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Hunting for the X_b via radiative decays

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ABSTRACT

In this paper, we study radiative decays of X_b, the counterpart of the famous $X(3872)$ in the bottomonium-sector as a candidate for meson–meson molecule, into the $\gamma\Upsilon(nS)$ $(n = 1, 2, 3)$. Since it is likely that the X_b is below the $B\bar{B}^*$ threshold and the mass difference between the neutral and charged bottom meson is small compared to the binding energy of the X_b, the isospin violating decay mode $X_b \to \Upsilon(nS)\pi^+\pi^-$ would be greatly suppressed. This will promote the importance of the radiative decays. We use the effective Lagrangian based on the heavy quark symmetry to explore the rescattering mechanism and calculate the partial widths. Our results show that the partial widths into $\gamma\Upsilon(nS)$ are about 1 keV, and thus the branching fractions may be sizeable, considering the fact the total width may also be smaller than a few MeV like the $X(3872)$. These radiative decay modes are of great importance in the experimental search for the X_b particularly at hadron collider. An observation of the X_b will provide a deeper insight into the exotic hadron spectroscopy and is helpful to unravel the nature of the states connected by the heavy quark symmetry.

1. Introduction

In the past decades, there has been great progress in hadron spectroscopy thanks to the unprecedented data sample accumulated by the B factories and hadron–hadron colliders. A number of charmonium-like and bottomonium-like states have been discovered on these experimental facilities so far but not all of them can be placed in the ordinary $\bar{q}q$ (for reviews, see Refs. [1–4]).

The $X(3872)$ is the first and perhaps the most renowned exotic candidate. It was first discovered in 2003 by Belle in the $B^+ \to K^+ + J/\psi\pi^+\pi^-$ final state [5] and subsequently confirmed by the BaBar Collaboration [6]. Complementary observation is also found in proton–proton/antiproton collisions at the Tevatron [7,8] and LHC [9,10]. Though the existence is well established, the nature of the $X(3872)$ is still ambiguous due to a few peculiar properties. First, compared to typical hadronic widths the total width is tiny. Only an upper bound has been measured experimentally: $\Gamma < 1.2$ MeV [11]. The mass lies closely to the $D^0\bar{D}^{*0}$ threshold, $M_{X(3872)} - M_{D^0} - M_{D^{*0}} = (-0.12 \pm 0.24)$ MeV [12], which leads to speculations that the $X(3872)$ is presumably a meson–meson molecular state [13,14].

These peculiar features have stimulated considerable research interest in investigating the production and decays of the $X(3872)$ towards understanding its nature. A very important aspect involves the discrimination of a compact multiquark configuration and a loosely bound hadronic molecule configuration. In this viewpoint, it would be also valuable to look for the analogue in the bottom sector, referred to as X_b following the notation suggested in Ref. [15], as states related by heavy quark symmetry may have universal behaviors. Since the X_b is expected to be very heavy and its J^{PC} of is 1^{++}, it is less likely for a direct discovery at the current electron–positron collision facilities, though the Super KEKB may provide an opportunity in $\Upsilon(5S, 6S)$ radiative decays [16].

In Ref. [17], the production of the X_b at the LHC and the Tevatron has been investigated, along the same line with the studies on the search for exotic states at hadron colliders [18–24]. It is shown that the production rates at the LHC and the Tevatron are sizeable [17]. On the other hand, the search for the X_b also depends on reconstructing the X_b, which motivates us to study the X_b decays. Since this meson is expected to be far below threshold, the isospin violating decay mode for instance $X_b \to \Upsilon\pi^+\pi^-$ is highly suppressed, and this may explain the escape of X_b in the recent CMS search [25]. As a consequence, radiative decays of the X_b will be of high priority, on which we will focus in this paper. As we will show in the following, these radiative modes have sizeable decay widths. It is also necessary to stress that though $X_b \to \Upsilon\pi^+\pi^-$ is expected to be suppressed, the $X_b \to \Upsilon\pi^+\pi^-\pi^0$ and $X_b \to \chi_{bJ}\pi^+\pi^-$ decays may have sizeable branching fractions as pointed out in Refs. [26,27]. Thus these pionic transitions can be used to search for the X_b and should be investigated as well.

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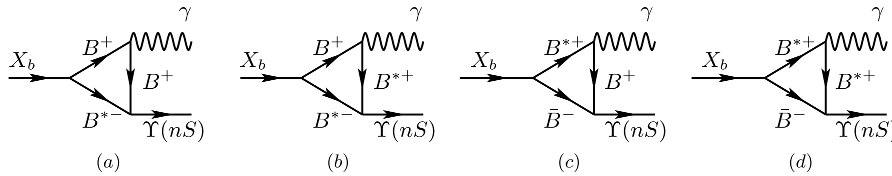

Fig. 1. Feynman diagrams for the radiative decays $X_b \to \gamma\Upsilon(nS)$ with the $B\bar{B}^*$ as the intermediate states.

