

ODD-PARITY DYNAMICALLY GENERATED  
BARYON RESONANCES WITH BEAUTY FLAVOR\*

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We study baryon resonances with heavy flavor in a molecular approach, thus as dynamically generated by baryon–meson scattering. This is accomplished by using a unitary coupled-channel model taking, as bare interaction, the extension of the Weinberg–Tomozawa  $SU(3)$  Lagrangian. A special attention is paid to the inclusion of heavy-quark spin symmetry and the study of the generated baryon resonances that complete the heavy-quark spin multiplets. Our model reproduces the  $\Lambda_b(5912)$  and  $\Lambda_b(5920)$  baryons, which were recently observed by the LHCb Collaboration. According to our analysis, these two states are heavy-quark spin symmetric partners. We also make predictions for few  $\Xi_b$  baryon resonances, which belong to the same  $SU(3) \times HQSS$  multiplets as the  $\Lambda_b$  particles.

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## 1. Introduction

Using  $pp$  collision data, the LHCb Collaboration [1] has reported the discovery of two narrow states, observed in the  $\Lambda_b^0\pi^+\pi^-$  spectrum, with masses  $5911.97\pm 0.12$  (stat)  $\pm 0.02$  (syst)  $\pm 0.66$  ( $\Lambda_b^0$  mass) MeV, and  $5919.77\pm 0.08$  (stat)  $\pm 0.02$  (syst)  $\pm 0.66$  ( $\Lambda_b^0$  mass) MeV. These states are interpreted as the orbitally-excited  $\Lambda_b^0(5912)$  and  $\Lambda_b^0(5920)$  bottom baryon resonances, with spin-parity  $J^P = 1/2^-$  and  $J^P = 3/2^-$ , respectively. The limits on the natural widths of these states are  $\Gamma_{\Lambda_b^0(5912)} \leq 0.83$  MeV and  $\Gamma_{\Lambda_b^0(5920)} \leq 0.75$  MeV at the 95% confidence level [1]. These results reported by the LHCb Collaboration are in good agreement with an old prediction by Capstick and Isgur [2]. Their relativistic quark model predicts 5912 MeV and 5920 MeV for the masses of the lightest orbitally-excited states. However, the same model yields a mass of the ground state  $\Lambda_b^0$  ( $J^P = 1/2^+$ ) which is about 35 MeV smaller than the measured value [3]. At the same time, some other existing quark-models predictions [4–7] differ by few tenths of MeV from the LHCb experimental ones.

We adopt a different approach and describe these states as dynamically generated resonances obtained within a unitarized baryon–meson coupled-channel scheme. The unitarization in coupled-channels has proven to be very successful in describing some of the existing experimental data. Thus, there have been different successful studies based on the chiral perturbation theory amplitudes for scattering of  $0^-$  octet Goldstone bosons off baryons of the  $1/2^+$  nucleon octet in the charmless sector (*e.g.* [8–11]). Unitarized coupled-channel methods have been further extended to the baryon–meson sector with charm degrees of freedom in several ways. In some works, *e.g.* [12, 13] a bare baryon–meson interaction is used, saturated with the  $t$ -channel exchange of vector mesons between pseudoscalar mesons and baryons. Some other works [14, 15] are based on the Jülich meson-exchange model and those in [16–18] make use of the hidden gauge formalism, and the same approach has been extended to the bottom sector in [19]. An extended Weinberg–Tomozawa (WT) interaction implementing heavy-quark spin symmetry (HQSS) is applied in [20–23] for the charm sector, while in [24] it was also used for bottom-flavored baryon states. In this paper, we review some of the results of [24].

We use hadronic degrees of freedom in a unitarized baryon–meson coupled-channel calculation. We rely on a tree-level interaction that embodies the approximate pattern of chiral symmetry, when Goldstone bosons are involved, and HQSS when heavy hadrons are present. Moreover, it enjoys spin-flavor symmetry in the light ( $u$ ,  $d$ ,  $s$ ) flavor sector [24].

## 2. Theoretical framework

We follow the approach previously applied for charm systems in Refs. [20–22]. We consider baryon resonances with one bottom quark ( $B = -1$ ), in particular  $\Lambda_b$  states with strangeness, isospin and spin-parity  $(S, I, J^P) = (0, 0, 1/2^-)$  quantum numbers,  $\Lambda_b^*$  with  $(0, 0, 3/2^-)$ ,  $\Xi_b$  with  $(-1, 1/2, 1/2^-)$ , and  $\Xi_b^*$  with  $(-1, 1/2, 3/2^-)$ .

