Search for XYZ states in Λ_b decays at the LHCb

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Abstract

We consider X(3872) and Y(4140) as the vector tetraquark states of \( X_c^0 \equiv c\bar{c}u\bar{u}(d\bar{d}) \) and \( c\bar{c}s\bar{s} \), respectively. By connecting \( \Lambda_b \to X_c^0\Lambda \) to \( B^- \to X_c^0K^- \), we predict that the branching ratios of \( \Lambda_b \to \Lambda(X(3872) \to J/\psi\pi^+\pi^-) \) and \( \Lambda_b \to \Lambda(Y(4140) \to J/\psi\phi) \) are \( (5.2 \pm 1.8) \times 10^{-6} \) and \( (4.7 \pm 2.6) \times 10^{-6} \), which are accessible to the experiments at the LHCb, respectively. The measurements of these \( \Lambda_b \) modes would be the first experimental evidences for the XYZ states in baryonic decays.
I. INTRODUCTION

With the quantum numbers of $J^{PC} = 1^{++}$ determined by the $B^- \rightarrow X(3872)^0 K^-$ decay \[^{[1]}\] \[^{[1]}\], the state of $X(3872)^0$ has been established as one of the $XYZ$ states \[^{[2]}\], which are regarded to be exotic due to the non-pure $c\bar{c}$ components. However, it is still a puzzle whether $X(3872)^0$ is really a tetraquark state (four-quark bound state) with the quark content $c\bar{c}u\bar{u}(d\bar{d})$ \[^{[3]}\]. Note that, while there is no sign of its charged partner to be the $c\bar{c}ud(d\bar{u})$ state, $Y(4140)$ can be a tetraquark consisting of $c\bar{c}s\bar{s}$ \[^{[4]}\], of which the quantum numbers of $J^{PC}$ are not experimentally assigned. As more investigations are apparently needed, the study of $X(3872)$ has been restricted in the $B$ decays of $B \rightarrow X(3872)^0 K^{(*)}$ and $B \rightarrow X(3872)^0 K\pi$ with $K\pi$ partly from $K^*$ \[^{[5, 6]}\], where the resonant $X^0(3872)$ decay channels can be $X(3872)^0 \rightarrow J/\psi\pi^+\pi^-$, $J/\psi\omega$, $J/\psi\gamma$ and $D\bar{D}^*$. At present, no other observation has been found beyond the $B$ decays.

On the other hand, being identified as the exotic meson, which could be the tetraquark \[^{[3]}\], $D\bar{D}^*$ molecule \[^{[7]}\], or hybrid $c\bar{c}g$ bound state \[^{[8]}\], the $X(3872)$ state causes the difficulty of the theoretical calculations. In this study, we will concentrate on the tetraquark scenario by denoting $X^0_c$ to be composed of $c\bar{c}q\bar{q}$, where $q\bar{q}$ can be $u\bar{u}$, $d\bar{d}$, or $s\bar{s}$. In particular, we take $X(3872)^0$ and $Y(4140)$ as two of these exotic $X^0_c$ states. Through the $b \rightarrow c\bar{c}s$ transition at the quark level in Fig. \[^{[9]}\] the decays of $B \rightarrow (X(3872)^0, J/\psi)K$ correspond to the processes of the $B \rightarrow K$ transition with the recoiled charmed mesons of $X(3872)^0$ and $J/\psi$, respectively. Although the $J/\psi$ formation from the $c\bar{c}$ currents can be calculated within the framework of QCD, the $X(3872)$ one cannot be done at the moment.

However, it is interesting to see in Fig. \[^{[9]}\] that all decays of $(B, \Lambda_b) \rightarrow (X^0_c, J/\psi)K$ are originated from the $b \rightarrow c\bar{c}s$ transition at the quark level, and therefore connected. As a result, despite the unknown matrix elements of the $X^0_c$ hadronization through the $c\bar{c}$ currents, we can relate these decays. In particular, we can predict the branching ratios of $\Lambda_b \rightarrow X^0_c\Lambda$. The experimental searches of these $\Lambda_b$ decays at the LHCb will clearly improve our understanding of the XYZ states.
FIG. 1. The doubly charmful $b$-hadron decays, where (a), (b), (c), and (d) depict $B \to J/\psi K$, $\Lambda_b \to J/\psi \Lambda$, $B \to X^0_c K$, and $\Lambda_b \to X^0_c \Lambda$, respectively, with $X^0_c$ as the tetraquark to consist of $c\bar{c}q\bar{q}$.

