The B_c mesons lie intermediate between $(c\bar{c})$ and $(b\bar{b})$ states both in mass and size, while the different quark masses leads to much richer dynamics. On the other hand, the B_c mesons cannot annihilate into gluons or photons and thus they are very stable. The B_c mesons provide a unique window to reveal information about heavy-quark dynamics and can deepen our understanding of both strong and weak interactions.

Although there have been many investigations in the literature [1–21] about the properties of B_c mesons, the excited B_c states, especially above threshold, are rarely explored. The ground state B_c meson was first observed by the CDF Collaboration at Fermilab [22] in 1998, while there was no reported evidence of the excited B_c state until 2014, the ATLAS Collaboration reported a structure with mass of 6842 ± 9 MeV [23], which is consistent with the value predicted for $B_c(2S)$. Recently, the excited $B_c(2^1S_0)$ and $B_c^*(2^3S_1)$ states have been observed in the $B_c^+\pi^+\pi^-$ invariant mass spectrum by the CMS and LHCb Collaboration, with their masses determined to be 6872.1 ± 2.2 MeV and 6841.2 ± 1.5 MeV [24,25], respectively. Since the low-energy photon in the intermediate decay $B_c^* \to B_c\gamma$ was not reconstructed, the mass of $B_c^*(2^3S_1)$ meson appears lower than that of $B_c(2^1S_0)$.

The successful observation of $B_c(2S)$ states stimulates the interest in searching for $B_c(3S)$ states. Motivated by this, in this work, we calculate the mass spectrum of $B_c(nS)$ states up to $n = 4$ in the framework of Bethe-Salpeter (BS) equation [26]. A long-ranged linear confining potential and a short-ranged one gluon exchange potential are used in our calculation. Our results indicate that the $B_c(3S)$ states lie above the threshold for decay into a BD meson pair. By combining $^3P_0$ model with the calculated relativistic BS wave functions, we investigate the strong decay properties of $B_c(3S)$ mesons. We also estimate the corresponding numbers of events at the Large Hadron Collider (LHC) experimental condition. Although similar topic has been studied in non-relativistic framework [3,8,11,13,14], the relativistic treatment of $B_c(3S)$ exclusive decays is evidently more close to the reality.

In quantum field theory, the BS equation provides a basic description for bound states. The BS wave function of a quark-antiquark bound state is defined as

$$\chi(x_1, x_2) = \langle 0|T\psi(x_1)\bar{\psi}(x_2)|P\rangle, \tag{1}$$

where x_1 and x_2 are the coordinates of the quark and antiquark respectively, P is the momentum of the bound state, T denotes the time ordering operator. The wave function in momentum space is

$$\chi_P(q) = e^{-iP\cdot X}\int d^4x e^{-iq\cdot x}\chi(x_1, x_2), \tag{2}$$

where q is the relative momentum between the quark and antiquark. The "center-of-mass coordinate" X and the "relative coordinate" x are defined as:

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$$X=\frac{m_1}{m_1+m_2}x_1+\frac{m_2}{m_1+m_2}x_2,\quad x=x_1-x_2, \tag{3}$$

where m_1 and m_2 are the masses of the quark and antiquark respectively. Then the bound state BS equation in momentum space reads

$$S_1^{-1}(p_1)\chi_P(q)S_2^{-1}(-p_2)=i\int\frac{d^4k}{(2\pi)^4}V(P;q,k)\chi_P(k). \tag{4}$$

Here $S_i(\pm p_i)=\frac{i}{\pm \not{p}_i-m_i}$ denotes the fermion propagator; $V(P;q,k)$ is the interaction kernel; p_1 and p_2 are the momenta of the quark and anti-quark respectively, which can be expressed as

$$p_i=\frac{m_i}{m_1+m_2}P+Jq, \tag{5}$$

where, $J=1$ for the quark ($i=1$) and $J=-1$ for the antiquark ($i=2$). With the definitions $p_{i_P}\equiv\frac{P\cdot p_i}{M}$ and $p_{i\perp}^{\mu}\equiv p_i^{\mu}-\frac{P\cdot p_i}{M^2}P^{\mu}$, the propagator $S_i(Jp_i)$ can be decomposed as

$$-iJS_i(Jp_i)=\frac{\Lambda_i^+(q_\perp)}{p_{i_P}-\omega_i+i\epsilon}+\frac{\Lambda_i^-(q_\perp)}{p_{i_P}+\omega_i-i\epsilon}, \tag{6}$$

where

$$\Lambda_i^{\pm}(q_\perp)\equiv\frac{1}{2\omega_i}\left[\frac{\not{P}}{M}\omega_i\pm(\not{p}_{i\perp}+Jm_i)\right],\quad \omega_i\equiv\sqrt{m_i^2-p_{i\perp}^2}. \tag{7}$$