Baryon–meson pairs with the same  $SIJ$  quantum numbers span the coupled-channel space. We study  $s$ -wave tree-level amplitudes between two coupled channels  $ij$ , which are given by

$$V_{ij}^{SIJ} = D_{ij}^{SIJ} \frac{2\sqrt{s} - M_i - M_j}{4f_i f_j} \sqrt{\frac{E_i + M_i}{2M_i}} \sqrt{\frac{E_j + M_j}{2M_j}}, \quad (1)$$

where  $\sqrt{s}$  is the center-of-mass (C.M.) energy of the system;  $E_i$  and  $M_i$  are, respectively, the C.M. energy and mass of the baryon in the channel  $i$ ; and  $f_i$  is the decay constant of the meson in the  $i$ -channel. The masses of the baryons and the mesons, and the meson decay constants used in this work can be found in [21, 24]. The coefficients  $D_{ij}^{SIJ}$  come from the underlying spin-flavor extended WT structure of the couplings of our model [20]. The various exact symmetries referred above (chiral, spin-flavor and HQSS) apply only to the coefficients  $D_{ij}^{SIJ}$ , while physical masses and decay meson constants are used throughout when solving the coupled-channel equations.

Further, we solve the Bethe–Salpeter equation in the complex plane, which provides the  $T$ -matrix as

$$T^{SIJ} = (1 - V^{SIJ} G^{SIJ})^{-1} V^{SIJ}, \quad (2)$$

where  $G^{SIJ}$  is a diagonal matrix containing the two particle propagator for each channel. The two particle propagator diverges logarithmically, thus the loop is renormalized by a subtraction constant (see [21] for discussion about the use of this method) such that  $G_{ii}^{SIJ} = 0$ , at  $\sqrt{s} = \mu^{SI}$ . To fix the subtraction point  $\mu^{SI}$ , we consider all sectors with a common  $SI$  and different  $J$  and all the corresponding channels. Then  $\mu^{SI}$  is taken as  $\sqrt{m_{\text{th}}^2 + M_{\text{th}}^2}$ , where  $m_{\text{th}}$  and  $M_{\text{th}}$  are, respectively, the masses of the meson and the baryon producing the lowest threshold for a given  $SI$  sector.

The dynamically-generated baryon resonances are obtained as poles of the scattering amplitudes in each of the  $SIJ$  sectors. The poles of the scattering amplitude on the first Riemann sheet that appear on the real axis below the threshold are interpreted as bound states, and those found on the second Riemann sheet below the real axis and above threshold are identified with resonances. The position  $\sqrt{s_R}$  of the pole on the complex energy plane

$\sqrt{s_R} = M_R - i\Gamma_R/2$  provides the mass ( $M_R$ ) and the width ( $\Gamma_R$ ) of the resonance, and the couplings to the different baryon–meson channels are obtained from the residues of the scattering amplitude around the pole.

### 3. Dynamically generated $\Lambda_b$ and $\Xi_b$ resonances

#### 3.1. $\Lambda_b$ and $\Lambda_b^*$ states

Our model generates four  $\Lambda_b$  resonances. Three lowest lying  $\Lambda_b$  states have masses of 5880 and 5949 MeV ( $J^P = 1/2^-$ ), and 5963 MeV ( $J^P = 3/2^-$ ). As one can expect, the situation in the  $J = 1/2^-$  channel keeps a close parallelism with that of the  $\Lambda_c(2595)$  resonance in the charm sector [20, 21]. For both heavy flavors, the structure obtained mimics the well-known two-pole pattern of the  $\Lambda(1405)$ , *e.g.* [11]. Thus, we find that the state at 5880 MeV strongly couples to the  $N\bar{B}$  and  $N\bar{B}^*$  channels, with a negligible  $\Sigma_b\pi$  coupling, while the 5949 MeV state has a sizable coupling to this latter channel. On the other hand, the  $J^P = 3/2^-$  state at 5963 MeV is generated mainly by the  $(N\bar{B}^*, \Sigma_b^*\pi)$  coupled-channel dynamics. This state is the bottom counterpart of the  $\Lambda(1520)$  and  $\Lambda_c^*(2625)$  resonances.

In order to achieve a better agreement with the  $\Lambda_b(5912)$  and  $\Lambda_b(5920)$  states reported by the LHCb Collaboration, we have slightly changed the value of the subtraction point in this sector, namely we have set the baryon–meson loop to be zero at the C.M. energy  $\sqrt{s} = \mu$  given by  $\mu^2 = \alpha (M_{\Sigma_b}^2 + m_\pi^2)$ . For  $\alpha = 0.967$ , we find two poles above the  $\Lambda_b^0\pi\pi$  threshold, with masses 5910.1 MeV ( $J^P = 1/2^-$ ) and 5921.5 MeV ( $J^P = 3/2^-$ ), which admit a natural identification with the two  $\Lambda_b$  resonances observed in [1]. Their masses lie below all two-body channels thresholds considered in our calculations. The lowest in mass  $J^P = 1/2^-$   $\Lambda_b$  resonance is located at 5797.6 MeV, and decays radiatively to  $\Lambda_b\gamma$ . The other spin-1/2 baryon resonance in this sector has a mass of 6009.3 MeV, which is above the  $\Sigma_b\pi$  threshold, but with less than 0.5 MeV width due to small coupling.