II. FORMALISM

From Fig. 1 through the effective Hamiltonian of the $b \to c\bar{c}s$ transition at the quark level, the amplitudes of $\Lambda_b \to M_c \Lambda$ and $B \to M_c K$ can be factorized as

$$\mathcal{A}(\Lambda_b \to M_c \Lambda) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* a_2 \langle M_c | \bar{c} \gamma^\mu (1 - \gamma_5) c | 0 \rangle \langle \Lambda | \bar{s} \gamma^\mu (1 - \gamma_5) b | \Lambda_b \rangle,$$

$$\mathcal{A}(B \to M_c K) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* \hat{a}_2 \langle M_c | \bar{c} \gamma^\mu (1 - \gamma_5) c | 0 \rangle \langle K | \bar{s} \gamma^\mu (1 - \gamma_5) b | B \rangle, \quad (1)$$

where $G_F$ is the Fermi constant, $V_{ij}$ are the CKM matrix elements, $M_c$ represents $J/\psi$ of $J^{PC} = 1^{--}$ or the exotic $X^0_c$ state with its constituent being $c\bar{c}q\bar{q}$. For simplicity, we take that the quantum numbers of $X^0_c$ are $J^{PC} = 1^{++}$, such as the established $X(3872)^0$ state. Note that $Y(4140)$, observed in the resonant $B^- \to Y(4140)K^-$, $Y(4140) \to J/\psi \phi$ decay [11, 12], is also assumed to be the $J^{PC} = 1^{++}$ state and treated as one of the $X^0_c$ states with the tetraquark of $c\bar{c}s\bar{s}$ [4]. To calculate the processes in Fig. 1 we need to know the matrix elements of $\langle X^0_c | \bar{c} \gamma^\mu (1 - \gamma_5) c | 0 \rangle$, which is the most difficult part unless these can be related to the observed quantities. In Eq. (1), the parameters $a_2$ and $\hat{a}_2$, involving the non-factorizable effects, can be extracted from the observed branching ratios of $\mathcal{B}(\Lambda_b \to J/\psi \Lambda)$ and $\mathcal{B}(B^- \to J/\psi K^-)$, respectively. The matrix elements of the $\Lambda_b \to \Lambda$ and $B \to K$
transitions in Eq. (1) are in the forms of

\[ \langle \Lambda | \bar{s} \gamma_\mu b | \Lambda_b \rangle = \bar{u}_\Lambda \left[ f_1 \gamma_\mu + \frac{f_2}{m_{\Lambda_b}} i \sigma_\mu q^\nu + \frac{f_3}{m_{\Lambda_b}} q_\mu \right] u_{\Lambda_b}, \]

\[ \langle \Lambda | \bar{s} \gamma_\mu \gamma_5 b | \Lambda_b \rangle = \bar{u}_\Lambda \left[ g_1 \gamma_\mu + \frac{g_2}{m_{\Lambda_b}} i \sigma_\mu q^\nu + \frac{g_3}{m_{\Lambda_b}} q_\mu \right] \gamma_5 u_{\Lambda_b}, \]

\[ \langle K | \bar{s} \gamma_\mu (1 - \gamma_5) b | B \rangle = \left[ (p_B + p_K)^\mu - \frac{m_B^2 - m_K^2}{t} q^\mu \right] F_{1BK}(t) + \frac{m_B^2 - m_K^2}{t} q^\mu F_{0BK}(t), \] (2)

with \( t \equiv q^2 \), where the momentum dependences of the form factors are given by

\[ f_1(t) = \frac{f_1(0)}{(1 - t/m_{\Lambda_b}^2)^2}, \quad g_1(t) = \frac{g_1(0)}{(1 - t/m_{\Lambda_b}^2)^2}, \] (3)

and

\[ F_{1BK}(t) = \frac{F_{1BK}(0)}{(1 - t/M_c^2)(1 - \frac{\sigma_{11t}}{M_c^2} + \frac{\sigma_{12t}^2}{M_c^2})}, \quad F_{0BK}(t) = \frac{F_{0BK}(0)}{1 - \frac{\sigma_{01t}}{M_c^2} + \frac{\sigma_{02t}^2}{M_c^2}}. \] (4)

