Hunting for the Xb via hidden bottomonium decays

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Ref: G. Li， W. Wang, PLB733, 100 (2014); G. Li, Z. Zhou, PRD91, 034020 (2015)

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Outline

- Background
- Model and Numerical results
- Summary

A summary of observed XYZ states

X. Liu, Chin. Sci. Bull. (2014) 59(29–30):3815–3830

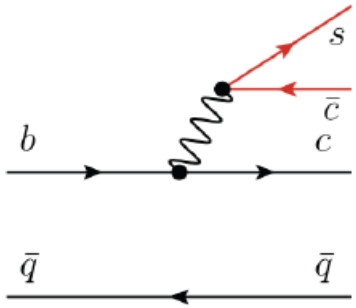
A [1–5]	B [6–10]	C [11, 12]	D [13–15]	E [16–20]
$X(3872)$	$Y(4260)$	$X(3940)$	$X(3915)$	$Z_b(10610)$
$Y(3940)$	$Y(4008)$	$X(4160)$	$X(4350)$	$Z_b(10650)$
$Z^+(4430)$	$Y(4360)$	–	$Z(3930)$	$Z_c(3900)$
$Z^+(4051)$	$Y(4660)$	–	–	$Z_c(4025)$
$Z^+(4248)$	$Y(4630)$	–	–	$Z_c(4020)$
$Y(4140)$	–	–	–	$Z_c(3885)$
$Y(4274)$				

X(3872): Belle, PRL91, 262001 (2003). Cited by 1228.

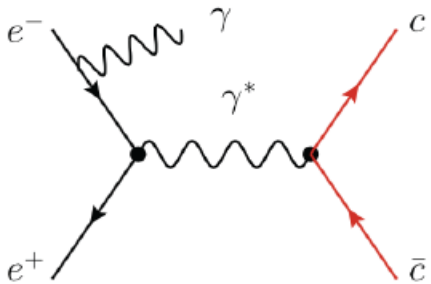
A summary of observed XYZ states

$X(3872)$
$Y(3940)$
$Z^+(4430)$
$Z^+(4051)$
$Z^+(4248)$
$Y(4140)$
$Y(4274)$

A: *B* meson decay



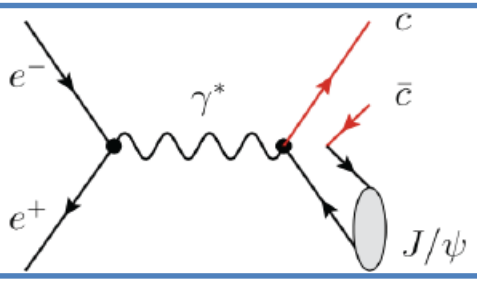
B: e^+e^- annihilation



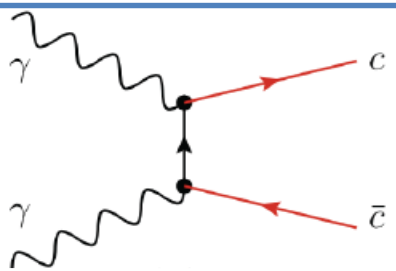
$Y(4260)$
$Y(4008)$
$Y(4360)$
$Y(4660)$
$Y(4630)$

C: The double charm production

$X(3940)$
$X(4160)$



D: $\gamma\gamma$ fusion process



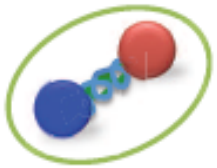
$X(3915)$
$X(4350)$
$Z(3930)$

E: Hidden-charm/bottom dipion and open-charm/bottom decays of higher charmonia/bottomonia and charmoniumlike/bottomoniumlike states

$Z_b(10610)$
$Z_b(10650)$
$Z_c(3900)$
$Z_c(4025)$
$Z_c(4020)$
$Z_c(3885)$

X. Liu, Chin. Sci. Bull. (2014) 59(29–30):3815–3830

Explanations of the XYZ states



Hybrid

⇒ Compact object with excited gluons and $Q\bar{Q}$

S.L. Zhu, PLB625(2005)212, E. Kou et al., PLB631(2005)164, F.E. Close et al., PLB628(2005)215, ...

