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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 $B^- \to X_c^0 K^-$, we predict that the branching ratios of $\Lambda_b \to \Lambda(X(3872)^0 \to) J/\psi\pi^+\pi^-$ 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 Λ_b modes would be the first experimental evidences for the XYZ states in baryonic decays.

1. Introduction

With the quantum numbers of $J^{PC} = 1^{++}$ determined by the $B^- \to X(3872)^0 K^-$ decay [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 $c\bar{c}u\bar{d}(d\bar{u})$ 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 $B \to X(3872)^0 K^{(*)}$ and $B \to X(3872)^0 K\pi$ with $K\pi$ partly from K^* [5,6], where the resonant $X^0(3872)$ decay channels can be $X(3872)^0 \to J/\psi\pi^+\pi^-$, $J/\psi\omega$, $J/\psi\gamma$ 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_c^0 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_c^0 states. Through the $b \to c\bar{c}s$ transition at the quark level in Fig. 1, the decays of $B \to (X(3872)^0, J/\psi)K$ correspond to the processes of the $B \to K$ transition with the recoiled charmed mesons of $X(3872)^0$ and J/ψ, respectively. Although the

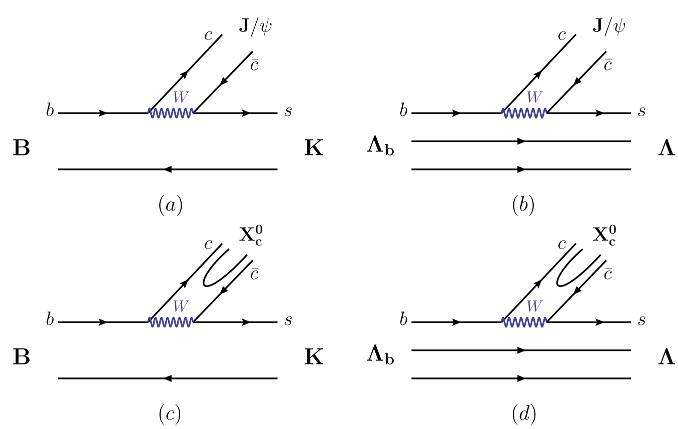

Fig. 1. The doubly charmful b-hadron decays, where (a), (b), (c), and (d) depict $B \to J/\psi K$, $\Lambda_b \to J/\psi\Lambda$, $B \to X_c^0 K$, and $\Lambda_b \to X_c^0\Lambda$, respectively, with X_c^0 as the tetraquark to consist of $c\bar{c}q\bar{q}$.

J/ψ 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. 1 that all decays of $(B, \Lambda_b) \to (X_c^0, J/\psi)K$ are originated from the $b \to c\bar{c}s$ transition at the quark level, and therefore connected. As a result, despite the unknown matrix elements of the X_c^0 hadronization through the $c\bar{c}$ currents, we can relate these decays. In particular, we can predict the branching ratios of $\Lambda_b \to X_c^0\Lambda$. The experimental searches of these Λ_b decays at the LHCb will clearly improve our understanding of the XYZ states.

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2. 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 [9,10]

$$\begin{aligned}
&\mathcal{A}(\Lambda_b \to M_c\Lambda) \\
&\quad= \frac{G_F}{\sqrt{2}} V_{cb}V_{cs}^* a_2 \,\langle M_c|\bar{c}\gamma^\mu(1-\gamma_5)c|0\rangle\langle\Lambda|\bar{s}\gamma_\mu(1-\gamma_5)b|\Lambda_b\rangle, \\
&\mathcal{A}(B \to M_c K) \\
&\quad= \frac{G_F}{\sqrt{2}} V_{cb}V_{cs}^* \hat{a}_2 \,\langle M_c|\bar{c}\gamma^\mu(1-\gamma_5)c|0\rangle\langle K|\bar{s}\gamma_\mu(1-\gamma_5)b|B\rangle, \quad (1)
\end{aligned}$$

where G_F is the Fermi constant, V_{ij} are the CKM matrix elements, M_c represents J/ψ of $J^{PC}=1^{--}$ or the exotic X_c^0 state with its constituent being $c\bar{c}q\bar{q}$. For simplicity, we take that the quantum numbers of X_c^0 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_c^0 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 $\langle X_c^0|\bar{c}\gamma_\mu(1-\gamma_5)c|0\rangle$, 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

