

Decipher the short-distance component of $X(3872)$ in B_c decays

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A foremost task in understanding the nature of the $X(3872)$ involves the discrimination of the two-quark and multiquark configurations. In this work, we propose a method to probe the short-distance component of the $X(3872)$ by measuring the ratio between the B_c semileptonic and nonleptonic decays into the $X(3872)$. We demonstrate that if the $X(3872)$ production mechanism is through the $\bar{c}c$ component, the ratios would be universal and could be reliably predicted in theory. Measurements of these ratios at LHC and the next-generation electron-positron colliders are capable of validating/invalidating this production mechanism and providing deeper insights into the nature of the $X(3872)$.

Thanks to the unprecedented data samples accumulated by the two B factories and high energy hadron colliders, dramatic progresses have been made in the study of hadron spectroscopy in the past decades. In particular, in the heavy quarkonium sector, a number of unexpected resonance-like structures have been discovered at these experimental facilities, among which the $X(3872)$ is one most notable example [1–4].

The $X(3872)$ was first discovered in the exclusive decay $B^\pm \rightarrow K^\pm X(3872) \rightarrow K^\pm \pi^+ \pi^- J/\psi$ by Belle Collaboration at the e^+e^- collider located at KEK [5] and then confirmed by the BaBar Collaboration in the same channel [6]. This meson has also been observed in the high energy hadron-hadron colliders at the Tevatron [7–10] and LHC [11–13]. Based on the data corresponding to an integrated luminosity of $3.0fb^{-1}$ of proton-proton collisions, the LHCb collaboration has performed an angular analysis of the $X(3872)$ decay and found the quantum numbers $J^{PC} = 1^{++}$ [13]. The $X(3872)$ meson is peculiar in several aspects, and its nature is still not well-understood. Its width is tiny compared to typical hadronic widths and only an upper bound has been set to date: $\Gamma < 1.2$ MeV [14]. The mass lies in the vicinity to the $D^0 \bar{D}^{*0}$ threshold, $M_{X(3872)} - M_{D^0} - M_{D^{*0}} = (-0.12 \pm 0.24)$ MeV [15], which leads to speculations of the $X(3872)$ as a hadronic molecule: a $D^0 \bar{D}^{*0}$ loosely bound state [16] or a virtual state [17]. Meanwhile other non-charmonium explanations were also proposed in the literature, such as $\bar{c}cg$ hybrid meson [18], glueball [19], and a compact tetraquark state as the diquark cluster [20].

A very important task in understanding the nature of the $X(3872)$ involves the discrimination of a two-quark configuration as the $\chi_{c1}(2P)$, a compact multiquark configuration and a hadronic molecule [21–26]. But in fact, there are few experimental processes which can provide a clean

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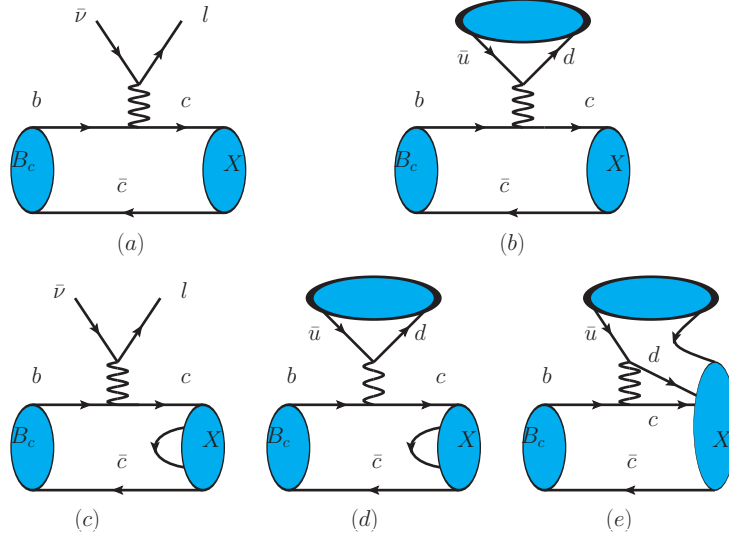


FIG. 1: Feynman diagrams for the B_c decays into the $X(3872)$: the upper two diagrams for the $\bar{c}c$ structure, and the lower ones for the four-quark assignments.

discrimination among these descriptions, which makes the situation obscure. In this work, we propose an approach that is able to directly examine the structure of the $X(3872)$ at short distance, and probe its short-distance component in the B_c semileptonic and nonleptonic decays. As we will show later, the ratios between branching fractions in the B_c semileptonic and nonleptonic decays are almost universal for different polarizations of the $X(3872)$ and can be reliably predicted in theory if the production is dominated by the $\bar{c}c$. The decay modes include the semileptonic $B_c^- \rightarrow X(3872)\ell^-\bar{\nu}$, and the $B_c^- \rightarrow X(3872)\rho^-, X(3872)a_1^-(1260)$ decays. The light meson in the final state can also be replaced by the strange mesons $K^*(892)$, $K_1(1270)$ or $K_1(1400)$, with the cost of the reduced branching fractions due to the suppressed CKM matrix element $|V_{us}|$.