Tetraquark

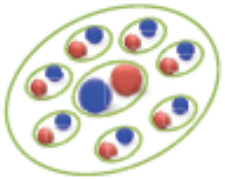
⇒ Compact object formed from Qq and $\bar{Q}\bar{q}$

L. Maiani et al., PRD89(2014)114010, L. Maiani et al., PRD87(2013)111102,...

⇒ Compact object with color spin interaction

H.Hogaasen et. al., PRD73(2006)054013, F.Buccella et. al., EPJC49(2007)743, ...

Hadro-Quarkonium



⇒ Compact $Q\bar{Q}$ embedded in light quarks

M.B. Voloshin, Prog.Part.Nucl.Phys.61(2008)455, S. Dubynskiy et al., PLB666(2008)344,...

Hadronic molecule

⇒ Extended object made of $Q\bar{q}$ and $\bar{Q}q$

N. A. Tö rnqvist, PLB590(2004)209, C.E. Thomas, PRD78(2008)034007, ...

Some meson molecule candidates

States	Constituent	J^{PC}	Mass (GeV)
X(3872)	DD*	1^{++}	3.87169
Xb	BB*	1^{++}	?
Zc(3900)	DD*	1^{+-}	3.8887
Zc(4020)	D*D*	1^{+-}	4.0239
Zb(10610)	BB*	1^{+-}	10.6072
Zb(10650)	B*B*	1^{+-}	10.6522

Conterpart of X(3872)—Xb states

Conterpart of X(3872): $J^{PC} = 1^{++}; I = 0;$ BB* molecule?

Very Heavy: difficult to directly produce at e^+e^-

PHYSICAL REVIEW D **74**, 017504 (2006)

Searching for the bottom counterparts of $X(3872)$ and $Y(4260)$ via $\pi^+\pi^-\Upsilon$

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The $X(3872)$ and $Y(4260)$, among a host of charmoniumlike mesons, have rather unusual properties: the former has very small total width, the latter has large rate into $\pi^+\pi^- J/\psi$ channel. It would not be easy to settle between the many suggested explanations for their composition. We point out that discovering the bottom counterparts should shed much light on the issue. The narrow state can be searched for at the Tevatron via $p\bar{p} \to \pi^+\pi^-\Upsilon + X$, but the LHC should be much more promising. The state with large overlap with Υ can be searched for at B factories via radiative return $e^+e^- \to \gamma_{\rm ISR} + \pi^+\pi^-\Upsilon$ on $\Upsilon(5S)$, or by $e^+e^- \to \pi^+\pi^-\Upsilon$ direct scan.

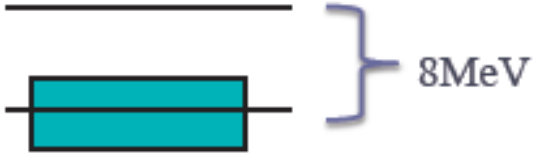
Conterpart of X(3872)--Xb states

- X(3872):$M(D^+)+M(D^{*-})$=3879.87±0.17MeV

  $M(D^0)+M(D^{*0})$=3871.8±0.17 MeV

  M(X(3872))=3871.69±0.17 MeV

→ X(3872)→J/ψρ is large, isospin breaking



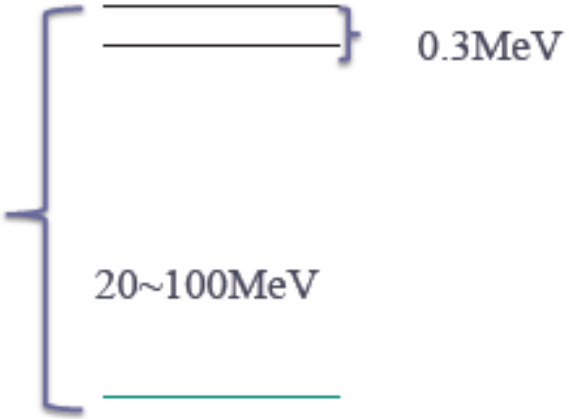
- X_b: $M(B^0)+M(B^{*0})$=10604.8±0.57MeV

  $M(B^+)+M(B^{*-})$=10604.5±0.57MeV

  $M(X_b)$=10504 MeV *0911.2787*

  10580 MeV *1303.6608*

→ X_b->Yρ may be suppressed by isospin.