Under the instantaneous approximation, the interaction kernel in the center of mass frame takes the form $V(P;q,k)|_{\vec{P}=0}\approx V(q_\perp,k_\perp)$. Then the BS equation can be reduced to

$$\chi_P(q)=S_1(p_1)\eta_P(q_\perp)S_2(-p_2), \tag{8}$$

with

$$\eta_P(q_\perp)=\int\frac{d^3k_\perp}{(2\pi)^3}V(q_\perp,k_\perp)\varphi_P(k_\perp), \tag{9}$$

where $\varphi_P(q_\perp^{\mu})\equiv i\int\frac{dq_P}{2\pi}\chi_P(q)$ is the 3-dimensional BS wave function. By introducing the notation $\varphi_P^{\pm\pm}(q_\perp)$ as:

$$\varphi_P^{\pm\pm}(q_\perp)\equiv\Lambda_1^{\pm}(q_\perp)\frac{\not{P}}{M}\varphi_P(q_\perp)\frac{\not{P}}{M}\Lambda_2^{\pm}(q_\perp), \tag{10}$$

the wave function can be decomposed as

$$\varphi_P(q_\perp)=\varphi_P^{++}(q_\perp)+\varphi_P^{+-}(q_\perp)+\varphi_P^{-+}(q_\perp)+\varphi_P^{--}(q_\perp). \tag{11}$$

And the BS equation (8) can be decomposed into four equations

$$(M-\omega_1-\omega_2)\varphi_P^{++}(q_\perp)=\Lambda_1^+(q_\perp)\eta_P(q_\perp)\Lambda_2^+(q_\perp), \tag{12}$$
$$(M+\omega_1+\omega_2)\varphi_P^{--}(q_\perp)=-\Lambda_1^-(q_\perp)\eta_P(q_\perp)\Lambda_2^-(q_\perp), \tag{13}$$
$$\varphi_P^{+-}(q_\perp)=\varphi_P^{-+}(q_\perp)=0. \tag{14}$$

To solve the BS equation, one must have a good command of the potential between two quarks. According to lattice QCD calculations, the potential for a heavy quark-antiquark pair in the static limit is well described by a long-ranged linear confining potential (Lorentz scalar V_S) and a short-ranged one gluon exchange potential (Lorentz vector V_V) [27–29]:

$$\begin{aligned}V(r)&=V_S(r)+\gamma_\mu\otimes\gamma^\mu V_V(r),\\ V_S(r)&=\lambda r\frac{(1-e^{-\alpha r})}{\alpha r}+V_0,\\ V_V(r)&=-\frac{4}{3}\frac{\alpha_s(r)}{r}e^{-\alpha r}.\end{aligned} \tag{15}$$

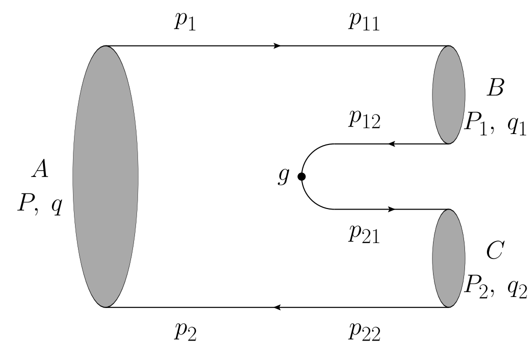

Fig. 1. The Feynman diagram of OZI-allowed two-body decay process with a $^3P_0$ vertex.