Hereafter we will use the abbreviation X to denote the $X(3872)$ for the sake of simplicity. Feynman diagrams for the semileptonic and nonleptonic $B_c \rightarrow X(3872)$ transitions are given in Fig. 1: the upper two diagrams correspond to the $\bar{c}c$ configuration, while the lower ones correspond to the four-quark case.

We will first discuss the implications from the $\bar{c}c$ component and start with the semileptonic decay mode, in which the $B_c \rightarrow X$ transition induced by the vector and axial-vector currents is parametrized by:

$$\begin{aligned}
 \langle X | \bar{c}\gamma_\mu\gamma_5 b | B_c^- \rangle &= -\frac{2iA(q^2)}{m_{B_c} - m_X} \epsilon_{\mu\nu\rho\sigma} \epsilon^{*\nu} p_{B_c}^\rho p_X^\sigma, \\
 \langle X | \bar{c}\gamma_\mu b | B_c^- \rangle &= -2m_X V_0(q^2) \frac{\epsilon^* \cdot q}{q^2} q_\mu - (m_{B_c} - m_X) V_1(q^2) \left[\epsilon_\mu^* - \frac{\epsilon^* \cdot q}{q^2} q_\mu \right] \\
 &\quad + V_2(q^2) \frac{\epsilon^* \cdot q}{m_{B_c} - m_X} \left[P_\mu - \frac{m_{B_c}^2 - m_X^2}{q^2} q_\mu \right],
 \end{aligned} \tag{1}$$

with $P = p_{B_c} + p_X$, $q = p_{B_c} - p_X$, and $\epsilon^{0123} = +1$.

We will consider the $\ell = e, \mu$ and thus neglect the lepton mass. The differential decay width for the $B_c^- \rightarrow X\ell^-\bar{\nu}_\ell$ is given as

$$\frac{d\Gamma(B_c^- \rightarrow X\ell^-\bar{\nu}_\ell)}{dq^2} = \frac{\sqrt{\lambda(q^2)}q^2 G_F^2 |V_{cb}|^2}{192\pi^3 m_{B_c}^3} \times [|\mathcal{A}_0^1(q^2)|^2 + |\mathcal{A}_\perp^1(q^2)|^2 + |\mathcal{A}_\parallel^1(q^2)|^2], \quad (2)$$

where $|V_{cb}|$ is the CKM matrix element and G_F is the Fermi constant. The q^2 as the lepton pair invariant mass square and

$$\lambda(q^2) = (m_{B_c}^2 + m_X^2 - q^2)^2 - 4m_{B_c}^2 m_X^2.$$

The polarised decay amplitudes are defined as

$$\begin{aligned} \mathcal{A}_0^1(q^2) &= \frac{1}{2m_X \sqrt{q^2}} \left[-\frac{\lambda(q^2)}{m_{B_c} - m_X} V_2(q^2) + (m_{B_c}^2 - m_X^2 - q^2)(m_{B_c} - m_X) V_1(q^2) \right], \\ \mathcal{A}_\perp^1(q^2) &= (m_{B_c} - m_X) V_1(q^2) \mp \frac{\sqrt{\lambda(q^2)}}{m_{B_c} - m_X} A(q^2), \\ \mathcal{A}_{\perp/\parallel}^1(q^2) &= \frac{1}{\sqrt{2}} [\mathcal{A}_+^1(q^2) \mp \mathcal{A}_-^1(q^2)]. \end{aligned} \quad (3)$$

After the integration of the off-shell W -boson, the effective Hamiltonian for the $b \rightarrow c\bar{u}d$ transition is given as