$X_b \to \Upsilon(nS)\gamma, \chi_{bJ}\pi\pi, \Upsilon\omega$ should be of high priority.

G.Li, W.Wang, PLB733,100; G.Li, Z.Zhou, PRD91,034020.

Heavy-meson loops effects in the production and decays of ordinary states and exotic state candidates

- Q. Wang, C. Hanhart and Q. Zhao, Phys. Rev. Lett. 111, 132003 (2013); F. -K. Guo, C. Hanhart, U. -G. Meißner, Q. Wang and Q. Zhao, Phys. Lett. B 725, 127 (2013); Q. Wang, C. Hanhart and Q. Zhao, Phys. Lett. B 725, no. 1-3, 106 (2013); M. Cleven, Q. Wang, F. -K. Guo, C. Hanhart, U. -G. Meißner and Q. Zhao, Phys. Rev. D 87, no. 7, 074006 (2013).

- D. -Y. Chen, X. Liu and T. Matsuki, Phys. Rev. D 84, 074032 (2011); D. -Y. Chen, X. Liu and T. Matsuki, arXiv:1208.2411 [hep-ph]; D. -Y. Chen, X. Liu and T. Matsuki, Phys. Rev. D 88, 036008 (2013); D. -Y. Chen, X. Liu and T. Matsuki, Phys. Rev. D 88, 014034 (2013); D. -Y. Chen and X. Liu, Phys. Rev. D 84, 094003 (2011).

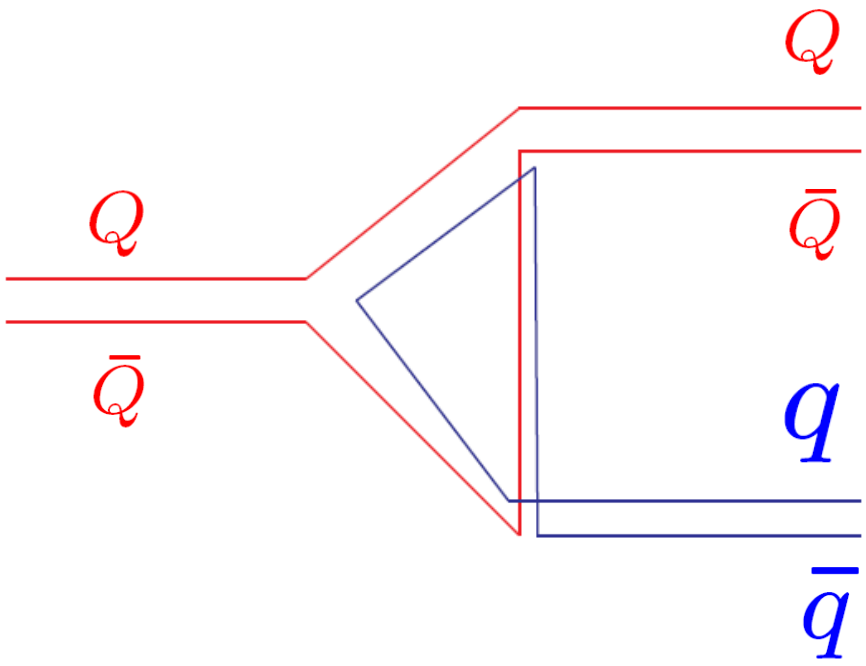
- M. B. Voloshin, Phys. Rev. D 87, no. 7, 074011 (2013);M. B. Voloshin, Phys. Rev. D 84, 031502 (2011).

- A. E. Bondar, A. Garmash, A. I. Milstein, R. Mizuk and M. B. Voloshin, Phys. Rev. D 84, 054010 (2011).

