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Hidden beauty molecules with the local hidden gauge approach and heavy quark spin symmetry

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Using a coupled channel unitary approach, combining the heavy quark spin symmetry and the dynamics of the local hidden gauge, we investigate the meson-meson interaction with hidden beauty. We have investigated both $I = 0$ and $I = 1$ states, and obtain several new states of isospin $I = 0$: six bound states, and weakly bound six more possible states which depend on the influence of the coupled channel effects. But there is no state found in the $I = 1$ sector since the interactions are too weak to create any bound states within our framework.

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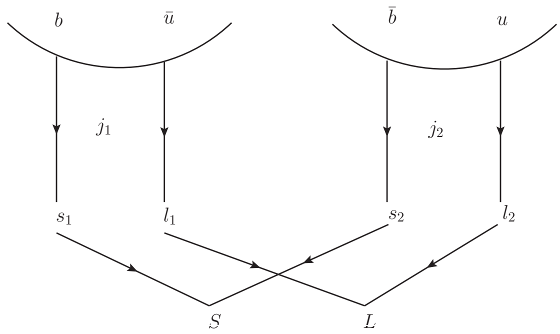

Figure 1: Diagrams for the hidden beauty systems.

1. Introduction

The world of heavy quarks, charm and beauty, is experiencing a fast development, with a plethora of new states being found in facilities as BABAR, CLEO, BELLE, BES. Recently, the discovery of the hidden beauty $Z_b(10610)$ and $Z_b(10650)$ states [1], has driven more attention to the beauty sector [2, 3].

In this work, we investigate the hidden beauty system of meson-meson interaction [4, 5, 6]. We take into account the heavy quark spin symmetry (HQSS) [7, 8, 9, 10] for the hidden beauty sector, and then, under the lower order HQSS constrain, we use the local hidden gauge approach [11, 12] to determine the interaction potentials.

2. Formalism

In our work, we use the coupled channel approach to study the meson-meson interaction in the hidden beauty sector, with the coupled channels of $B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}$: (1) $J=0,\ I=0$, $B\bar{B}$, $B_s\bar{B}_s$, $B^*\bar{B}^*$, $B^*_s\bar{B}^*_s$; (2) $J=0,\ I=1$ $B\bar{B}$, $B^*\bar{B}^*$; (3) $J=1,\ I=0$, $B\bar{B}^*$ $(B^*\bar{B})$, $B_s\bar{B}^*_s$ $(B^*_s\bar{B}_s)$, $B^*\bar{B}^*$, $B^*_s\bar{B}^*_s$; (4) $J=1,\ I=1$, $B\bar{B}^*$ $(B^*\bar{B})$, $B^*\bar{B}^*$; (5) $J=2,\ I=0$, $B^*\bar{B}^*$, $B^*_s\bar{B}^*_s$; (6) $J=2,\ I=1$, $B^*\bar{B}^*$.

In our case, all the hidden beauty systems are made by a meson (M) $-$ antimeson $(\bar{M})$ state, which are shown in Fig. 1. Then, with the HQSS constrain [10], we use the local hidden gauge formalism to evaluate the interaction potential (more details, seen in our recent paper [13]), following development of Refs. [14, 15]. In principle one is using SU(4) symmetry to evaluate the couplings. However, recently we have shown in [16, 17] that the leading terms respecting HQSS correspond in our approach to having the beauty quarks as spectators. In this case all couplings can be obtained using SU(3).

3. Results

We use the Bethe-Salpeter equation in coupled channels to evaluate the scattering amplitudes,

$$T = [1 - VG]^{-1} V. \tag{3.1}$$

For the G function, we take

$$G(s) = \int \frac{d^3\vec{q}}{(2\pi)^3} f^2(\vec{q}) \frac{\omega_1+\omega_2}{2\,\omega_1\,\omega_2} \frac{1}{P^{0\,2}-(\omega_1+\omega_2)^2+i\varepsilon}; \quad f(\vec{q}) = \frac{m_V^2}{\vec{q}^{\,2}+m_V^2}, \tag{3.2}$$

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

Our results of the poles and the couplings for the $J^{PC}=2^{++}$ channel with $q_{max}=415$ MeV (left panel) and $q_{max}=830$ MeV (right panel), are shown as Table 1. When ignoring the coupled channel effect, the results are shown in Table 2.