Here, the factor $e^{-\alpha r}$ is introduced not only to avoid the infrared divergence but also to incorporate the color screening effects of the dynamical light quark pairs on the "quenched" potential [30]. The potentials in momentum space are

$$\begin{aligned}V(\vec{p})&=(2\pi)^3V_S(\vec{p})+\gamma_\mu\otimes\gamma^\mu(2\pi)^3V_V(\vec{p}),\\ V_S(\vec{p})&=-\left(\frac{\lambda}{\alpha}+V_0\right)\delta^3(\vec{p})+\frac{\lambda}{\pi^2}\frac{1}{(\vec{p}^{\,2}+\alpha^2)^2},\\ V_V(\vec{p})&=-\frac{2\alpha_s}{3\pi^2}\frac{1}{\vec{p}^{\,2}+\alpha^2}.\end{aligned} \tag{16}$$

Here, α_s is the strong coupling constant, the constants α, λ and V_0 are the parameters that characterize the potential. In the following, we will employ this potential to both the B_c system and the heavy-light quark system as an assumption.

In the numerical calculation, following parameters are used:

$$m_b=4.977\text{ GeV},\quad m_c=1.628\text{ GeV},\quad \alpha_s=0.21,$$
$$\alpha=0.06\text{ GeV},\quad \lambda=0.315\text{ GeV}^2,\quad V_0=-0.829\text{ GeV}.$$

Here the heavy quark masses m_b and m_c are taken from Ref. [5], the strong coupling constant α_s is taken from Ref. [4]. The parameters α, λ and V_0 are fixed by fitting the mass spectrum to the latest experimental data [24,25]:

$$M(B_c(1^1S_0))=6271\text{ MeV},\quad M(B_c(2^1S_0))=6872\text{ MeV},$$
$$M(B_c^*(2^3S_1))-M(B_c^*(1^3S_1))=570\text{ MeV}.$$

Based on the formalism and parameters above, we calculate the masses of $B_c(nS)$ states up to $n=4$. The numerical results are shown in Table 1. For comparison, results obtained from other approaches are also listed. Note, since we fit to the latest experimental data of $B_c(2S)$ states, the masses of excited B_c states of this work are generally larger than those of others.

Our results indicate that the $B_c(3S)$ states lie above the threshold for decay into a BD meson pair. The corresponding OZI-allowed two body decay can be depicted by $^3P_0$ model, where the additional light quark-antiquark pair is assumed to be created from vacuum, as shown in Fig. 1. The usual $^3P_0$ model is a non-relativistic model with a transition operator $\sqrt{3}g\int d^3x\bar{\psi}(\vec{x})\psi(\vec{x})$, and it can be extended to a relativistic form $i\sqrt{3}g\int d^4x\bar{\psi}(x)\psi(x)$ [31,32]. The coupling constant g can be parameterized as $2m_q\gamma$, where m_q is the constitute quark mass and γ is a dimensionless parameter which can be extracted from experimental data. Here we take $m_u=0.305$ GeV, $m_d=0.311$ GeV, and $\gamma=0.253\pm0.010$ [33].

The transition amplitude for the OZI-allowed two body decay process (with the momenta assigned as in Fig. 1) can be written as

Table 1
Masses (MeV) of $B_c(nS)$ mesons.

State	This work	EQ [2]	GI [5]	LLLLGZ [13]	AAMS [14]	Lattice [12]
$B_c(1^1S_0)$	6271	6264	6271	6271	6318	6276
$B_c^*(1^3S_1)$	6346	6337	6338	6326	6336	6331
$B_c(2^1S_0)$	6873	6856	6855	6871	6741	···
$B_c^*(2^3S_1)$	6916	6899	6887	6890	6747	···
$B_c(3^1S_0)$	7273	7244	7250	7239	7014	···
$B_c^*(3^3S_1)$	7304	7280	7272	7252	7018	···
$B_c(4^1S_0)$	7584	7562	···	7540	7239	···
$B_c^*(4^3S_1)$	7606	7594	···	7550	7242	···

