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A study of beauty baryons with extended local hidden gauge approach

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Abstract

In present work we investigate the interaction of $\bar{B}N$, $\bar{B}\Delta$, $\bar{B}^*N$ and $\bar{B}^*\Delta$ states, together with their coupled channels. Taking into account the heavy quark spin symmetry for pion exchange and the results of the Weinberg Tomozawa term in the extended local hidden gauge approach, we search for states dynamically generated from the interaction, and find two states with small width, which we associate to the $\Lambda_b(5912)$ and $\Lambda_b(5920)$ states. In addition to these two Λ_b states, we find three more states with $I = 0$ and eight more states in $I = 1$, some of which are degenerate in different spin J.

Keywords: coupled channels, box diagram, heavy quark spin symmetry

1. Introduction

Recently, the discovery of the two Λ_b excited states by the LHC$_b$ collaboration [1], $\Lambda_b(5912)$ and $\Lambda_b(5920)$ with $J^P = 1/2^-, 3/2^-$ respectively, drives more attention to the beauty sector, since the widths of these two states are very small, less than 1 MeV. The higher one is also confirmed by the CDF collaboration [2, 3].

In the present work, following the works [4, 5, 6, 7], we investigate the open beauty system of meson-baryon interaction, using the extended local hidden gauge formalism and the coupled channel approach. The assumption that the heavy quarks act as spectators at the quark level automatically leads us to the results of the heavy quark spin symmetry for pion exchange.

2. Formalism

We investigate the coupled channels $\pi\Sigma_b$, $\pi\Lambda_b$, $\eta\Lambda_b$, $\eta\Sigma_b$, $\bar{B}N$ with $I = 0, 1$. Similarly, we also study the $\bar{B}^*N$ and $\pi\Sigma_b^*$, $\eta\Sigma_b^*$, $\bar{B}\Delta$, $\bar{B}^*\Delta$ channels, belonging to a decuplet of $3/2^+$ states. Using the local hidden gauge approach, the meson- baryon interaction proceeds via the exchange of vector mesons as depicted in Fig. 1.

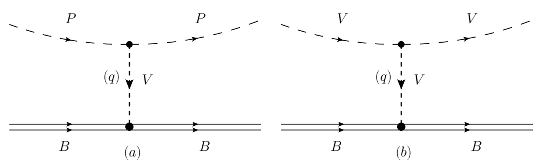

Figure 1: Diagrammatic representation of the pseudoscalar-baryon interaction (a) and vector-baryon interaction (b).

Assuming that the heavy quarks act as spectators in the dominant terms of the interaction, with the extended local hidden gauge approach from the exchange of light vector mesons, the transition potential is given by

$$V_{ij} = -C_{ij}\frac{1}{4f^2}(2\sqrt{s} - M_{B_i} - M_{B_j}) \times \sqrt{\frac{M_{B_i} + E_i}{2M_{B_i}}}\sqrt{\frac{M_{B_j} + E_j}{2M_{B_j}}}, \quad (1)$$

with f the pion decay constant (for light vector mesons exchange, taking $f = f_\pi = 93$ MeV), $\sqrt{s}$ the energy in the center mass frame, M_{B_i}, E_i (M_{B_j}, E_j) the mass, energy of baryon of i (j) channel. The C_{ij} coefficients

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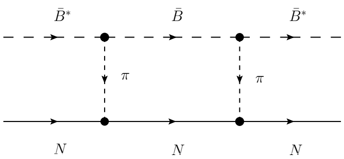
are given in Refs. [8, 9] for the pseudoscalar meson-baryon interactions and in Refs. [10, 11] for the vector meson-baryon interactions.

In coupled channels we use the Bethe-Salpeter equation to evaluate the scattering amplitudes

$$T = [1 - V G]^{-1} V, \tag{2}$$

where G is the diagonal matrix of the loop function for the propagating intermediate meson baryon channels, and the elements of the kernel V are given by Eq. (1). First, using the coupled channels approach, we investigate the sector of $\bar{B}N$ and its coupled channels, and the sector of $\bar{B}^*N$ and its coupled channels, respectively. But, it is difficult to dynamically reproduce the two Λ_b excited states with a reasonable cutoff. More details can be seen in our recent paper [12].