Table 1: The poles and couplings for the $J^{PC}=2^{++}$: $q_{max}=415$ MeV (left panel) and $q_{max}=830$ MeV (right panel), 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

Table 2: The poles and couplings for the $J^{PC}=2^{++}$ ignoring coupled channels (two panels and units the same as before, also the same for below.

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

For the $J=1,\ I=0$ sector, the results with coupled channels and without coupled channels are shown in Tables 3 and 4.

Table 3: The poles and couplings for the $J^{PC}=1^{+-}$ and $J^{PC}=1^{++}$.

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

Table 4: The poles and couplings for the $J^{PC}=1^{+-}$ and $J^{PC}=1^{++}$ ignoring 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

Finally, we get results for the $J^{PC}=0^{++}$ sector as listing in Tables 5 and 6.

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Table 5: The poles and couplings for the $J^{PC} = 0^{++}$.

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

Table 6: The poles and couplings for the $J^{PC} = 0^{++}$ ignoring 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

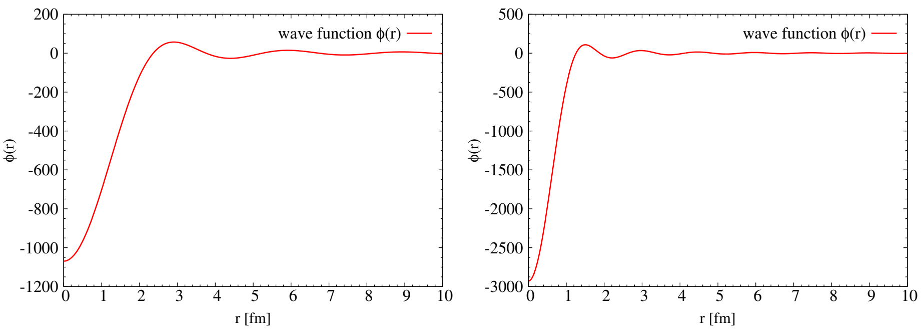

Figure 2: The wave functions of $B\bar{B}$ state, Left: $q_{max} = 415$ MeV; Right: $q_{max} = 830$ MeV.

4. Discussions

For a resonance or bound state, the sum rule [18] is fulfilled: $P_p = -\sum_i g_i^2 \left[\frac{dG_i}{dE}\right]_{E=E_p} = 1$. For $B\bar{B}$ state, taking $q_{max} = 415$ MeV, we get $P_{B\bar{B}} = 0.985$, 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 of the free parameters of our formalism, which can be seen in Table 7.

Table 7: The poles in the $J^{PC} = 0^{++}$ channel when the cut off is changed (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. By performing some derivation, we get

$$\phi(\vec{r}) = \frac{1}{(2\pi)^{3/2}} \frac{4\pi}{r} \frac{1}{C} \int_{q_{max}} p\,dp\,sin(pr) \frac{\Theta(q_{max} - |\vec{p}\,|)}{E - \omega_1(\vec{p}) - \omega_2(\vec{p})} \frac{m_V^2}{\vec{q}^{\,2} + m_V^2}, \tag{4.1}$$

where we take $m_V = m_\rho = 775$ MeV. For the $B\bar{B}$ state, using Eq. (4.1), we show the results of wave function in Fig.2. The radii of the states are given in Table 8, which are of the same order of magnitude as Refs. [2, 19].

Table 8: The radii of the states.

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

5. Conclusions

In our work, combining the local hidden gauge symmetry with heavy quark spin symmetry, we investigate the hidden beauty sector: $B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}$. In the $I = 0$ sector, we obtain 6 hidden beauty resonances with binding energies 34 MeV (178 MeV) for $q_{max} = 415$ MeV (830 MeV), and 6 hidden beauty-hidden strange states with binding energies 2 MeV (18 MeV). But, for the $I = 1$ sector, the interaction is too weak to form any bound states. We hope that these states can be found in experiments in the future.

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