Note that the other form factors \( f_{2,3}(g_{2,3}) \) in Eq. (2) that need the loop calculations to flip the valence quark spins have been calculated to be small and safely ignored. In terms of the \( SU(3) \) flavor and \( SU(2) \) spin symmetries, one can relate \( f_1(0) \) and \( g_1(0) \) in Eq. (3) to be

\[ f_1(0) = g_1(0) = -\sqrt{2/3} C_F, \] (5)

with \( C_F \) to be extracted from the measured \( \Lambda_b \to p(K^-, \pi^-) \) decays. With \( X_c^0 \) being \( J^{PC} = 1^{++} \), the matrix elements in Eq. (1) of the \( 0 \to J/\psi \) and \( 0 \to X_c^0 \) productions can be parameterized as

\[ \langle J/\psi | \bar{c} \gamma_\mu c | 0 \rangle = m_{J/\psi} f_{J/\psi} \epsilon_\mu^*, \]

\[ \langle X_c^0 | \bar{c} \gamma_\mu \gamma_5 c | 0 \rangle = m_{X_c^0} f_{X_c^0} \epsilon_\mu^*, \] (6)

where \( m_{J/\psi(X_c^0)} \), \( f_{J/\psi(X_c^0)} \) and \( \epsilon_\mu^* \) are the mass, decay constant and polarization for \( J/\psi(X_c^0) \), respectively. Because of the exotic nature of the \( X_c^0 \) state, which could be the \( D\bar{D}^* \) molecule, the hybrid \( c\bar{c}g \) state, or the tetraquark state, no present QCD model can derive \( f_{X_c^0} \). Nonetheless, as we propose that \( \Lambda_b \to X_c^0 \Lambda \) and \( B \to X_c^0 K \) are connected, we are able to eliminate the unknown \( f_{X_c^0} \) and predict \( \mathcal{B}(\Lambda_b \to X_c^0 \Lambda, X_c^0 \to J/\psi \pi^+ \pi^-) \) in terms of the observed \( \mathcal{B}(B \to X_c^0 K, X_c^0 \to J/\psi \pi^+ \pi^-) \).
III. NUMERICAL ANALYSIS AND DISCUSSIONS

For the numerical analysis, the theoretical inputs of the CKM matrix parameters in terms of the Wolfenstein parameterization are taken to be \((\lambda, A, \rho, \eta) = (0.225, 0.814, 0.120 \pm 0.022, 0.362 \pm 0.013)\) \cite{5}. For the form factor in Eq. (5), we choose \(C_F = 0.136 \pm 0.009\) \cite{13}, which is consistent with other QCD model calculations and used to explain the data in the \(\Lambda_b\) decays \cite{9, 13}. In addition, from Ref. \cite{14} we get \(F_{BK}(0) = F_{BK}^0(0) = 0.36\) with \(\sigma_{11} = 0.43, \sigma_{12} = 0, \sigma_{01} = 0.70, \sigma_{02} = 0.27\) and \(M_V = 5.42\) GeV. For the parameters \(a_2, \hat{a}_2\), we take \((a_2, \hat{a}_2) = (0.154 \pm 0.024, 0.268 \pm 0.004)\), which are extracted from \(\Lambda_b \rightarrow J/\psi \Lambda\) \cite{9} and \(B^- \rightarrow J/\psi K^-\) \cite{5}, respectively. In terms of Eq. (1), we obtain

\[ R_{X_0} \equiv \frac{B(\Lambda_b \rightarrow X_0^0 \Lambda)}{B(B^- \rightarrow X_0^- K^-)} = 0.61 \pm 0.20, \tag{7} \]

where the unknown decay constant \(f_{X_0}\) has been eliminated. The measurements for \(B^-(3872)^0 K^-\) and \(B^-(4140)^0 K^-\) give \cite{5}

\[ B(B^- \rightarrow K^-(X(3872)^0 \rightarrow J/\psi \pi^+ \pi^-)) = (8.6 \pm 0.8) \times 10^{-6} \tag{8} \]

and \cite{11, 12}

\[ B(B^- \rightarrow K^-(Y(4140) \rightarrow J/\psi \phi)) = (0.149 \pm 0.039 \pm 0.024)B(B^- \rightarrow J/\psi \phi K^-) = (7.7 \pm 3.5) \times 10^{-6} \tag{9} \]