To calculate the radiative decays, we study the intermediate meson loop contributions, which have been one of the important nonperturbative transition mechanisms in various transitions, and their impact on the heavy quarkonium transitions, also referred to as coupled-channel effects, has been noticed for a long time [28–30]. The intermediate meson loops mechanism has been applied to study the production and decays of ordinary and exotic states [31–48] and B decays [49–56], and a global agreement with experimental data is found. Thus this approach may be an effective approach to handle the X_b radiative decays.

The paper is organized as follows. In Section 2, we will introduce the formalism used in this work. Based on this framework, numerical results are presented in Section 3 and the summary will be given in Section 4.

2. Radiative decays

The calculation of contributions from the meson loops requests the leading order effective Lagrangian. Based on the heavy quark symmetry, we employ the relevant effective Lagrangian for the $\Upsilon(nS)$ [56,57]

$$\begin{aligned}\mathcal{L}_{\Upsilon(nS)B^{(*)}B^{(*)}} = {} & ig_{\Upsilon BB}\Upsilon_\mu\left(\partial^\mu B\bar{B} - B\partial^\mu\bar{B}\right)\\ & - g_{\Upsilon B^*B}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu\Upsilon_\nu\left(\partial_\alpha B^*_\beta\bar{B} + B\partial_\alpha\bar{B}^*_\beta\right)\\ & - ig_{\Upsilon B^*B^*}\left\{\Upsilon^\mu\left(\partial_\mu B^{*\nu}\bar{B}^*_\nu - B^{*\nu}\partial_\mu\bar{B}^*_\nu\right)\right.\\ & + \left(\partial_\mu\Upsilon_\nu B^{*\nu} - \Upsilon_\nu\partial_\mu B^{*\nu}\right)\bar{B}^{*\mu}\\ & \left. + B^{*\mu}\left(\Upsilon^\nu\partial_\mu\bar{B}^*_\nu - \partial_\mu\Upsilon^\nu\bar{B}^*_\nu\right)\right\}, \end{aligned} \tag{1}$$

where $B^{(*)} = (B^{(*)+}, B^{(*)0})$ and $\bar{B}^{(*)T} = (B^{(*)-}, \bar{B}^{(*)0})$ correspond to the bottom meson isodoublets. $\epsilon^{\mu\nu\alpha\beta}$ is the anti-symmetric Levi-Civita tensor and $\epsilon^{0123} = -1$. Due to the heavy quark symmetry, the following relationships of the couplings are valid [56, 57]

$$\begin{aligned} & g_{\Upsilon(nS)BB} = 2g_n\sqrt{m_{\Upsilon(nS)}}m_B, \qquad g_{\Upsilon(nS)B^*B} = \frac{g_{\Upsilon(nS)BB}}{\sqrt{m_B m_{B^*}}},\\ & g_{\Upsilon(nS)B^*B^*} = g_{\Upsilon(nS)B^*B}\sqrt{\frac{m_{B^*}}{m_B}}m_{B^*}, \end{aligned} \tag{2}$$

where $g_n = \sqrt{m_{\Upsilon(nS)}}/(2m_B f_{\Upsilon(nS)})$; $m_{\Upsilon(nS)}$ and $f_{\Upsilon(nS)}$ denote the mass and decay constant of $\Upsilon(nS)$, respectively. The decay constant $f_{\Upsilon(nS)}$ can be extracted from the $\Upsilon(nS) \to e^+e^-$:

$$\Gamma\left(\Upsilon(nS) \to e^+e^-\right) = \frac{4\pi\alpha^2}{27}\frac{f^2_{\Upsilon(nS)}}{m_{\Upsilon(nS)}}, \tag{3}$$

where $\alpha = 1/137$ is the electromagnetic fine-structure constant. Using the masses and leptonic decay widths of the $\Upsilon(nS)$ states: $\Gamma(\Upsilon(1S) \to e^+e^-) = 1.340 \pm 0.018$ keV, $\Gamma(\Upsilon(2S) \to e^+e^-) = 0.612 \pm 0.011$ keV, $\Gamma(\Upsilon(3S) \to e^+e^-) = 0.443 \pm 0.008$ keV [11], one can obtain $f_{\Upsilon(1S)} = 715.2$ MeV, $f_{\Upsilon(2S)} = 497.5$ MeV, and $f_{\Upsilon(3S)} = 430.2$ MeV.