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb} V_{ud}^* \left\{ C_1 O_1 + C_2 O_2 \right\}, \quad (4)$$

where C_1 and C_2 are Wilson coefficients for the operators O_1 and O_2 . V_{cb}, V_{ud} are the CKM matrix elements. If the $X(3872)$ is composed of the $\bar{c}c$, the above effective Hamiltonian leads to

$$\Gamma(B_c^- \rightarrow X\rho^-) = \frac{|\vec{p}|}{8\pi m_{B_c}^2} \left| \frac{G_F}{\sqrt{2}} V_{cb} V_{ud}^* a_1 f_\rho m_\rho \right|^2 \times [|\mathcal{A}_0^1(m_\rho^2)|^2 + |\mathcal{A}_\perp^1(m_\rho^2)|^2 + |\mathcal{A}_\parallel^1(m_\rho^2)|^2], \quad (5)$$

where $a_1 = C_1 + C_2/3$ and $|\vec{p}|$ is the three momentum of the $X(3872)$ in the B_c rest frame. The f_ρ and m_ρ is the ρ meson decay constant and mass, respectively. In deriving the above formulas, we have assumed the factorization theorem, which can be proved at leading power in $1/m_b$ using soft-collinear-effective theory [27, 28] similar with the proof for the $\bar{B}^0 \rightarrow D^+\pi^-$ channel [29].

From Eq. (2) and Eq. (5), we can see most hadronic effects will cancel if we consider the ratios of branching fractions:

$$R_i(\rho) = \int_{(m_\rho - \delta)^2}^{(m_\rho + \delta)^2} dq^2 \frac{d\mathcal{B}(B_c^- \rightarrow X_i \ell^- \bar{\nu}_\ell)}{dq^2} \frac{1}{\mathcal{B}(B_c^- \rightarrow X_i \rho^-)}. \quad (6)$$

In Eq. (6) the subscript i denotes the polarization, with $i = 0, \perp, \parallel$ or $i = 0, \pm 1$, or the total decay width. In order to access the semileptonic decay modes on the experimental side, we have limited the analysis to the mass region around the ρ meson mass, with the parameter δ charactering the size of the bin.

In the case that the production of the $X(3872)$ is dominated by the $\bar{c}c$, the above ratios are predicted as

$$\begin{aligned} R_0(\rho) &= (10.9 \pm 0.1) \times 10^{-3}, \\ R_\perp(\rho) &= (11.1 \pm 0.1) \times 10^{-3}, \\ R_{||}(\rho) &= (11.1 \pm 0.1) \times 10^{-3}, \\ R_{\text{total}}(\rho) &= (10.9 \pm 0.1) \times 10^{-3}, \end{aligned} \quad (7)$$

where for illustration we have used $\delta = 0.1$ GeV which is at the same order of magnitude with the ρ meson width. Choosing a different δ will be similar. The errors given in Eq. (7) arise from transition form factors. For an estimate, we have used the constant form factors, the calculation in covariant light-front approach [30], and light-cone sum rules [31]. In the numerics, we have also used $m_\rho = 0.77526$ GeV and $a_1 = 1.07$ [32]. The $f_\rho = (209.4 \pm 0.4)$ MeV is extracted from the data on $\tau \rightarrow \rho^- \nu_\tau$ decay [14]. As we can see the above ratios are universal and stable against the hadronic uncertainties.

The ρ^- meson mainly decays into the $\pi^-\pi^0$, in which the neutral pion may be difficult to reconstruct. In this case, it may be more advantageous to consider the $a_1(1260)$ which decays into three pions. In fact, the decay of $B_c \rightarrow J/\psi \pi^+ \pi^- \pi^-$ has been observed by LHCb [33] and CMS [34] collaboration, in which the $a_1(1260)$ provides the dominant contribution. For our purpose, we can similarly define

$$R_i(a_1) = \int_{(m_{a_1}-\delta)^2}^{(m_{a_1}+\delta)^2} dq^2 \frac{d\mathcal{B}(B_c^- \rightarrow X_i \ell^- \bar{\nu})}{dq^2} \frac{1}{\mathcal{B}(B_c^- \rightarrow X_i a_1^-)}. \quad (8)$$

Again if the production is mostly through the $\bar{c}c$, the above ratios are predicted as

$$\begin{aligned} R_0(a_1) &= (13.5 \pm 0.1 \pm 1.1) \times 10^{-3}, \\ R_\perp(a_1) &= (13.5 \pm 0.1 \pm 1.1) \times 10^{-3}, \\ R_{||}(a_1) &= (13.5 \pm 0.1 \pm 1.1) \times 10^{-3}, \\ R_{\text{total}}(a_1) &= (13.5 \pm 0.1 \pm 1.1) \times 10^{-3}. \end{aligned} \quad (9)$$

The first errors originate from the $B_c \rightarrow X$ form factors and the second ones are from the f_{a_1} for which we have used $f_{a_1} = (238 \pm 10)$ MeV [35]. This sizable error is reducible using the experimental data on $\tau \rightarrow a_1^-(1260) \nu_\tau$.