We find that the states  $\Lambda_b(5912)$  and  $\Lambda_b^*(5920)$  are HQSS partners. These two states would be a part of a  $3^*$  irreducible representation (irrep) of SU(3), embedded in a **15** irrep of SU(6) (this was checked using the adiabatic symmetry breaking described in [21]). Thus, the light quark structure of these two states is the same, and the coupling of the  $b$ -quark spin with the spin of the light degrees of freedom yields  $J = 1/2$  and  $J = 3/2$ , and  $\Lambda_b(5912)$  and  $\Lambda_b^*(5920)$  states form an approximate degenerate doublet.

As it was already mentioned in the introduction, different quark models [2, 4–7] have also conjectured the existence of one or more excited  $\Lambda_b(1/2^-)$  and  $\Lambda_b(3/2^-)$  states. The early work of Capstick and Isgur [2] generated the first two excited  $\Lambda_b(1/2^-)$  and  $\Lambda_b(3/2^-)$  states with masses that are particularly in very good agreement with the ones observed by the LHCb

Collaboration, but the ground state  $\Lambda_b(1/2^+)$  mass in this scheme is below the experimental one. Our model reproduces the experimental  $\Lambda_b(5912)$  and  $\Lambda_b(5920)$  with an alternative explanation of their nature as molecular states.

### 3.2. $\Xi_b$ and $\Xi_b^*$ states

In this work, we found three  $\Xi_b$  and one  $\Xi_b^*$ , which belong to the same  $SU(3) \times HQSS$  multiplets of the  $\Lambda_b$  and  $\Lambda_b^*$  states introduced in the previous subsection. For the subtraction point in this sector, we use  $\mu^2 = M_{\Xi_b}^2 + m_\pi^2$ . We find a  $\Xi_b(5874)$  spin-1/2 state, which does not have possible hadronic decays, and thus its main decay mode is  $\Xi_b \gamma$ . Further, we find  $\Xi_b(6035.4)$   $J^P = 1/2^-$  and  $\Xi_b(6043.3)$   $J^P = 3/2^-$ , both with negligible width, which lie above the  $\Xi_b \pi$  threshold. The fourth resonance we find in this sector is  $\Xi_b(6072.8)$  with a small width of 0.3 MeV and two possible strong decay modes  $\Xi_b \pi$  and  $\Xi_b' \pi$ . We find that  $\Lambda_b(5797.6)$  and  $\Xi_b(5874)$  belong to the same irreducible representation, and similarly the  $\Lambda_b(6009.3)$  and  $\Xi_b(6072.8)$  states. Also, the pair  $\Xi_b(6035.4)$  and  $\Xi_b^*(6043.3)$ , in the **15** irrep of  $SU(6)$ , form the HQSS doublet related by  $SU(3)$  to the doublet formed by the  $\Lambda_b(5910.1)$  and  $\Lambda_b^*(5921.5)$  states.

None of these beauty-flavored states have been seen experimentally yet. Schemes based on quark models [2, 4–7] predict  $\Xi_b(1/2^-)$  and  $\Xi_b(3/2^-)$  states with similar masses to our estimates, though there exist some differences between the various predictions.

## 4. Summary

We have analyzed odd-parity baryons with one bottom quark by means of a unitarized baryon–meson coupled-channel model which implements heavy-quark spin symmetry. In our model, pseudoscalar and vector heavy mesons are treated on an equal footing. We rely on a relatively simple tree-level interaction already used in the charm sector [20, 21]. This interaction has the virtue of embodying the approximate patterns of chiral symmetry, when Goldstone bosons are involved, and HQSS when heavy hadrons are present. The experimental states  $\Lambda_b^0(5912)$  and  $\Lambda_b^0(5920)$  reported by the LHCb Collaboration are obtained as dynamically generated baryon–meson molecular states. Within our scheme, these states are identified as HQSS partners, what naturally explains their approximate mass degeneracy. Other  $\Lambda_b$  states coming from the same attractive  $SU(6) \times HQSS$  representations are also analyzed. Mass and decay mode predictions are also obtained for  $\Xi_b(1/2^-)$  and  $\Xi_b(3/2^-)$  resonances, which belong to the same  $SU(3)$  multiplets as the  $\Lambda_b(1/2^-)$  and  $\Lambda_b(3/2^-)$  states, and the related underlying symmetry structure is analyzed.

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