We consider the iso-scalar X_b as an S-wave molecular state with the positive charge parity given by the superposition of $B^0\bar{B}^{*0} + c.c$ and $B^-\bar{B}^{*+} + c.c$ hadronic configurations as

$$|X_b\rangle = \frac{1}{2}\left[\left(\left|B^0\bar{B}^{*0}\right\rangle - \left|B^{*0}\bar{B}^0\right\rangle\right) + \left(\left|B^+B^{*-}\right\rangle - \left|B^-B^{*+}\right\rangle\right)\right]. \tag{4}$$

The coupling of X_b to the bottomed meson is based on the effective Lagrangian

$$\begin{aligned}\mathcal{L} = {} & \frac{1}{2}X^\dagger_{b\mu}\left[x_1\left(B^{*0\mu}\bar{B}^0 - B^0\bar{B}^{*0\mu}\right)\right.\\ & \left. + x_2\left(B^{*+\mu}B^- - B^+B^{*-\mu}\right)\right] + h.c., \end{aligned} \tag{5}$$

where x_i denotes the coupling constant.

For a bound state below an S-wave two-hadron threshold, the effective coupling of this state to the two-body channel is related to the probability of finding the two-hadron component in the physical wave function of the bound states and the binding energy, $E_{X_b} = m_B + m_{B^*} - m_{X_b}$ [33,58,59]

$$x_i^2 \equiv 16\pi(m_B + m_{B^*})^2 c_i^2\sqrt{\frac{2E_{X_b}}{\mu}}, \tag{6}$$

where $c_i = 1/\sqrt{2}$, $\mu = m_B m_{B^*}/(m_B + m_{B^*})$ is the reduced mass.

The magnetic coupling of the photon to heavy bottom meson is described by the Lagrangian [60,61]

$$\mathcal{L}_\gamma = \frac{e\beta Q_{ab}}{2}F^{\mu\nu}\mathrm{Tr}\left[H^\dagger_b\sigma_{\mu\nu}H_a\right] + \frac{eQ'}{2m_Q}F^{\mu\nu}\mathrm{Tr}\left[H^\dagger_a H_a\sigma_{\mu\nu}\right], \tag{7}$$

with

$$H = \left(\frac{1+\not{v}}{2}\right)\left[\mathcal{B}^{*\mu}\gamma_\mu - \mathcal{B}\gamma_5\right], \tag{8}$$

where $Q = \mathrm{diag}\{2/3, -1/3, -1/3\}$ is the light quark charge matrix, β is an unknown parameter and Q' is the heavy quark electric charge (in units of e). In the nonrelativistic constituent quark model $\beta \simeq 3.0\ \mathrm{GeV}^{-1}$, which has been adopted in the study of radiative D^* decays [61]. Note heavy quark symmetry ensures that β is the same in the b and c systems, so we take the same value as Ref. [61]. The first term is the magnetic moment coupling of the light quarks, while the second one is the magnetic moment coupling of the heavy quark and hence is suppressed by $1/m_Q$.

The decay amplitudes for the transitions in Fig. 1 can be expressed in a generic form in the effective Lagrangian approach as follows,

$$M_{fi} = \int\frac{d^4q_2}{(2\pi)^4}\sum_{B^*\ \mathrm{pol.}}\frac{V_1V_2V_3}{a_1a_2a_3}\mathcal{F}\left(m_2, q_2^2\right) \tag{9}$$

where V_i and $a_i = q_i^2 - m_i^2$ $(i = 1, 2, 3)$ are the vertex functions and the denominators of the intermediate meson propagators. For example, in Fig. 1 (a), V_i $(i = 1, 2, 3)$ are the vertex functions for the initial X_b, final bottominum and photon, respectively. a_i $(i = 1, 2, 3)$ are the denominators for the intermediate B^+, B^{*-} and B^+ propagators, respectively.

Since the final-state interactions are of order $1/m_Q$, it is necessary to ensure that the loop contribution vanishes in the heavy quark limit and that the calculation is perturbatively reliable. To do so we introduce a dipole form factor,

Table 1
Predicted partial widths (in unit of keV) of the X_b decays. The parameter in the form factor is chosen as $\alpha = 2.0$ and $\alpha = 3.0$.

	$X_b \to \gamma\Upsilon(1S)$		$X_b \to \gamma\Upsilon(2S)$		$X_b \to \gamma\Upsilon(3S)$	
Dipole form factor	$\alpha = 2.0$	$\alpha = 3.0$	$\alpha = 2.0$	$\alpha = 3.0$	$\alpha = 2.0$	$\alpha = 3.0$
$E_{X_b} = 1$ MeV	0.12	0.41	0.34	0.96	0.22	0.46
$E_{X_b} = 2$ MeV	0.19	0.62	0.42	1.18	0.28	0.57
$E_{X_b} = 5$ MeV	0.28	0.92	0.53	1.53	0.33	0.70
$E_{X_b} = 20$ MeV	0.36	1.20	0.66	1.96	0.30	0.66
Monopole form factor	$\alpha = 2.0$	$\alpha = 3.0$	$\alpha = 2.0$	$\alpha = 3.0$	$\alpha = 2.0$	$\alpha = 3.0$
$E_{X_b} = 1$ MeV	0.02	0.06	0.05	0.11	0.03	0.06
$E_{X_b} = 2$ MeV	0.04	0.08	0.07	0.16	0.04	0.08
$E_{X_b} = 5$ MeV	0.06	0.13	0.12	0.26	0.07	0.12
$E_{X_b} = 20$ MeV	0.13	0.30	0.26	0.56	0.12	0.22