$$\begin{aligned}
&\langle P_1P_2|S|P\rangle = (2\pi)^4\delta^4(P-P_1-P_2)\mathcal{M}\\
&= -ig\int \frac{d^4q}{(2\pi)^4}\frac{d^4q_1}{(2\pi)^4}\frac{d^4q_2}{(2\pi)^4}\mathrm{Tr}[\chi_P(q)S_2^{-1}(p_2)(2\pi)^4\\
&\quad\times\delta^4(p_2-p_{22})\bar{\chi}_{P_2}(q_2)(2\pi)^4\delta^4(p_{12}-p_{21})\\
&\quad\times\bar{\chi}_{P_1}(q_1)S_1^{-1}(p_1)(2\pi)^4\delta^4(p_1-p_{11})]\\
&= -ig(2\pi)^4\delta^4(P-P_1-P_2)\\
&\quad\times\int\frac{d^4q}{(2\pi)^4}\mathrm{Tr}[\chi_P(q)S_2^{-1}(-p_2)\bar{\chi}_{P_2}(q_2)\bar{\chi}_{P_1}(q_1)S_1^{-1}(p_1)],
\end{aligned}\tag{17}$$

where $q_i = q+(-1)^{i+1}\left(\frac{m_i}{m_1+m_2}P-\frac{m_{ii}}{m_{i1}+m_{i2}}P_i\right)$. The Feynman amplitude takes the form [31]:

$$\begin{aligned}
\mathcal{M} &= -ig\int\frac{d^4q}{(2\pi)^4}\mathrm{Tr}[\chi_P(q)S_2^{-1}(-p_2)\bar{\chi}_{P_2}(q_2)\bar{\chi}_{P_1}(q_1)S_1^{-1}(p_1)]\\
&\approx g\int\frac{d^3q_\perp}{(2\pi)^3}\mathrm{Tr}[\frac{\not{P}}{M}\varphi_P^{++}(q_\perp)\frac{\not{P}}{M}\overline{\varphi}_{P_2}^{++}(q_{2\perp})\overline{\varphi}_{P_1}^{++}(q_{1\perp})].
\end{aligned}\tag{18}$$

Note, to get the last line of Eq. (18), we have used the fact that the wave function is strongly suppressed when $|q_\perp|$ is large. With the method developed in Refs. [34,35], the positive energy wave function can be determined by numerically solving Eq. (12).

The strong decay widths of $B_c(3S)$ mesons are shown in Table 2. We obtain $\Gamma\left(B_c(3^1S_0)\to B^*D\right) = 26.02^{+2.33}_{-2.21}$ MeV, $\Gamma\left(B_c^*(3^3S_1)\to BD\right) = 3.39^{+0.27}_{-0.26}$ MeV, $\Gamma\left(B_c^*(3^3S_1)\to B^*D\right) = 14.77^{+1.40}_{-1.33}$ MeV and $\Gamma\left(B_c^*(3^3S_1)\to BD^*\right) = 6.14^{+0.58}_{-0.54}$ MeV. In Table 3, we compare the strong decay widths with those of the non-relativistic $^3P_0$ model [11,13] and those of the Cornell coupled-channel model [3]. Our results are generally smaller than others, and we have following comments on the discrepancy:

1. In the $^3P_0$ model with $\mathcal{H}_{\rm int} = i\sqrt{3}g\bar{\psi}(x)\psi(x)$, the transition operator contains a factor $\frac{g}{2\omega_q}$, where ω_q is the energy of the created light quark. This factor reduces to $\frac{g}{2m_q}$ in the non-relativistic limit. Since the parameter g is extracted from the fit of the non-relativistic $^3P_0$ model to the experimental data, our widths are in fact suppressed by $\frac{m_q^2}{\omega_q^2}$. By multiplying the compensation factor $\frac{\omega_q^2}{m_q^2}$, we find the decay widths are enhanced by a factor of about 3. In this sense, our results are compatible with those of Ref. [3].
2. In Ref. [11] and Ref. [13], the coupling constant g is set to be about 0.292 GeV and 0.264 GeV, respectively, while here we tend to take the value of 0.155 GeV as given and discussed in Ref. [33]. This may lead to 3.5 and 3 times difference in decay width, respectively.
3. The relativistic effect of the wave functions is non-negligible, as discussed in Ref. [36].
4. The masses of $B_c(3S)$ states are different from each other between our work, Ref. [11] and Ref. [13]. This may lead to a deviation of about 20% – 50% in decay widths [3].

Table 2
Partial widths (Γ) and branching ratios (Br) of $B_c(3S)$ mesons. The number of events (NE) are estimated under the LHC experimental condition.

