New Hidden beauty molecules predicted by the local hidden gauge approach and heavy quark spin symmetry

Chu-Wen Xiao

IFIC, University of Valencia, Spain

xiaochw@ific.uv.es

Collaborators

A. Ozpineci and E. Oset

Oct. 27-30,Chiral2013, Beijing

Overview

1. Introduction

Recently, the discovery of the hidden beauty $Z_b(10610)$ and $Z_b(10650)$ states [1], takes more attention to the beauty sector [2,3].

[1] A. Bondar et al. [Belle Collaboration], Phys. Rev. Lett. 108, 122001 (2012).
[2] Z. -F. Sun, J. He, X. Liu, Z. -G. Luo and S. -L. Zhu, Phys. Rev. D 84, 054002 (2011).
[3] M. Cleven, Q. Wang, F. -K. Guo, C. Hanhart, U. -G. Meissner and Q. Zhao, Phys. Rev. D 87, 074006 (2013).

In this work, we investigate the hidden beauty system of meson-meson interaction. There are some works on this subject:

[4] Y. -J. Zhang, H. -C. Chiang, P. -N. Shen and B. -S. Zou, Phys. Rev. D 74, 014013 (2006).
[5] S. Ohkoda, Y. Yamaguchi, S. Yasui, K. Sudoh and A. Hosaka, Phys. Rev. D 86, 034019 (2012).
[6] M. T. Li, W. L. Wang, Y. B. Dong and Z. Y. Zhang, J. Phys. G 40, 015003 (2013).

We take into account the heavy quark spin symmetry (HQSS) for the hidden beauty sector, which is revealed in these works:

[7] N. Isgur and M. B. Wise, Phys. Lett. B 232, 113 (1989).
[8] M. Neubert, Phys. Rept. 245, 259 (1994).
[9] F. -K. Guo, C. Hanhart and U. -G. Meissner, Phys. Rev. Lett. 102, 242004 (2009).
[10] C. Garcia-Recio, V. K. Magas, T. Mizutani, J. Nieves, A. Ramos, L. L. Salcedo and L. Tolos, Phys. Rev. D 79, 054004 (2009).

Under the lower order HQSS constrain, we also use the local hidden gauge approach to determine the interaction potentials, which is studied in:

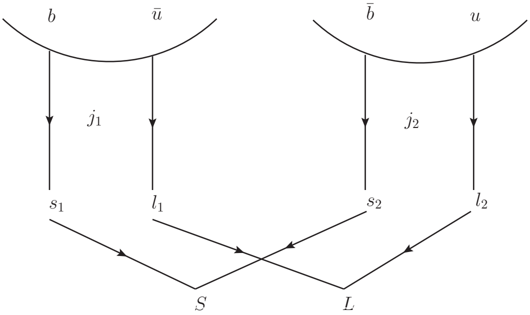
[11] M. F. M. Lutz and E. E. Kolomeitsev, Nucl. Phys. A 730, 110 (2004).
[12] J. Hofmann and M. F. M. Lutz, Nucl. Phys. A 763, 90 (2005).

2. HQSS Formalism

In our work, we use the coupled channel approach to study the meson-meson interaction in hidden beauty sector, which are these coupled channels:

- $J = 0,\ I = 0$
  $B\bar{B},\ B_s\bar{B}_s,\ B^*\bar{B}^*,\ B_s^*\bar{B}_s^*.$
- $J = 0,\ I = 1$
  $B\bar{B},\ B^*\bar{B}^*.$
- $J = 1,\ I = 0$
  $B\bar{B}^*\ (B^*\bar{B}),\ B_s\bar{B}_s^*\ (B_s^*\bar{B}_s),\ B^*\bar{B}^*,\ B_s^*\bar{B}_s^*.$
- $J = 1,\ I = 1$
  $B\bar{B}^*\ (B^*\bar{B}),\ B^*\bar{B}^*.$
- $J = 2,\ I = 0$
  $B^*\bar{B}^*,\ B_s^*\bar{B}_s^*.$
- $J = 2,\ I = 1$
  $B^*\bar{B}^*.$