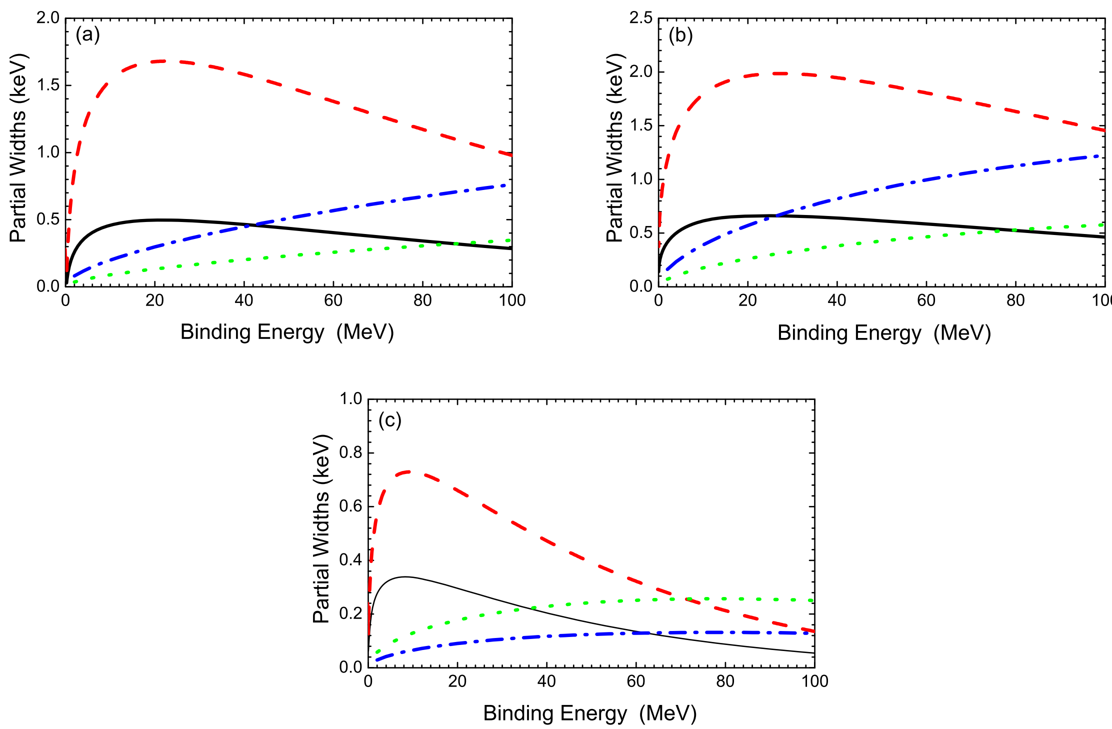

Fig. 2. The dependence of partial widths of $X_b \to \gamma\Upsilon(1S)$ on the E_{X_b} using dipole form factors with $\alpha = 2.0$ (solid lines) and $\alpha = 3.0$ (dashed lines), and monopole form factors with $\alpha = 2.0$ (dotted lines) and $\alpha = 3.0$ (dash-dotted lines), respectively. Panels (b) and (c) corresponds to the ones in the $X_b \to \gamma\Upsilon(2S)$ and $3S$, respectively.

$$\mathcal{F}(m_2, q_2^2) \equiv \left(\frac{\Lambda^2 - m_2^2}{\Lambda^2 - q_2^2}\right)^2, \tag{10}$$

where $\Lambda \equiv m_2 + \alpha\Lambda_{\rm QCD}$ and the QCD energy scale $\Lambda_{\rm QCD} = 220$ MeV. This form factor is supposed to compensate the off-shell effects arising from the intermediate exchanged particle and the non-local effects of the vertex functions [62–64], and phenomenological studies have suggested $\alpha \sim 2$. We will also use a monopole form factor and explore the dependence on the form factor:

$$\mathcal{F}(m_2, q_2^2) \equiv \frac{\Lambda^2 - m_2^2}{\Lambda^2 - q_2^2}. \tag{11}$$

The explicit expression of transition amplitudes can be found in Appendix (A.6) in Ref. [65], where radiative decays of charmonium are studied extensively based on effective Lagrangian approach.

3. Numerical results

The existence of the X_b was predicted in both the tetraquark model [66] and hadronic molecular calculations [27,67,68]. The mass of the lowest-lying 1^{++} $\bar{b}\bar{q}bq$ tetraquark was predicted to be 10504 MeV in Ref. [66], while the mass of the $B\bar{B}^*$ molecule based on the mass of the $X(3872)$ is a few tens of MeV higher [27,68]. In Ref. [27], the mass was predicted to be (10580^{+9}_{-8}) MeV, corresponding to a binding energy of (24^{+8}_{-9}) MeV. These studies have provided a range for the binding energy, for which in the following we will choose a few illustrative values: $E_{X_b} = (1, 2, 5, 20)$ MeV.