Next, we break the degeneracy of the $1/2^-$, $3/2^-$ states of the $\bar{B}^*N$ sector, by mixing states of $\bar{B}^*N$ and $\bar{B}N$ in both sectors. This means that it is sufficient to evaluate the contribution of the box diagrams as below:



Finally we obtain the following results for the $\bar{B}^*N \to \bar{B}N \to \bar{B}^*N$ box diagram

$$\begin{aligned} J &= 1/2: \quad \delta V = FAC\Big(\frac{\partial}{\partial m_\pi^2} I_1' + 2\, I_2' + I_3'\Big), \\ J &= 3/2: \quad \delta V = FAC\Big(\frac{\partial}{\partial m_\pi^2} I_1'\Big), \end{aligned} \tag{3}$$

where

$$\begin{aligned} I_1' &= \int \frac{d^3q}{(2\pi)^3} \frac{4}{3} \vec{q}^{\,4} \frac{1}{2\omega_B(\vec{q}\,)} \frac{M_N}{E_N(\vec{q}\,)} \frac{Num}{Den}, \\ I_2' &= \int \frac{d^3q}{(2\pi)^3} 2\vec{q}^{\,2} \frac{1}{2\omega_B(\vec{q}\,)} \frac{M_N}{E_N(\vec{q}\,)} \frac{Num}{Den}, \\ I_3' &= \int \frac{d^3q}{(2\pi)^3} \frac{3}{2\omega_B(\vec{q}\,)} \frac{M_N}{E_N(\vec{q}\,)} \\ &\quad \times \frac{1}{P_{in}^0 + K_{in}^0 - E_N(\vec{q}\,) - \omega_B(\vec{q}\,) + i\epsilon}, \end{aligned} \tag{4}$$

with

$$\begin{aligned} FAC &= \frac{9}{2} g^2 \Big(\frac{m_{B^*}}{m_{K^*}}\Big)^2 \Big(\frac{F+D}{2f_\pi}\Big)^2, \\ Num &= K_{in}^0 - E_N(\vec{q}\,) - 2\omega_\pi(\vec{q}\,) - \omega_B(\vec{q}\,) + P_{in}^0, \\ Den &= 2\omega_\pi(\vec{q}\,)[P_{in}^0 - \omega_\pi(\vec{q}\,) - \omega_B(\vec{q}\,) + i\epsilon] \\ &\quad \times [K_{in}^0 - E_N(\vec{q}\,) - \omega_\pi(\vec{q}\,) + i\epsilon] \\ &\quad \times [P_{in}^0 + K_{in}^0 - E_N(\vec{q}\,) - \omega_B(\vec{q}\,) + i\epsilon], \end{aligned}$$

and P_{in}^0, K_{in}^0 the energies of incoming $\bar{B}^*$ and N, $g = m_V/2f_\pi$ with $m_V \approx 780$ MeV, $D = 0.75$ and $F = 0.51$ [13].

For the other boxes, such as $\bar{B}N \to \bar{B}^*N \to \bar{B}N$ for $I = 0$, and for $I = 1$ $\bar{B}\Delta \to \bar{B}^*\Delta \to \bar{B}\Delta$, $\bar{B}^*\Delta \to \bar{B}\Delta \to \bar{B}^*\Delta$, $\bar{B}\Delta \to \bar{B}^*N \to \bar{B}\Delta$, $\bar{B}^*\Delta \to \bar{B}N \to \bar{B}^*\Delta$, we obtain similar results and more details can be referred to our paper [12].

3. Results

When we consider the mixing of $\bar{B}^*N$ and $\bar{B}N$ states by taking into account the contribution of the box diagram for the channels of $\bar{B}^*N$ and $\bar{B}N$ with their coupled channels, we obtain the energy splitting of 10 MeV between the $J = 1/2$ and $J = 3/2$ in the sector of $\bar{B}^*N$ and its coupled channels, which is rather independent of the cutoff used. Thus, by tuning the cutoff q_{max} to get the right binding, we find $q_{max} = 776$ MeV leading naturally to two Λ_b states, where the energy of the $J = 1/2$ state is 5910 MeV, and the one of the $J = 3/2$ state 5920 MeV, associating them to the $\Lambda_b(5912)$ and $\Lambda_b(5920)$. Then, with this fixed cutoff, we search the generated states in other isospin $I = 0$ and $I = 1$ sectors. Finally, since we have many intermediate results, we summarize all the results that we obtain with $q_{max} = 776$ MeV. The results are shown in Table 1, where we also write for a quick intuition the main component of the states.