In our case, all the hidden beauty systems are made by a meson(M) − antimeson($\bar{M}$) state, which are shown in the figure:



Thus, we have the correspondence,

generic:	l_1	l_2	s_1	s_2	j_1	j_2	L	S	J
HQSS:	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$J_M(0,1)$	$J_{\bar{M}}(0,1)$	$\mathcal{L}(0,1)$	$S_{b\bar{b}}(0,1)$	$J(0,1,2)$.

with J: total spin of the hidden beauty meson system, $\mathcal{L}$: total spin of the light quarks system, $S_{b\bar{b}}$: total spin of the $b\bar{b}$ subsystem, J_M and $J_{\bar{M}}$ the total spin of the meson and antimeson respectively.

So, there are 12 orthogonal states in the HQSS basis, given by

- $|S_{b\bar{b}} = 0, \mathcal{L} = 0\,;\, J = 0\rangle$, $|S_{b\bar{b}} = 0, \mathcal{L} = 0\,;\, J = 0\rangle_s$,
- $|S_{b\bar{b}} = 0, \mathcal{L} = 1\,;\, J = 1\rangle$, $|S_{b\bar{b}} = 0, \mathcal{L} = 1\,;\, J = 1\rangle_s$,
- $|S_{b\bar{b}} = 1, \mathcal{L} = 0\,;\, J = 1\rangle$, $|S_{b\bar{b}} = 1, \mathcal{L} = 0\,;\, J = 1\rangle_s$,
- $|S_{b\bar{b}} = 1, \mathcal{L} = 1\,;\, J = 0\rangle$, $|S_{b\bar{b}} = 1, \mathcal{L} = 1\,;\, J = 0\rangle_s$,
- $|S_{b\bar{b}} = 1, \mathcal{L} = 1\,;\, J = 1\rangle$, $|S_{b\bar{b}} = 1, \mathcal{L} = 1\,;\, J = 1\rangle_s$,
- $|S_{b\bar{b}} = 1, \mathcal{L} = 1\,;\, J = 2\rangle$, $|S_{b\bar{b}} = 1, \mathcal{L} = 1\,;\, J = 2\rangle_s$.

The subindex s means that the light quarks are strange.

When these HQSS basis is used, we can simplify the interaction elements under the HQSS constrain by

$$\langle S'_{b\bar{b}}, \mathcal{L}'; J', \alpha' | H^{QCD} | S_{b\bar{b}}, \mathcal{L}; J, \alpha \rangle = \delta_{\alpha\alpha'} \delta_{JJ'} \delta_{S'_{b\bar{b}} S_{b\bar{b}}} \delta_{\mathcal{L}\mathcal{L}'} \langle \mathcal{L}; \alpha || H^{QCD} || \mathcal{L}; \alpha \rangle. \quad (1)$$

Therefore, we have 6 unknown low energy constants (LEC's):

- Three LEC's associated to $\mathcal{L} = 0$

$$\begin{aligned} \lambda_0^\alpha &= \langle \mathcal{L} = 0; \alpha || H^{QCD} || \mathcal{L} = 0; \alpha \rangle \\ \lambda_{0s}^\alpha &= {}_s\langle \mathcal{L} = 0; \alpha || H^{QCD} || \mathcal{L} = 0; \alpha \rangle_s \\ \lambda_{0m}^\alpha &= \langle \mathcal{L} = 0; \alpha || H^{QCD} || \mathcal{L} = 0; \alpha \rangle_s \end{aligned}$$