Choosing two different form factors and two values for the cutoff parameter α, we have predicted the partial decay widths and the numerical results are collected in Table 1. From this table, we can see that the widths for the X_b radiative decays are about 1 keV. It is noteworthy to recall that the upper bound for the $\Gamma(X(3872))$ is 1.2 MeV [11]. If the X_b were similarly narrow, our results would indicate a sizeable branching fractions, at least 10^{-3}, for these radiative decay modes.

In Fig. 2, we present the partial widths for the $X_b \to \gamma\Upsilon(1S)$ (panel a), $\gamma\Upsilon(2S)$ (panel b), and $\gamma\Upsilon(3S)$ (panel c) in terms of the E_{X_b} with the dipole form factors $\alpha = 2.0$ (solid lines) and 3.0 (dashed lines), respectively. Results with the monopole form factors $\alpha = 2.0$ and $\alpha = 3.0$ are also shown in this figure as dotted and dash-dotted curves. The uncertainties caused by the form factors indicate our limited knowledge on the applicability of the

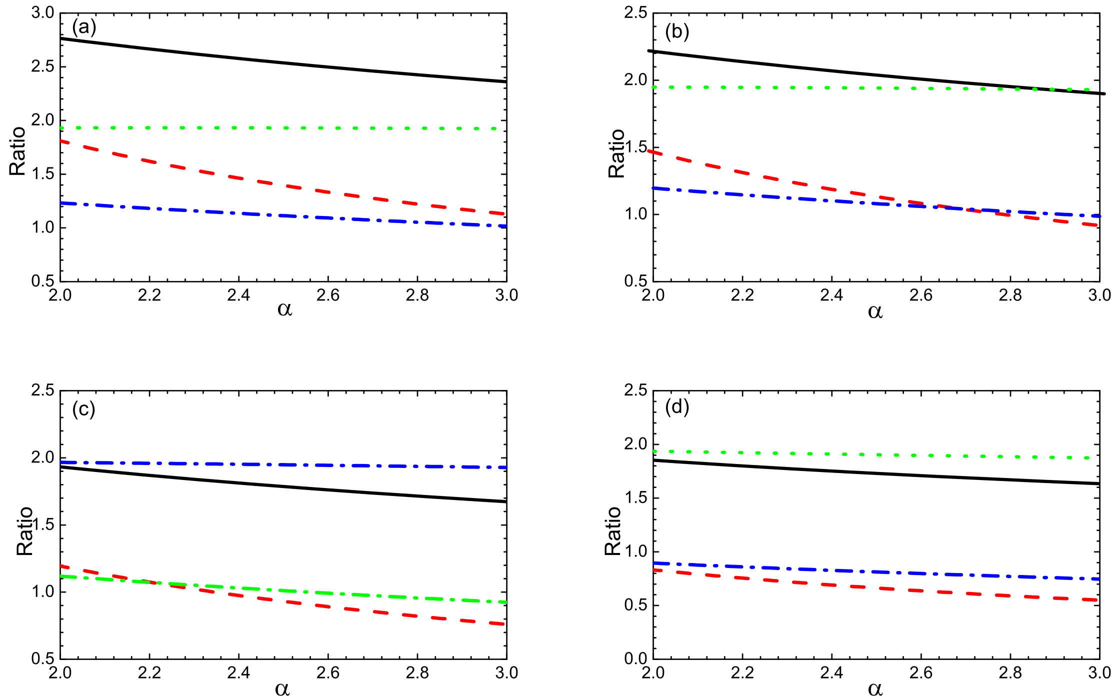

Fig. 3. (a) The α-dependence of the ratios of R_1 (solid line), and R_2 (dashed line) defined in Eq. (12) with dipole form factors and $E_{X_b} = 1$ MeV. The dotted and dash-dotted lines correspond to R_1 and R_2 defined in Eq. (12) with monopole form factors. (b), (c), and (d) corresponds to $E_{X_b} = 2$ MeV, 5 MeV, and 20 MeV, respectively.