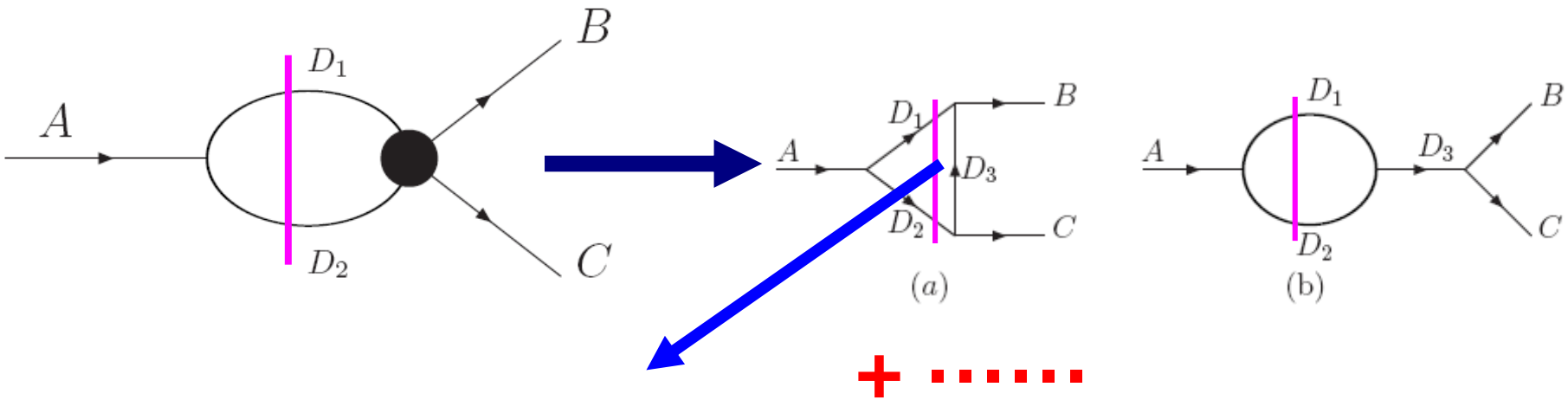
- G. Li, F. -l. Shao, C. -W. Zhao and Q. Zhao, Phys. Rev. D 87, no. 3, 034020 (2013); X. -H. Liu and G. Li, Phys. Rev. D 88, 014013 (2013); G. Li and X. -H. Liu, Phys. Rev. D 88, 094008 (2013).

  …….

Quark-level descriptions of hadronic loop mechanism



Decomposition of intermediate meson loop transitions



$$\mathcal{F}(t, m_{D_3}) = \left(\frac{\Lambda^2 - m_{D_3}^2}{\Lambda^2 - p^2}\right)^n$$

$X_b \to \Upsilon(nS)\gamma$

G.Li, W. Wang, Phys. Lett. B733, 100.

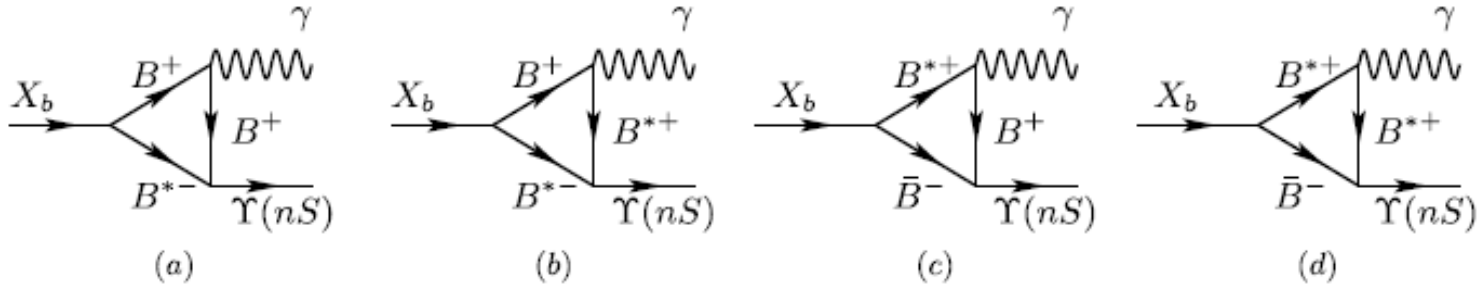


Fig. 1. Feynman diagrams for the radiative decays $X_b \to \gamma\Upsilon(nS)$ with the $B\bar{B}^*$ as the intermediate states.