- Three LEC's associated to $\mathcal{L} = 1$

$$\begin{aligned} \lambda_1^\alpha &= \langle \mathcal{L} = 1; \alpha || H^{QCD} || \mathcal{L} = 1; \alpha \rangle \\ \lambda_{1s}^\alpha &= {}_s\langle \mathcal{L} = 1; \alpha || H^{QCD} || \mathcal{L} = 1; \alpha \rangle_s \\ \lambda_{1m}^\alpha &= \langle \mathcal{L} = 1; \alpha || H^{QCD} || \mathcal{L} = 1; \alpha \rangle_s \end{aligned}$$

To exploit Eq. (1), we should express the physical meson–meon states in terms of the HQSS basis, such as for $J = 0$, we have

$$
\begin{aligned}
|B\bar{B}\rangle &= \frac{1}{2}|S_{b\bar{b}} = 0,\, \mathcal{L} = 0\,;\, J = 0\,\rangle + \frac{\sqrt{3}}{2}|S_{b\bar{b}} = 1,\, \mathcal{L} = 1\,;\, J = 0\,\rangle \\
|B^*\bar{B}^*\rangle &= -\Big(\frac{\sqrt{3}}{2}|S_{b\bar{b}} = 0,\, \mathcal{L} = 0\,;\, J = 0\,\rangle - \frac{1}{2}|S_{b\bar{b}} = 1,\, \mathcal{L} = 1\,;\, J = 0\,\rangle\Big) \\
|B_s\bar{B}_s\rangle &= \frac{1}{2}|S_{b\bar{b}} = 0,\, \mathcal{L} = 0\,;\, J = 0\,\rangle_s + \frac{\sqrt{3}}{2}|S_{b\bar{b}} = 1,\, \mathcal{L} = 1\,;\, J = 0\,\rangle_s \\
|B_s^*\bar{B}_s^*\rangle &= -\Big(\frac{\sqrt{3}}{2}|S_{b\bar{b}} = 0,\, \mathcal{L} = 0\,;\, J = 0\,\rangle_s - \frac{1}{2}|S_{b\bar{b}} = 1,\, \mathcal{L} = 1\,;\, J = 0\,\rangle_s\Big)
\end{aligned}
$$

Using Eq. (1), we can get the interaction matrices of every sector, such as

- $J = 0$, $I = 0$

$$
\begin{array}{cccc}
B\bar{B} & B^*\bar{B}^* & B_s\bar{B}_s & B_s^*\bar{B}_s^*
\end{array}
$$

$$
\left(\begin{array}{cccc}
\frac{1}{4}\lambda_0 + \frac{3}{4}\lambda_1 & -\frac{\sqrt{3}}{4}\lambda_0 + \frac{\sqrt{3}}{4}\lambda_1 & \frac{1}{4}\lambda_{0m} + \frac{3}{4}\lambda_{1m} & -\frac{\sqrt{3}}{4}\lambda_{0m} + \frac{\sqrt{3}}{4}\lambda_{1m} \\
-\frac{\sqrt{3}}{4}\lambda_0 + \frac{\sqrt{3}}{4}\lambda_1 & \frac{3}{4}\lambda_0 + \frac{1}{4}\lambda_1 & -\frac{\sqrt{3}}{4}\lambda_{0m} + \frac{\sqrt{3}}{4}\lambda_{1m} & \frac{3}{4}\lambda_{0m} + \frac{1}{4}\lambda_{1m} \\
\frac{1}{4}\lambda_{0m} + \frac{3}{4}\lambda_{1m} & -\frac{\sqrt{3}}{4}\lambda_{0m} + \frac{\sqrt{3}}{4}\lambda_{1m} & \frac{1}{4}\lambda_{0s} + \frac{3}{4}\lambda_{1s} & -\frac{\sqrt{3}}{4}\lambda_{0s} + \frac{\sqrt{3}}{4}\lambda_{1s} \\
-\frac{\sqrt{3}}{4}\lambda_{0m} + \frac{\sqrt{3}}{4}\lambda_{1m} & \frac{3}{4}\lambda_{0m} + \frac{1}{4}\lambda_{1m} & -\frac{\sqrt{3}}{4}\lambda_{0s} + \frac{\sqrt{3}}{4}\lambda_{1s} & \frac{3}{4}\lambda_{0s} + \frac{1}{4}\lambda_{1s}
\end{array}\right) \tag{2}
$$

More details, seen in our recent paper: *Phys.Rev. D* **88** *(2013) 034018*.