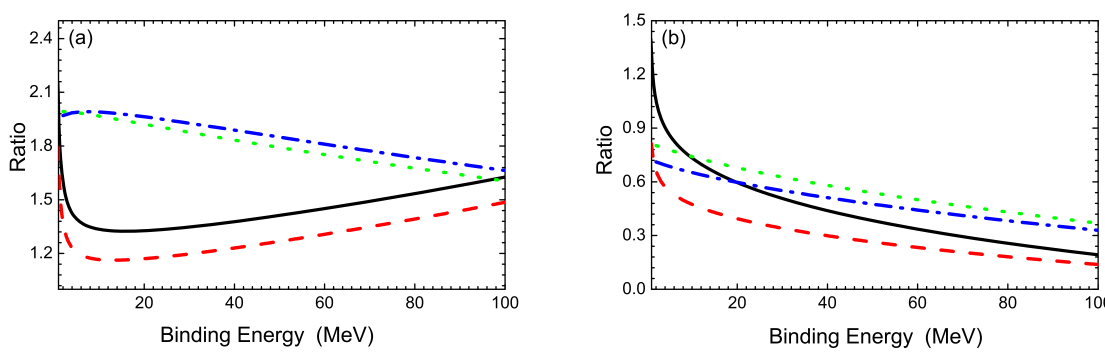

Fig. 4. (a) The ratio R_1 defined in Eq. (12) in terms of the E_{X_b} with dipole form factors $\alpha = 2.0$ (solid line) and $\alpha = 3.0$ (dashed line), and monopole form factors with $\alpha = 2.0$ (dotted lines) and $\alpha = 3.0$ (dash-dotted lines), respectively. (b) The same notation with (a) except for R_2 defined in Eq. (12).

effective Lagrangian. However fortunately the dependence of the partial widths are not drastically sensitive, which indicates a reasonable cutoff of the ultraviolet contributions by the empirical form factors.

It would be interesting to further clarify the uncertainties arising from the introduction of the form factors by studying the ratios between different partial decay widths. We define the following ratios

$$R_1 = \frac{\Gamma(X_b \to \gamma\Upsilon(2S))}{\Gamma(X_b \to \gamma\Upsilon(1S))}, \qquad R_2 = \frac{\Gamma(X_b \to \gamma\Upsilon(3S))}{\Gamma(X_b \to \gamma\Upsilon(1S))}, \tag{12}$$

which are plotted in Fig. 3 for the dependence on the cutoff parameter and Fig. 4 for the dependence on binding energy. Since the first coupling vertices are the same for those decay channels when taking the ratio, so the ratio only reflects the open threshold effects through the intermediate bottomed meson loops. The ratios are less sensitive to the cutoff parameter, which is a consequence of the fact that the involved loops are the same. As can be seen from this figure, when the cutoff parameter α increases, the ratios decrease. These predictions can be tested by the experimental measurements in future.

4. Summary

Our understanding of hadron spectroscopy will be greatly improved by studies of exotic states that may defy the conventional models of $q\bar{q}$ meson spectroscopy, and accordingly great progress has been made in the past decades. One of the most important aspects in the study of exotics is the discrimination of a compact multiquark configuration and a loosely bound hadronic molecule. Such task requests a large amount of efforts on both experimental and theoretical sides in future.

In this work, we have investigated the radiative decays of the X_b, the counterpart of the famous $X(3872)$ in the bottomonium-sector as a candidate for meson–meson molecule, into the $\gamma\Upsilon(nS)$. Since this state may be far below the $B\bar{B}^*$ threshold, the isospin violating decay mode $X_b \to \Upsilon\pi^+\pi^-$ would be highly suppressed, and stimulate the importance of the radiative decays. We have made used of the effective Lagrangian based on the heavy quark symmetry, and explore the rescattering mechanism. Our results have shown that the partial widths for the $X_b \to \gamma\Upsilon(nS)$ are about 1 keV, and thus the branching fractions may be sizeable, taking into account the fact the total width may also be smaller than a few MeV like $X(3872)$. This study of radiative decays and the previous work on production rates in hadron–hadron collisions have indicated a promising prospect to find the X_b at hadron collider in particular the LHC, and we suggest our experimental colleagues to perform an analysis. Such attempt will likely lead to the discovery of the X_b and thus enrich the exotics garden in the heavy quarkonium sector.