$$\begin{aligned}
\langle\Lambda|\bar{s}\gamma_\mu b|\Lambda_b\rangle &= \bar{u}_\Lambda\left[f_1\gamma_\mu + \frac{f_2}{m_{\Lambda_b}} i\sigma_{\mu\nu}q^\nu + \frac{f_3}{m_{\Lambda_b}} q_\mu\right]u_{\Lambda_b}, \\
\langle\Lambda|\bar{s}\gamma_\mu\gamma_5 b|\Lambda_b\rangle &= \bar{u}_\Lambda\left[g_1\gamma_\mu + \frac{g_2}{m_{\Lambda_b}} i\sigma_{\mu\nu}q^\nu + \frac{g_3}{m_{\Lambda_b}} q_\mu\right]\gamma_5 u_{\Lambda_b}, \\
\langle K|\bar{s}\gamma_\mu(1-\gamma_5)b|B\rangle &= \left[(p_B+p_K)^\mu - \frac{m_B^2-m_K^2}{t}q^\mu\right]F_1^{BK}(t) \\
&\quad + \frac{m_B^2-m_K^2}{t}q^\mu F_0^{BK}(t), \qquad (2)
\end{aligned}$$

with $t \equiv q^2$, where the momentum dependences of the form factors are given by [13]

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

and [14]

$$\begin{aligned}
F_1^{BK}(t) &= \frac{F_1^{BK}(0)}{(1-\frac{t}{M_V^2})(1-\frac{\sigma_{11}t}{M_V^2}+\frac{\sigma_{12}t^2}{M_V^4})}, \\
F_0^{BK}(t) &= \frac{F_0^{BK}(0)}{1-\frac{\sigma_{01}t}{M_V^2}+\frac{\sigma_{02}t^2}{M_V^4}}. \qquad (4)
\end{aligned}$$

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 [9]

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

with C_F to be extracted from the measured $\Lambda_b \to p(K^-,\pi^-)$ decays [13]. 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

$$\begin{aligned}
\langle J/\psi|\bar{c}\gamma_\mu c|0\rangle &= m_{J/\psi} f_{J/\psi}\varepsilon_\mu^*, \\
\langle X_c^0|\bar{c}\gamma_\mu\gamma_5 c|0\rangle &= m_{X_c^0} f_{X_c^0}\varepsilon_\mu^*, \qquad (6)
\end{aligned}$$

where $m_{J/\psi(X_c^0)}$, $f_{J/\psi(X_c^0)}$ and ε_μ^* 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 $\mathcal{B}(B \to X_c^0 K, X_c^0 \to J/\psi\pi^+\pi^-)$.

3. 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 $(\lambda, A, \rho, \eta) = (0.225, 0.814, 0.120 \pm 0.022, 0.362 \pm 0.013)$ [5]. For the form factor in Eq. (5), we choose $C_F = 0.136 \pm 0.009$ [13], which is consistent with other QCD model calculations and used to explain the data in the Λ_b decays [9,13]. In addition, from Ref. [14] we get $F_1^{BK}(0) = F_0^{BK}(0) = 0.36$ 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 $\Lambda_b \to J/\psi\Lambda$ [9] and $B^- \to J/\psi K^-$ [5], respectively. In terms of Eq. (1), we obtain

$$\mathcal{R}_{X_c^0} \equiv \frac{\mathcal{B}(\Lambda_b \to X_c^0\Lambda)}{\mathcal{B}(B^- \to X_c^0 K^-)} = 0.61 \pm 0.20, \qquad (7)$$

where the unknown decay constant $f_{X_c^0}$ has been eliminated. The measurements for $B^- \to X(3872)^0K^-$ and $B^- \to Y(4140)^0K^-$ give [5]

$$\begin{aligned}
&\mathcal{B}(B^- \to K^-(X(3872)^0 \to)J/\psi\pi^+\pi^-) \\
&= (8.6 \pm 0.8) \times 10^{-6} \qquad (8)
\end{aligned}$$

and [11,12]

$$\begin{aligned}
&\mathcal{B}(B^- \to K^-(Y(4140) \to)J/\psi\phi) \\
&\quad= (0.149 \pm 0.039 \pm 0.024)\mathcal{B}(B^- \to J/\psi\phi K^-) \\
&\quad= (7.7 \pm 3.5) \times 10^{-6} \qquad (9)
\end{aligned}$$