3. Hidden gauge formalism for LEC's

In the formalism of the local hidden gauge, the Lagrangians involving the exchanged vector mesons are given by

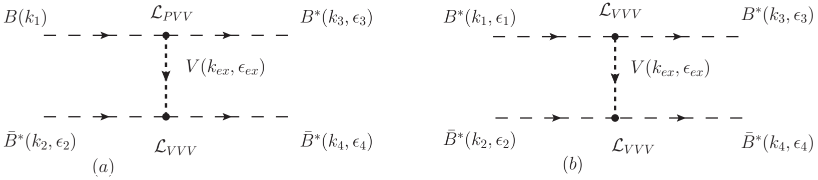
$$\mathcal{L}_{VVV} = ig \, \langle [V_\nu, \partial_\mu V_\nu] V^\mu \rangle,$$
$$\mathcal{L}_{PPV} = -ig \, \langle [P, \partial_\mu P] V^\mu \rangle,$$
$$\mathcal{L}_{VVP} = \frac{G'}{\sqrt{2}} \, \epsilon^{\mu\nu\alpha\beta} \, \langle \partial_\mu V_\nu \partial_\alpha V_\beta P \rangle,$$

where $g = m_V/2f$ with $f = 93$ MeV the pion decay constant and $G' = 3m_V^2/(16\pi^2 f^3)$, and taking $m_V = m_\rho$. We need to extrapolate the formalism to SU(4), as done in:

[13] J. -J. Wu, R. Molina, E. Oset and B. S. Zou, Phys. Rev. Lett. 105, 232001 (2010).
[14] J. -J. Wu, R. Molina, E. Oset and B. S. Zou, Phys. Rev. C 84, 015202 (2011).

Under the lower order HQSS constrain, we can determine these unknown LEC's, λ_i^I, λ_{is}^I and λ_{im}^I ($i = 0, 1$) easily by just choosing some channels with the local hidden gauge approach.

Taking the transitions $B\bar{B}^* \to B^*\bar{B}^*$ and $B^*\bar{B}^* \to B^*\bar{B}^*$ for example, we show in the figure:



For the diagram of (a), using the local hidden gauge formalism, we obtain

$$t_{B\bar{B}^* \to B^*\bar{B}^*} = \frac{1}{2}(-\lambda_0 + \lambda_1) \approx 0,$$

$$\Longrightarrow \quad \lambda_0 = \lambda_1.$$

Analogously, we have

$$\lambda_{0s} = \lambda_{1s},$$
$$\lambda_{0m} = \lambda_{1m}.$$

which are generalized for all $I = 0, 1$ sectors with different spin J since these LEC's are spin independent. So, some non diagonal elements of Eq. (2) are zero in our hidden gauge model.

For the diagram of (b), ignoring possible terms with Υ exchange and taking $m_\rho \approx m_\omega = m_V$, we obtain

$$\lambda_1^{I=0} = \frac{1}{4} g^2 \left(\frac{3}{m_\rho^2} + \frac{1}{m_\omega^2}\right)(m_1^2 + m_2^2 + m_3^2 + m_4^2 - 3s),$$
$$\lambda_1^{I=1} = 0.$$

Similarly, for the others of LEC's, taking the interactions of $B_s^* \bar{B}_s^* \to B_s^* \bar{B}_s^*$ and $B^* \bar{B}^* \to B_s^* \bar{B}_s^*$, required ϕ and K^* exchange, we have

$$\begin{aligned}
\lambda_{1s}^{I=0} &= \frac{1}{2} g^2 \frac{1}{m_\phi^2}(m_1^2 + m_2^2 + m_3^2 + m_4^2 - 3s), \\
\lambda_{1s}^{I=1} &= 0, \\
\lambda_{1m}^{I=0} &= \frac{1}{\sqrt{2}} g^2 \frac{1}{m_{K^*}^2}(m_1^2 + m_2^2 + m_3^2 + m_4^2 - 3s), \\
\lambda_{1m}^{I=1} &= 0,
\end{aligned}$$