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References

[1] N. Brambilla, S. Eidelman, B.K. Heltsley, R. Vogt, G.T. Bodwin, E. Eichten, A.D. Frawley, A.B. Meyer, et al., Eur. Phys. J. C 71 (2011) 1534, arXiv:1010.5827 [hep-ph].
[2] S. Godfrey, S.L. Olsen, Annu. Rev. Nucl. Part. Sci. 58 (2008) 51, arXiv:0801.3867 [hep-ph].
[3] N. Drenska, R. Faccini, F. Piccinini, A. Polosa, F. Renga, C. Sabelli, Riv. Nuovo Cimento 033 (2010) 633, arXiv:1006.2741 [hep-ph].
[4] G.T. Bodwin, E. Braaten, E. Eichten, S.L. Olsen, T.K. Pedlar, J. Russ, arXiv:1307.7425.
[5] S.K. Choi, et al., Belle Collaboration, Phys. Rev. Lett. 91 (2003) 262001, arXiv:hep-ex/0309032.
[6] B. Aubert, et al., BaBar Collaboration, Phys. Rev. D 71 (2005) 071103, arXiv:hep-ex/0406022.
[7] V.M. Abazov, et al., D0 Collaboration, Phys. Rev. Lett. 93 (2004) 162002, arXiv:hep-ex/0405004.
[8] T. Aaltonen, et al., CDF Collaboration, Phys. Rev. Lett. 103 (2009) 152001, arXiv:0906.5218 [hep-ex].
[9] S. Chatrchyan, et al., CMS Collaboration, J. High Energy Phys. 1304 (2013) 154, arXiv:1302.3968 [hep-ex].
[10] R. Aaij, et al., LHCb Collaboration, Phys. Rev. Lett. 110 (22) (2013) 222001, arXiv:1302.6269 [hep-ex].
[11] J. Beringer, et al., Particle Data Group Collaboration, Phys. Rev. D 86 (2012) 010001.
[12] J.P. Lees, et al., The BABAR Collaboration, Phys. Rev. D 88 (2013) 071104, arXiv:1308.1151 [hep-ex].
[13] N.A. Tornqvist, Phys. Lett. B 590 (2004) 209, arXiv:hep-ph/0402237.
[14] C. Hanhart, Y.S. Kalashnikova, A.E. Kudryavtsev, A.V. Nefediev, Phys. Rev. D 76 (2007) 034007, arXiv:0704.0605 [hep-ph].
[15] W.-S. Hou, Phys. Rev. D 74 (2006) 017504, arXiv:hep-ph/0606016.
[16] T. Aushev, W. Bartel, A. Bondar, J. Brodzicka, T.E. Browder, P. Chang, Y. Chao, K.F. Chen, et al., arXiv:1002.5012 [hep-ex].
[17] F.-K. Guo, U.-G. Meißner, W. Wang, arXiv:1402.6236 [hep-ph].
[18] C. Bignamini, B. Grinstein, F. Piccinini, A.D. Polosa, C. Sabelli, Phys. Rev. Lett. 103 (2009) 162001, arXiv:0906.0882 [hep-ph].
[19] A. Esposito, F. Piccinini, A. Pilloni, A.D. Polosa, J. Mod. Phys. 4 (2013) 1569, arXiv:1305.0527 [hep-ph].
[20] P. Artoisenet, E. Braaten, Phys. Rev. D 81 (2010) 114018, arXiv:0911.2016 [hep-ph].
[21] P. Artoisenet, E. Braaten, Phys. Rev. D 83 (2011) 014019, arXiv:1007.2868 [hep-ph].
[22] A. Ali, W. Wang, Phys. Rev. Lett. 106 (2011) 192001, arXiv:1103.4587 [hep-ph].
[23] A. Ali, C. Hambrock, W. Wang, Phys. Rev. D 88 (2013) 054026, arXiv:1306.4470 [hep-ph].
[24] F.-K. Guo, U.-G. Meißner, W. Wang, Commun. Theor. Phys. 61 (2014) 354, arXiv:1308.0193 [hep-ph].
[25] S. Chatrchyan, et al., CMS Collaboration, Phys. Lett. B 727 (2013) 57, arXiv:1309.0250 [hep-ex].
[26] M. Karliner, arXiv:1401.4058 [hep-ph].
[27] F.-K. Guo, C. Hidalgo-Duque, J. Nieves, M.P. Valderrama, Phys. Rev. D 88 (2013) 054007, arXiv:1303.6608 [hep-ph].
[28] H.J. Lipkin, Nucl. Phys. B 291 (1987) 720.
[29] H.J. Lipkin, S.F. Tuan, Phys. Lett. B 206 (1988) 349.
[30] P. Moxhay, Phys. Rev. D 39 (1989) 3497.
[31] Q. Wang, C. Hanhart, Q. Zhao, Phys. Rev. Lett. 111 (2013) 132003, arXiv:1303.6355 [hep-ph].
[32] X.-H. Liu, G. Li, Phys. Rev. D 88 (2013) 014013, arXiv:1306.1384 [hep-ph].
[33] F.-K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao, Phys. Lett. B 725 (2013) 127, arXiv:1306.3096 [hep-ph].
[34] Q. Wang, C. Hanhart, Q. Zhao, Phys. Lett. B 725 (1–3) (2013) 106, arXiv:1305.1997 [hep-ph].