Table 1: Energies and widths of the states obtained and the channels to which the states couple most strongly.

channels	J	I	(E, Γ) [MeV]	Exp.
$\bar{B}N$	$\frac{1}{2}$	0	5820.9, 0	-
$\pi\Sigma_b$	$\frac{1}{2}$	0	5969.5, 49.2	-
$\bar{B}^*N$	$\frac{1}{2}$	0	5910.7, 0	$\Lambda_b(5912)$
$\bar{B}^*N$	$\frac{3}{2}$	0	5920.7, 0	$\Lambda_b(5920)$
$\rho\Sigma_b$	$\frac{1}{2}$	0	6316.6, 2.8	-
$\rho\Sigma_b$	$\frac{3}{2}$	0	6315.7, 3.8	-
$\bar{B}N$, $\pi\Sigma_b$	$\frac{1}{2}$	1	6179.4, 122.8	-
$\pi\Sigma_b$	$\frac{1}{2}$	1	6002.8, 132.4	-
$\bar{B}\Delta$, $\pi\Sigma_b^*$	$\frac{3}{2}$	1	5932.9, 0	-
$\pi\Sigma_b^*$	$\frac{3}{2}$	1	6063.8, 167.0	-
$\bar{B}^*N$	$\frac{1}{2}, \frac{3}{2}$	1	6202.2, 0	-
$\rho\Sigma_b$	$\frac{1}{2}, \frac{3}{2}$	1	6477.2, 10.0	-
$\bar{B}^*\Delta$	$\frac{1}{2}, \frac{3}{2}, \frac{5}{2}$	1	6022.9, 0	-
$\rho\Sigma_b^*$	$\frac{1}{2}, \frac{3}{2}, \frac{5}{2}$	1	6491.7, 1.6	-

In the work of Ref. [5], the same interaction as here is used for the main diagonal channels, but the transition between different coupled channels is not obtained through vector or pion exchange as done here, but invoking a combined SU(6) and heavy quark spin symmetry. Comparing the results with Ref. [5], we obtained some consistent results in $I = 0$. The two states associated to the $\Lambda_b(5912)$ and $\Lambda_b(5920)$ exhibit, as here, a substantial coupling to $\bar{B}^*N$. There is also a $1/2^-$ state in that work at 5797 MeV which we find at 5820 MeV, only 33 MeV higher, and another state at 6009 MeV that we find at 5969 MeV, 40 MeV below. The mostly $\rho\Sigma_b$ state found here at 6316 MeV, basically degenerate in $J = 1/2,\ 3/2$, was either not found or not searched for in that work because of its higher mass.

The states of $I = 1$ are not investigated in that work. Thus, these states are our predictions with the same parameters in $I = 0$, and we find quite a few, some of them narrow enough for a clear experimental observation.

In summary, we predict 6 states with $I = 0$, two of them corresponding to the $\Lambda_b(5912)$ and $\Lambda_b(5920)$, and 8 states with $I = 1$. The energies of the states range from about 5800 MeV to 6500 MeV.

4. Conclusion

The interaction of $\bar{B}N$, $\bar{B}\Delta$, $\bar{B}^*N$ and $\bar{B}^*\Delta$ states with its coupled channels are investigated in the present work by using dynamics mapped from the light quark sector to the heavy one. We studied the interaction of the $\bar{B}N$, $\bar{B}\Delta$, $\bar{B}^*N$ and $\bar{B}^*\Delta$ with their coupled channels $\pi\Sigma_b$, $\pi\Lambda_b$, $\eta\Sigma_b$ (for the $\bar{B}N$); $\pi\Sigma_b^*$, $\eta\Sigma_b^*$ (for the $\bar{B}\Delta$); $\rho\Sigma_b$, $\omega\Lambda_b$, $\phi\Lambda_b$, $\rho\Sigma_b^*$, $\omega\Sigma_b^*$, $\phi\Sigma_b^*$ (for the $\bar{B}^*N$); and $\rho\Sigma_b^*$, $\omega\Sigma_b^*$, $\phi\Sigma_b^*$ (for the $\bar{B}^*\Delta$), and looked for poles of the scattering matrix in different states of spin and isospin. We found six states in $I = 0$, with one of them degenerate in spin $J = 1/2,\ 3/2$ and two of them associated to the experimental $\Lambda_b(5912)$ and $\Lambda_b(5920)$ states, which couple mostly to $\bar{B}^*N$. We also obtained eight states in $I = 1$, less bound, two of them degenerate in spin $J = 1/2,\ 3/2$, and two more degenerate in spin $J = 1/2,\ 3/2,\ 5/2$. We look forward to future experiment searches of the baryon states with open beauty predicted here.

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