Thus, getting an $I = 1$ zero potential in the limit of $m_\rho = m_\omega$, obviously we **do not have interaction in $I = 1$.**

This maybe because of the weak or subdominant potentials in $I = 1$ and Thus we can not explain the $Z_b(10610)$ and $Z_b(10650)$ resonances, which are assumed as molecular states [2,3] (*Z.-F. Sun et al and M. Cleven et al*), since the interaction is subdominant in our approach in $I = 1$ and we neglect it.

4. Results

We use the Bethe-Salpeter equation in coupled channels to evaluate the scattering amplitudes. For the G function, we take

$$G(s) = \int \frac{d^3\vec{q}}{(2\pi)^3}\, f^2(\vec{q}\,)\, \frac{\omega_1 + \omega_2}{2\,\omega_1\,\omega_2}\, \frac{1}{P^{0\,2} - (\omega_1 + \omega_2)^2 + i\varepsilon},$$

where $f(\vec{q}\,)$ is the form factor, which comes from the light vector meson exchange, and is given by

$$f(\vec{q}\,) = \frac{m_V^2}{\vec{q}^{\,2} + m_V^2}.$$

The couplings are defined as:

$$g_i^2 = \lim_{s \to s_R} (s - s_R)\, T_{ii}.$$

(1) $J^{PC} = 2^{++}$ sector

Our results for the $J^{PC} = 2^{++}$ channel for $q_{max} = 415$ MeV (left panel) and $q_{max} = 830$ MeV (right panel), are shown as below (all units in MeV):

10613	$B^*\bar{B}^*$	$B_s^*\bar{B}_s^*$	10469	$B^*\bar{B}^*$	$B_s^*\bar{B}_s^*$
g_i	86168	45864	g_i	174393	92843

When ignoring coupled channel effect, we have

10616	$B^*\bar{B}^*$	$B_s^*\bar{B}_s^*$	10500	$B^*\bar{B}^*$	$B_s^*\bar{B}_s^*$
g_i	81595	0	g_i	159102	0
10828	$B^*\bar{B}^*$	$B_s^*\bar{B}_s^*$	10812	$B^*\bar{B}^*$	$B_s^*\bar{B}_s^*$
g_i	0	19787	g_i	0	44102

(2) $J^{PC} = 1^{+-}$ and $J^{PC} = 1^{++}$ sector

For the $J = 1,\ I = 0$ sector, the results are shown (two panels are for $q_{max} = 415$ MeV and $q_{max} = 830$ MeV respectively, all units in MeV):

10568	$B\bar{B}^*\pm$c.c.	$B_s\bar{B}_s^*\pm$c.c.	10425	$B\bar{B}^*\pm$c.c.	$B_s\bar{B}_s^*\pm$c.c.
g_i	85433	45560	g_i	172908	92232

Without coupled channels

10571	$B\bar{B}^*\pm$c.c.	$B_s\bar{B}_s^*\pm$c.c.	10455	$B\bar{B}^*\pm$c.c.	$B_s\bar{B}_s^*\pm$c.c.
g_i	80884	0	g_i	157691	0
10783	$B\bar{B}^*\pm$c.c.	$B_s\bar{B}_s^*\pm$c.c.	10768	$B\bar{B}^*\pm$c.c.	$B_s\bar{B}_s^*\pm$c.c.
g_i	0	19611	g_i	0	43776

(3) $J^{PC} = 0^{++}$ sector

For this sector, we get (two panels the same as before, all units in MeV):