One can also use $K^*(892)$ or $K_1(1270)/K_1(1400)$ to tag the production mechanism for the $X(3872)$. The price to pay is that the decay amplitude is proportional to the smaller CKM matrix element V_{us} compared to the V_{ud} in the associated production of ρ and $a_1(1260)$. For the $K^*(892)$ final state, we have

$$\begin{aligned} R_0(K^*) &= (0.245 \pm 0.001 \pm 0.014), \\ R_\perp(K^*) &= (0.247 \pm 0.001 \pm 0.014), \\ R_{||}(K^*) &= (0.249 \pm 0.001 \pm 0.014), \\ R_{\text{total}}(K^*) &= (0.246 \pm 0.001 \pm 0.014) \end{aligned} \quad (10)$$

where again the errors are from the $B_c \rightarrow X$ transition form factors and the K^* decay constant extracted from the $\tau \rightarrow K^* \nu$: $f_{K^*} = (205 \pm 6) \text{ MeV}$.

Based on the huge amount of data samples, the LHC experiment is playing an important role in the study of hadron exotics. The LHCb collaboration has measured the B decays into the $X(3872)$ and determined its quantum numbers [12, 13]. Based on the 1.0 fb^{-1} data at the center-of-mass (c.m.) energy of 7 TeV, the LHCb collaboration is also able to extract the ratio of B_c^+ branching fractions to $J/\psi \pi^+$ and $J/\psi \mu^+ \nu_\mu$ [36]. For the nonleptonic B_c decays into the $X(3872)$, a theoretical estimate of their branching fractions is given in Ref. [30]

$$\begin{aligned} \mathcal{B}(B_c^- \rightarrow X \rho^-) &= (5.0_{-1.7}^{+2.0}) \times 10^{-3}, \\ \mathcal{B}(B_c^- \rightarrow X K^{*-}) &= (2.9_{-1.0}^{+1.1}) \times 10^{-4}, \end{aligned} \quad (11)$$

where the $X(3872)$ is treated as a $\chi_{c1}(2P)$ state. In the future the data sample will be increased by at least one order of magnitude, and thus it is very likely for the LHCb to observe the B_c decays into the $X(3872)$ due to the sizable branching fractions. In addition, the experimental prospect at the next-generation electron-positron collider is also promising, for instance, the CEPC will produce about 10^{11} $b\bar{b}$ events at the c.m. energy $\sqrt{s} = m_Z$ [37].

The independence on hadronic effects of the above ratios is evident for the processes of Fig. 1 (a) and (b). If the $X(3872)$ is composed of four-quarks at short-distance, as either a compact tetraquark or hadronic molecule, the situation will be different. In this case, the production Feynman diagrams are demonstrated in Fig. 1 (c),(d), and (e). Since a pair of light-quarks are produced at short-distance compared to Fig. 1 (a) and (b), the production rates will be greatly suppressed by the strong coupling constant and powers of the $1/m_b$, which can lead to very small branching fractions for the $B_c \rightarrow X$ transition. Moreover, there will be sources spoiling the relation for the ratios as given in Fig. 1 (e). So a sizable production rate and the agreement between the data and predictions on ratios between branching fractions of B_c decays will imply the presence of a $\bar{c}c$ core within the $X(3872)$. Alternatively, a mismatch of the predicted ratios will clearly indicate the short-distance non- $\bar{c}c$ component in the $X(3872)$.

To summarize, although the $X(3872)$ meson has been well established in experiment, its nature is still under debate due to prescriptions from different scenarios. In this work, we propose a method to explore its short-distance $\bar{c}c$ component in the semileptonic and nonleptonic B_c decays by measuring the production ratios of branching fractions. We demonstrate that these ratios are almost universal and can be reliably predicted if there exist a $\bar{c}c$ component within the $X(3872)$. These predictions could be directly tested by the measurements in the future. Significant deviations from the results in Eqs. (7), (9) and (10) would be a clear signal for the non-standard charmonium structure at the short distance. With the large amount of data in the future, we would expect that the above predictions can be examined and much deeper insights into the nature of the $X(3872)$ can be achieved.

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