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

$$\begin{aligned}
&\mathcal{B}(\Lambda_b \to \Lambda(X(3872)^0 \to)J/\psi\pi^+\pi^-) \\
&\quad= (5.2 \pm 1.8) \times 10^{-6}, \qquad (10) \\
&\mathcal{B}(\Lambda_b \to \Lambda(Y(4140) \to)J/\psi\phi) = (4.7 \pm 2.6) \times 10^{-6}, \qquad (11)
\end{aligned}$$

respectively, which can be reliable predictions to be compared with the future data. We remark that $\mathcal{B}(\bar{B}^0 \to \bar{K}^0(X(3872)^0 \to)J/\psi\pi^+\pi^-) = (4.3 \pm 1.3) \times 10^{-6}$ [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. [15] and 1^{-+} in Ref. [16] besides 1^{++} in Ref. [4]. We emphasize that, even it is finally measured to have $J^{PC} = 0^{++}$ [17] or 1^{-+}, the decay of $\Lambda_b \to \Lambda(Y(4140) \to)J/\psi\phi$ 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 $B^- \to X(3872)^0 K^-$, which receives the dominant contribution from the doubly charmful $b \to c\bar{c}s$ transition, the decay of $B^- \to X(3872)^- \bar{K}^0$ is forbidden in Fig. 1 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 Λ_b decays [19,20]. As a result, in the charmless B decays, the branching ratios of the three possible exotic decays of $\bar{B}^0 \to X_c^+ K^-$, $X_c^+\pi^-$, 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 $c\bar{c}u\bar{d}$ [21, 22]. Moreover, the analogous statements for the corresponding Λ_b decays can also be drawn.

4. 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 $c\bar{c}s\bar{s}$ in the Λ_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 $(5.2\pm1.8)\times10^{-6}$ and $(4.7\pm2.6)\times10^{-6}$, 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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References

[1] R. Aaij, et al., LHCb Collaboration, Phys. Rev. Lett. 110 (2013) 222001;
R. Aaij, et al., LHCb Collaboration, Phys. Rev. D 92 (2015) 011102.
[2] H.X. Chen, W. Chen, X. Liu, S.L. Zhu, arXiv:1601.02092 [hep-ph].
[3] L. Maiani, et al., Phys. Rev. D 71 (2005) 014028.
[4] F. Stancu, J. Phys. G 37 (2010) 075017.
[5] K.A. Olive, et al., Particle Data Group Collaboration, Chin. Phys. C 38 (2014) 090001.
[6] A. Bala, et al., Belle Collaboration, Phys. Rev. D 91 (2015) 051101.
[7] E. Braaten, M. Kusunoki, Phys. Rev. D 69 (2004) 074005;
E.S. Swanson, Phys. Lett. B 588 (2004) 189;
N.A. Tornqvist, Phys. Lett. B 590 (2004) 209;
M.B. Voloshin, Phys. Lett. B 604 (2004) 69.
[8] B.A. Li, Phys. Lett. B 605 (2005) 306.
[9] Y.K. Hsiao, P.Y. Lin, C.C. Lih, C.Q. Geng, Phys. Rev. D 92 (2015) 114013.
[10] C.M. Zanetti, M. Nielsen, R.D. Matheus, Phys. Lett. B 702 (2011) 359.
[11] T. Aaltonen, et al., CDF Collaboration, Phys. Rev. Lett. 102 (2009) 242002.
[12] T. Aaltonen, et al., CDF Collaboration, arXiv:1101.6058 [hep-ex].
[13] Y.K. Hsiao, C.Q. Geng, Phys. Rev. D 91 (2015) 116007.
[14] D. Melikhov, B. Stech, Phys. Rev. D 62 (2000) 014006.
[15] X. Liu, S.L. Zhu, Phys. Rev. D 80 (2009) 017502;
X. Liu, S.L. Zhu, Phys. Rev. D 85 (2012) 019902.
[16] N. Mahajan, Phys. Lett. B 679 (2009) 228.
[17] Z.G. Wang, Eur. Phys. J. C 74 (2014) 2963, arXiv:1601.05541 [hep-ph].
[18] B. Aubert, et al., BaBar Collaboration, Phys. Rev. D 71 (2005) 031501.
[19] Y.K. Hsiao, C.Q. Geng, Phys. Lett. B 751 (2015) 572.
[20] R. Aaij, et al., LHCb Collaboration, Phys. Rev. Lett. 115 (2015) 072001.
[21] R. Aaij, et al., LHCb Collaboration, Phys. Rev. Lett. 112 (2014) 222002.
[22] S.J. Brodsky, R.F. Lebed, Phys. Rev. D 91 (2015) 114025.