Meson	Decay mode	Γ (MeV)	Br (%)	NE (10^8)
$B_c^\pm(3^1S_0)$	$B^*D^\pm$	$13.05^{+1.17}_{-1.11}$	50.17	2.45
$B_c^\pm(3^1S_0)$	$B^{*\pm}D^0$	$12.97^{+1.16}_{-1.10}$	49.83	2.43
$B_c^\pm(3^3S_1)$	$B^0D^\pm$	$1.76^{+0.11}_{-0.11}$	7.25	1.04
$B_c^\pm(3^3S_1)$	$B^\pm D^0$	$1.63^{+0.16}_{-0.15}$	6.71	0.969
$B_c^\pm(3^3S_1)$	$B^*D^\pm$	$7.24^{+0.72}_{-0.68}$	29.79	4.30
$B_c^\pm(3^3S_1)$	$B^{*\pm}D^0$	$7.53^{+0.68}_{-0.65}$	30.99	4.47
$B_c^\pm(3^3S_1)$	$B^0D^{*\pm}$	$2.73^{+0.26}_{-0.24}$	11.21	1.62
$B_c^\pm(3^3S_1)$	$B^\pm D^{*0}$	$3.41^{+0.32}_{-0.30}$	14.04	2.02

Table 3
Comparison of the results for $B_c(3S)$ strong decay widths (MeV). In Ref. [3], the decay widths of $B_c(3S)$ states as functions of their masses are presented. The results cited here are obtained by setting the $B_c(3S)$ masses to our predicted values. The $B_c(3S)$ masses in Ref. [11] are $M(B_c(3^1S_0)) = 7249$ MeV and $M(B_c(3^3S_1)) = 7272$ MeV. The $B_c(3S)$ masses in Ref. [13] are shown in Table 1.

Meson	Decay mode	This work	EQ [3]	FS [11]	LLLLGZ [13]
$B_c^\pm(3^1S_0)$	B^*D	26.02	65.92	107	161
$B_c^\pm(3^3S_1)$	BD	3.39	7.78	13	28
$B_c^\pm(3^3S_1)$	B^*D	14.77	35.18	64	105
$B_c^\pm(3^3S_1)$	BD^*	6.14	15.56	–	–

According to non-relativistic quantum chromodynamics factorization formalism [37], the production rates of $B_c(3S)$ mesons can be estimated through

$$\sigma\left(B_c(3S)\right) = \sigma\left(B_c(1S)\right)\frac{|\Psi_{B_c(3S)}(0)|^2}{|\Psi_{B_c(1S)}(0)|^2},\tag{19}$$

where $\Psi_H(0)$ is the wave function at the origin for meson H. With the $\sigma\left(B_c(1S)\right)$ predicted in Ref. [38], and the wave functions calculated in Ref. [2], the cross sections of $B_c(3S)$ mesons at the LHC can be estimated as $\sigma\left(B_c(3^1S_0)\right) = 4.88$ nb and $\sigma\left(B_c^*(3^3S_1)\right) = 14.5$ nb. At an integrated luminosity of 100 fb^{-1}, the numbers of $B_c(3^1S_0)$ and $B_c^*(3^3S_1)$ events are 4.88×10^8 and 1.44×10^9, respectively. The number of events for different decay channels are also presented in Table 2.

In summary, since the relativistic effects are evidently important in $B_c(3S)$ exclusive decays to B and D mesons, we have investigated in this work the mass spectrum and strong decay properties of $B_c(3S)$ states in the framework of BS equation and relativistic $^3P_0$ model. The numerical estimation gives $M\left(B_c(3^1S_0)\right) = 7273$ MeV, $M\left(B_c^*(3^3S_1)\right) = 7304$ MeV, $\Gamma\left(B_c(3^1S_0)\to B^*D\right) = 26.02^{+2.33}_{-2.21}$ MeV, $\Gamma\left(B_c^*(3^3S_1)\to BD\right) = 3.39^{+0.27}_{-0.26}$ MeV,

$\Gamma\left(B_c^*(3^3S_1) \to B^*D\right) = 14.77^{+1.40}_{-1.33}$ MeV and $\Gamma\left(B_c^*(3^3S_1) \to BD^*\right) = 6.14^{+0.58}_{-0.54}$ MeV. We also estimate the number of events for different decay channels in the LHC experimental condition. Since a large number of events may be produced in experiment, we suggest to find the $B_c(3S)$ states in their exclusive strong decays.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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