10523	$B\bar{B}$.	$B_s\bar{B}_s$	10380	$B\bar{B}$	$B_s\bar{B}_s$
g_i	85045	45257	g_i	172046	91591

Without coupled channels

10526	$B\bar{B}$.	$B_s\bar{B}_s$	10410	$B\bar{B}$	$B_s\bar{B}_s$
g_i	80528	0	g_i	156968	0
10738	$B\bar{B}$	$B_s\bar{B}_s$	10723	$B\bar{B}$	$B_s\bar{B}_s$
g_i	0	19441	g_i	0	43443

5. Discussions

For a resonance or bound state, the sum rule is fulfilled: for $B\bar{B}$ state, taking $q_{max} = 415\ \mathrm{MeV}$

1. $P_p = -\sum_i g_i^2 \left[\frac{dG_i}{dE}\right]_{E=E_p} = 1$
1. $P_{B\bar{B}} = 0.985$

which means that the bound state is mostly made by $B\bar{B}$ with a minor $B_s\bar{B}_s$ component.

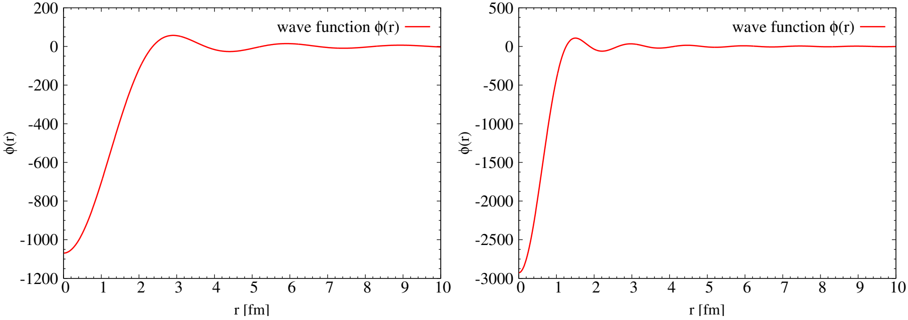
This $B\bar{B}$ state is stable and independent on free parameters of our formalism (units in MeV):

q_{max}	450	500	600	700	800
pole	10513	10498	10464	10427	10389

We also investigate the wave function and radius of the state:

$$\phi(\vec{r}\,) = \frac{1}{(2\pi)^{3/2}} \frac{4\pi}{r} \frac{1}{C} \int_{q_{max}} p\, dp\, sin(pr)\, \frac{\Theta(q_{max} - |\vec{p}\,|)}{E - \omega_1(\vec{p}) - \omega_2(\vec{p}\,)} \frac{m_V^2}{\vec{q}^{\,2} + m_V^2},$$

For the $B\bar{B}$ state, we show in figure (Left: $q_{max} = 415$ MeV; Right: $q_{max} = 830$ MeV):



The radii of the states are given in the table:

states	$q_{max} = 415$ MeV	$q_{max} = 830$ MeV
$B^*\bar{B}^*$	1.46 fm	0.72 fm
$B\bar{B}^*$	1.46 fm	0.72 fm
$B\bar{B}$	1.46 fm	0.72 fm

which are of the same order of magnitude as Refs [2,15] (*Z.-F. Sun et al and M. T. Li et al*):

[15] M. T. Li, W. L. Wang, Y. B. Dong and Z. Y. Zhang, Int. J. Mod. Phys. A 27, 1250161 (2012).

6. Conclusions

In our work, combining the local hidden gauge symmetry with heavy quark spin symmetry, we investigate the hidden beauty sector: $B_{(s)}^{(*)}\bar{B}_{(s)}^{(*)}$.

The $I = 0$ sector

6 hidden beauty resonances: binding energies 34 MeV (178 MeV);
6 hidden beauty-hidden strange states: binding energies 2 MeV (18 MeV).

The $I = 1$ sector

The interaction is too weak to form any bound states.

Hope that these states can be found in the experiment in the future.

Thank you!