Introduce form factors to kill the divergence and also compensate the off-shell effects of intermediate mesons

Monopole: $\mathcal{F}(m_2, q_2^2) \equiv \dfrac{\Lambda^2 - m_2^2}{\Lambda^2 - q_2^2}$

Dipole: $\mathcal{F}(m_2, q_2^2) \equiv \left(\dfrac{\Lambda^2 - m_2^2}{\Lambda^2 - q_2^2}\right)^2$

$$M_{fi} = \int \frac{d^4 q_2}{(2\pi)^4} \sum_{B^* \text{ pol.}} \frac{V_1 V_2 V_3}{a_1 a_2 a_3} \mathcal{F}(m_2, q_2^2)$$

$$\Lambda \equiv m_2 + \alpha \Lambda_{\rm QCD}$$

$$\Lambda_{\rm QCD} = 220 \text{ MeV}$$

Adopt the effective Lagrangian approach to do the calculation

$$\mathcal{L} = \frac{1}{2} X^{\dagger}_{b\mu}[x_1(B^{*0\mu}\bar{B}^0 - B^0\bar{B}^{*0\mu}) + x_2(B^{*+\mu}B^- - B^+B^{*-\mu})] + h.c.,$$

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

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

P. Colangelo, F. De Fazio, T.N. Pham, Phys. Rev. D 69 (2004) 054023, arXiv:hep-ph/0310084.

R. Casalbuoni, A. Deandrea, N. Di Bartolomeo, R. Gatto, F. Feruglio, G. Nardulli, Phys. Rep. 281 (1997) 145, arXiv:hep-ph/9605342.

J. Hu, T. Mehen, Phys. Rev. D 73 (2006) 054003, arXiv:hep-ph/0511321.

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.

Coupling constants determination

$$g_{\Upsilon BB} = 2g_2\sqrt{m_\Upsilon}m_B\ , \quad g_{\Upsilon B^*B} = \frac{g_{\Upsilon BB}}{\sqrt{m_B m_{B^*}}}\ , \quad g_{\Upsilon B^*B^*} = g_{\Upsilon B^*B}\sqrt{\frac{m_{B^*}}{m_B}}m_{B^*}\ ,$$

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

$$g_n = \sqrt{m_{\Upsilon(nS)}}/(2m_B f_{\Upsilon(nS)}) \qquad Q = \mathrm{diag}\{2/3, -1/3, -1/3\} \qquad \beta \simeq 3.0\ \mathrm{GeV}^{-1}$$

P. Colangelo, F. De Fazio, T.N. Pham, Phys. Rev. D 69 (2004) 054023, arXiv:hep-ph/0310084.

R. Casalbuoni, A. Deandrea, N. Di Bartolomeo, R. Gatto, F. Feruglio, G. Nardulli, Phys. Rep. 281 (1997) 145, arXiv:hep-ph/9605342.

J. Hu, T. Mehen, Phys. Rev. D 73 (2006) 054003, arXiv:hep-ph/0511321.

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.

F.-K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao, Phys. Lett. B 725 (2013) 127, arXiv:1306.3096 [hep-ph].

S. Weinberg, Phys. Rev. 137 (1965) B672.

V. Baru, J. Haidenbauer, C. Hanhart, Y. Kalashnikova, A.E. Kudryavtsev, Phys. Lett. B 586 (2004) 53, arXiv:hep-ph/0308129.

Numerical results

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

The predicted widths are about 1 keV.