[35] M. Cleven, Q. Wang, F.-K. Guo, C. Hanhart, U.-G. Meißner, Q. Zhao, Phys. Rev. D 87 (7) (2013) 074006, arXiv:1301.6461 [hep-ph].
[36] D.-Y. Chen, X. Liu, Phys. Rev. D 84 (2011) 094003, arXiv:1106.3798 [hep-ph].
[37] G. Li, F.-l. Shao, C.-W. Zhao, Q. Zhao, Phys. Rev. D 87 (3) (2013) 034020, arXiv:1212.3784 [hep-ph].
[38] G. Li, X.-H. Liu, Phys. Rev. D 88 (2013) 094008, arXiv:1307.2622 [hep-ph].
[39] M.B. Voloshin, Phys. Rev. D 87 (7) (2013) 074011, arXiv:1301.5068 [hep-ph].
[40] M.B. Voloshin, Phys. Rev. D 84 (2011) 031502, arXiv:1105.5829 [hep-ph].
[41] A.E. Bondar, A. Garmash, A.I. Milstein, R. Mizuk, M.B. Voloshin, Phys. Rev. D 84 (2011) 054010, arXiv:1105.4473 [hep-ph].
[42] F.-K. Guo, C. Hanhart, U.-G. Meißner, Phys. Rev. Lett. 103 (2009) 082003; F.-K. Guo, C. Hanhart, U.-G. Meißner, Phys. Rev. Lett. 104 (2010) 109901 (Erratum), arXiv:0907.0521 [hep-ph].
[43] F.-K. Guo, C. Hanhart, G. Li, U.-G. Meissner, Q. Zhao, Phys. Rev. D 82 (2010) 034025, arXiv:1002.2712 [hep-ph].
[44] F.-K. Guo, C. Hanhart, G. Li, U.-G. Meißner, Q. Zhao, Phys. Rev. D 83 (2011) 034013, arXiv:1008.3632 [hep-ph].
[45] D.-Y. Chen, X. Liu, T. Matsuki, Phys. Rev. D 84 (2011) 074032, arXiv:1108.4458 [hep-ph].
[46] D.-Y. Chen, X. Liu, T. Matsuki, arXiv:1208.2411 [hep-ph].
[47] D.-Y. Chen, X. Liu, T. Matsuki, Phys. Rev. D 88 (2013) 036008, arXiv:1304.5845 [hep-ph].
[48] D.-Y. Chen, X. Liu, T. Matsuki, Phys. Rev. D 88 (2013) 014034, arXiv:1306.2080 [hep-ph].
[49] D.-S. Du, X.-Q. Li, Z.-T. Wei, B.-S. Zou, Eur. Phys. J. A 4 (1999) 91, arXiv:hep-ph/9805260.
[50] C.-H. Chen, H.-n. Li, Phys. Rev. D 63 (2001) 014003, arXiv:hep-ph/0006351.
[51] X. Liu, X.-Q. Li, Phys. Rev. D 77 (2008) 096010, arXiv:0707.0919 [hep-ph].
[52] P. Colangelo, F. De Fazio, T.N. Pham, Phys. Lett. B 542 (2002) 71, arXiv:hep-ph/0207061.
[53] H.-Y. Cheng, C.-K. Chua, A. Soni, Phys. Rev. D 71 (2005) 014030, arXiv:hep-ph/0409317.
[54] C.-D. Lu, Y.-L. Shen, W. Wang, Phys. Rev. D 73 (2006) 034005, arXiv:hep-ph/0511255.
[55] X. Liu, Z.-T. Wei, X.-Q. Li, Eur. Phys. J. C 59 (2009) 683, arXiv:0805.2804 [hep-ph].
[56] P. Colangelo, F. De Fazio, T.N. Pham, Phys. Rev. D 69 (2004) 054023, arXiv:hep-ph/0310084.
[57] R. Casalbuoni, A. Deandrea, N. Di Bartolomeo, R. Gatto, F. Feruglio, G. Nardulli, Phys. Rep. 281 (1997) 145, arXiv:hep-ph/9605342.
[58] S. Weinberg, Phys. Rev. 137 (1965) B672.
[59] V. Baru, J. Haidenbauer, C. Hanhart, Y. Kalashnikova, A.E. Kudryavtsev, Phys. Lett. B 586 (2004) 53, arXiv:hep-ph/0308129.
[60] J. Hu, T. Mehen, Phys. Rev. D 73 (2006) 054003, arXiv:hep-ph/0511321.
[61] J.F. Amundson, C.G. Boyd, E.E. Jenkins, M.E. Luke, A.V. Manohar, J.L. Rosner, M.J. Savage, M.B. Wise, Phys. Lett. B 296 (1992) 415, arXiv:hep-ph/9209241.
[62] X.-Q. Li, D.V. Bugg, B.-S. Zou, Phys. Rev. D 55 (1997) 1421.
[63] M.P. Locher, Y. Lu, B.S. Zou, Z. Phys. A 347 (1994) 281, arXiv:nucl-th/9311021.
[64] X.-Q. Li, B.-S. Zou, Phys. Lett. B 399 (1997) 297, arXiv:hep-ph/9611223.
[65] C.-W. Zhao, G. Li, X.-H. Liu, F.-L. Shao, Eur. Phys. J. C 73 (2013) 2482.
[66] A. Ali, C. Hambrock, I. Ahmed, M.J. Aslam, Phys. Lett. B 684 (2010) 28, arXiv:0911.2787 [hep-ph].
[67] N.A. Tornqvist, Z. Phys. C 61 (1994) 525, arXiv:hep-ph/9310247.
[68] M. Karliner, S. Nussinov, J. High Energy Phys. 1307 (2013) 153, arXiv:1304.0345 [hep-ph].