where we have used \(B(B^- \rightarrow J/\psi \phi K^-) = (5.2 \pm 1.7) \times 10^{-5}\) \cite{5}. By relating Eq. (7) to Eqs. (8) and (9), we find

\[ B(\Lambda_b \rightarrow \Lambda(X(3872)^0 \rightarrow J/\psi \pi^+ \pi^-)) = (5.2 \pm 1.8) \times 10^{-6}, \tag{10} \]

\[ B(\Lambda_b \rightarrow \Lambda(Y(4140) \rightarrow J/\psi \phi)) = (4.7 \pm 2.6) \times 10^{-6}, \tag{11} \]

respectively, which can be reliable predictions to be compared with the future data. We remark that \(B(\bar{B}^0 \rightarrow \bar{K}^0(X(3872)^0 \rightarrow J/\psi \pi^+ \pi^-)) = (4.3 \pm 1.3) \times 10^{-6}\) \cite{5} can also lead to similar results but with larger uncertainties than those in Eq. (10). It should be noted that the quantum numbers for \(Y(4140)\) have not been experimentally identified yet, although they are predicted to be \(J^{PC} = 0^{++} (2^{++})\) in Ref. \cite{15} and \(1^{-+}\) in Ref. \cite{16} besides \(1^{++}\) in Ref. \cite{4}. We emphasize that, even it is finally measured to have \(J^{PC} = 0^{++}\) \cite{17} or \(1^{-+}\), the decay of \(\Lambda_b \rightarrow \Lambda(Y(4140) \rightarrow J/\psi \phi)\) can still be examined by our method. However, the
factorization approach would not support the tensor (T) identification of the $J = 2$ state due to $\langle T|\bar{c}\gamma_\mu(1 - \gamma_5)c|0\rangle = 0$.

Finally, we note that unlike $B^- \to X(3872)^0K^-$, which receives the dominant contribution from the doubly charmful $b \to c\bar{s}s$ transition, the decay of $B^- \to X(3872)^-\bar{K}^0$ is forbidden in Fig. 11 as supported by the experiment due to its non-observation [18], where $X(3872)^-$ is the charged counterpart of $X(3872)^0$. However, this mode can proceed from the charmless $b \to d\bar{d}s$ transition, provided that the $c\bar{c}$ contents in $X(3872)^-$ come from the intrinsic charm within the $B$ meson, which is similar to the pentaquark state productions in the $\Lambda_b$ decays [19, 20]. As a result, in the charmless $B$ decays, the branching ratios of the three possible exotic decays of $\bar{B}^0 \to X_c^\pm K^-, X_c^+\pi^-$, and $B^- \to X_c^-\bar{K}^0$ can be at the same level. In addition, the intrinsic charm mechanism would be used to the productions of the charged $Y$ and $Z$ particles as $\bar{B}^0 \to Z(4430)^+K^-$ with $Z(4430)^+$ to consist of $c\bar{c}ud$ [21, 22]. Moreover, the analogous statements for the corresponding $\Lambda_b$ decays can also be drawn.

IV. CONCLUSIONS

We have explored the possibility to find the exotic meson states, such as the tetraquark four-quark bound states of $X_c^0 = c\bar{c}u\bar{u}(d\bar{d})$ and $c\bar{c}ss$ in the $\Lambda_b$ decays. In particular, by concentrating on the scenarios with $X(3872)^0$ and $Y(4140)$ being $J^{PC} = 1^{++}$, we have studied the doubly charmful $\Lambda_b \to X_c^0\Lambda$ decays. By connecting $\Lambda_b \to \Lambda X_c^0$ to $B^- \to K^-X_c^0$, we have found that $\mathcal{B}(\Lambda_b \to \Lambda(X(3872)^0 \to J/\psi\pi^+\pi^-)$ and $\mathcal{B}(\Lambda_b \to \Lambda(Y(4140) \to J/\psi\phi)$ are $(5.2 \pm 1.8) \times 10^{-6}$ and $(4.7 \pm 2.6) \times 10^{-6}$, respectively. As these predicted branching ratios are accessible to the experiments at the LHCb, a measurement will be the first clean experimental evidence for the $XYZ$ states in baryonic decays.

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