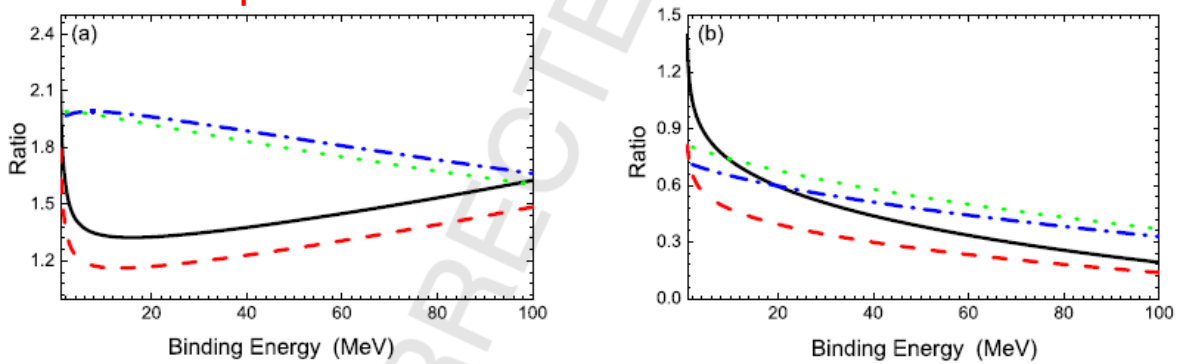


Fig. 4. (a) The ratio R_1 defined in Eq. (12) in terms of the E_{X_b} with dipole form factors $\alpha = 2.0$ (solid line) and $\alpha = 3.0$ (dashed line), and monopole form factors with $\alpha = 2.0$ (dotted lines) and $\alpha = 3.0$ (dash-dotted lines), respectively. (b) The same notation with (a)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

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

The ratio R are not sensitive to the long-range structure of the Xb.

$X_b \to \Upsilon(1S)\omega$

G. Li, Z. Zhou, Phys. Rev. D91, 034020.

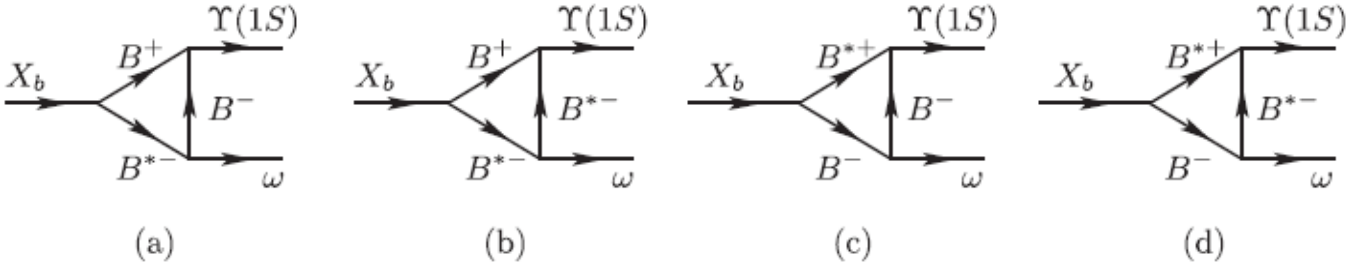


FIG. 1. Feynman diagrams for $X_b \to \Upsilon(1S)\omega$ with the $B\bar{B}^*$ as the intermediate states.

$$\mathcal{L} = \frac{1}{2} X^\dagger_{b\mu}\left[x_1\left(B^{*0\mu}\bar{B}^0 - B^0\bar{B}^{*0\mu}\right) + x_2\left(B^{*+\mu}B^- - B^+B^{*-\mu}\right)\right] + H.c.$$

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

$$\begin{aligned}\mathcal{L} = {} & -ig_{\mathcal{B}\mathcal{B}\mathcal{V}}\mathcal{B}^\dagger_i\overleftrightarrow{\partial}_\mu\mathcal{B}^j(\mathcal{V}^\mu)^i_j - 2f_{\mathcal{B}^*\mathcal{B}\mathcal{V}}\epsilon_{\mu\nu\alpha\beta}(\partial^\mu\mathcal{V}^\nu)^i_j\left(\mathcal{B}^\dagger_i\overleftrightarrow{\partial}^\alpha\mathcal{B}^{*j\beta} - \mathcal{B}^{*\beta\dagger}_i\overleftrightarrow{\partial}^\alpha\mathcal{B}^j\right) + ig_{\mathcal{B}^*\mathcal{B}^*\mathcal{V}}\mathcal{B}^{*\nu\dagger}_i\overleftrightarrow{\partial}_\mu\mathcal{B}^{*j}_\nu(\mathcal{V}^\mu)^i_j \\ & +4if_{\mathcal{B}^*\mathcal{B}^*\mathcal{V}}\mathcal{B}^{*\dagger}_{i\mu}(\partial^\mu\mathcal{V}^\nu - \partial^\nu\mathcal{V}^\mu)^i_j\mathcal{B}^{*j}_\nu,\end{aligned}$$

Coupling constants determinations

$$g_{\Upsilon(1S)BB} = 2g_1\sqrt{m_{\Upsilon(1S)}}m_B\ , \quad g_{\Upsilon(1S)B^*B} = \frac{g_{\Upsilon(1S)BB}}{\sqrt{m_B m_{B^*}}}\ , \quad g_{\Upsilon(1S)B^*B^*} = g_{\Upsilon(1S)B^*B}\sqrt{\frac{m_{B^*}}{m_B}}m_{B^*}$$

$$x_i^2 \equiv 16\pi(m_B + m_{B^*})^2 c_i^2\sqrt{\frac{2E_{X_b}}{\mu}} \qquad g_{\mathcal{B}\mathcal{B}\mathcal{V}} = g_{\mathcal{B}^*\mathcal{B}^*\mathcal{V}} = \frac{\beta g_V}{\sqrt{2}}, \quad f_{\mathcal{B}^*\mathcal{B}\mathcal{V}} = \frac{f_{\mathcal{B}^*\mathcal{B}^*\mathcal{V}}}{m_{\mathcal{B}^*}} = \frac{\lambda g_V}{\sqrt{2}}$$

$$g_1 = \sqrt{m_{\Upsilon(1S)}}/(2m_B f_{\Upsilon(1S)}) \qquad f_{\Upsilon(1S)} = 715.2\ \mathrm{MeV}$$

$$\beta = 0.9,\ \lambda = 0.56\ \mathrm{GeV}^{-1} \qquad g_V = m_\rho/f_\pi$$

S. Weinberg, Phys. Rev. 137, B672 (1965).

V. Baru, J. Haidenbauer, C. Hanhart, Y. Kalashnikova, and A. E. Kudryavtsev, Phys. Lett. B 586, 53 (2004).

P. Colangelo, F. De Fazio, and T. N. Pham, Phys. Rev. D 69,054023 (2004).

R. Casalbuoni, A. Deandrea, N. Di Bartolomeo, R. Gatto, F. Feruglio, and G. Nardulli, Phys. Rept. 281, 145 (1997).

C. Isola, M. Ladisa, G. Nardulli, and P. Santorelli, Phys.Rev. D 68, 114001 (2003).

D. Becirevic, B. Blossier, E. Chang, and B. Haas, Phys. Lett.B 679, 231 (2009).

Numerical results for $X_b \to \Upsilon(1S)\omega$

TABLE I. Predicted partial widths (in units of keV) of the X_b decays. The parameter in the form factor is chosen as $\alpha = 2.0$, 2.5, and 3.0, respectively. The units of the binding energy parameters E_{X_b} in column 1 are all MeV.

Dipole form factor	$\alpha = 2.0$	$\alpha = 2.5$	$\alpha = 3.0$
$E_{X_b} = 1$ MeV	4.03	8.55	15.53
$E_{X_b} = 5$ MeV	8.38	17.84	32.51
$E_{X_b} = 10$ MeV	11.17	23.84	43.56
$E_{X_b} = 25$ MeV	15.12	33.30	61.10
$E_{X_b} = 50$ MeV	18.63	40.14	73.96
$E_{X_b} = 100$ MeV	20.02	43.34	80.22

The widths are about tens of keVs, which indicate a sizeable branching ratios.

No significant signal for $X_b \to \Upsilon(1S)\omega$ has been seen by the Belle Collaboration.

X. H. He et al. [Belle Collaboration], Phys. Rev. Lett. 113,142001 (2014)

Detecting the structure of Xb

Based on the Xb being an S-wave BB* molecule ansatz

The processes $X_b \to \Upsilon(nS)\gamma, \Upsilon(1S)\omega$ are not sensitive to the BB* wave function at the long distance, but rather they are determined by the short distance part of the Xb.

The process $X_b \to B\bar{B}\gamma$ can be used to probe the long structure of Xb.

Summary

The widths of $X_b \to \Upsilon(nS)\gamma, \Upsilon(1S)\omega$ are about 1 keV and tens of keVs, respectively, which corresponds to sizeable branching ratios.

Heavy meson loops effects play an important role in the decays of exotic states, especially when the initial state mass are close to the intermediate meson pair thresholds.

The discrimination of a compact multiquark configuration and a loosely bound hadronic molecule is an important aspects in the study of exotics.

Thanks for your attention !