We study odd-parity baryonic resonances with one heavy and three light flavors, dynamically generated by meson-baryon interactions. Special attention is paid to Heavy Quark Spin Symmetry (HQSS), hence pseudoscalar and vector mesons and baryons with $J^{π} = 1/2^+$ and $3/2^+$ are considered as constituent hadrons. For the hidden-charm sector ($N_{c} = N_{\bar{c}} = 1$), the meson-baryon Lagrangian with Heavy Flavor Symmetry is constructed by a minimal extension of the SU(3) Weinberg-Tomozawa (WT) Lagrangian to fulfill HQSS, such that no new parameters are needed. This interaction can be presented in different formal ways: as a Field Lagrangian, as Hadron creation-annihilation operators, as SU(6)$\times$HQSS group projectors and as multichannel matrices. The multichannel Bethe-Salpeter equation is solved for odd-parity light baryons, hidden-charm $N$ and $\Delta$ and Beauty Baryons ($\Lambda_b$). Results of calculations with this model are shown in comparison with other models and experimental values for baryonic resonances.

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I. INTRODUCTION

The study of baryonic resonances with charm or beauty is an active field of research, stimulated by current experiments, such as CLEO, Belle and BABAR, as well as planned ones, in PANDA and CBM at FAIR. In this regard hot topics are to find exotic states and to uncover the nature of such resonances, either as most quark model-like or as hadronic molecule-like.

In the molecular description, the baryonic resonance is interpreted as a baryon-meson system. Theoretical work in this direction relies on unitarized coupled-channels dynamics with various kernels[1–16]. The same approach has been applied previously in the strangeness sector[17–30]. In our own approach to the problem we follow this route and use a contact interaction based on extending the Weinberg-Tomozawa term to enjoy SU(6) spin-flavor invariance and to comply with heavy-quark spin symmetry[31–33]. In particular, the latter requirement is unavoidable as HQSS becomes a rather good symmetry already at the charm scale and more so at the bottom scale, and explains noticeable regularities in the properties of the low-lying baryons and mesons with heavy quarks. The enforcement of HQSS has not always been applied in previous approaches and it is one of the strong points of our treatment. Our model applies to the study of odd-parity baryonic states with open or hidden-charm and with or without strangeness and naturally extends to bottom states.

II. THE MODEL

The standard WT interaction takes the form

$$V_{WT} = \frac{K(s)}{2f^2}J_i^p J_i^T,$$

$$i = 1, \ldots, N_F^2 - 1,$$  \hspace{1cm} (1)
where $J_{P,T}$ denote the SU($N_F$) flavor generators for projectile (a pseudo-Goldstone boson) and target (a baryon), with $N_F = 3$, and near threshold $K(s)$ is fixed by the chiral dynamics. Its spin-flavor extension is immediate by using the corresponding SU(2$N_F$) generators. Since spin-flavor multiplets are formed by 0$^-$ and 1$^-$ states in the meson sector and 1/2$^+$ and 3/2$^+$ states in the baryon sector, all these low-lying states are included in the coupled-channels dynamics. For the three flavors, this involves the pion octet and the ρ, and the nucleon octet and the Δ decuplet. Results in this sector have been reported in Ref. [36].

In order to include charm, we first extend the model to $N_F = 4$ and then break SU(4) flavor (and SU(8) spin-flavor) explicitly in order to enforce HQSS. Specifically, the SU(8)-extended meson-baryon WT interaction

$$\mathcal{H}_{WT}^{ed} = -\frac{i}{4f^2} : [\Phi, \partial_\mu \Phi]^A_B \mathcal{B}_{ACD} \mathcal{B}^{BCD} : , \quad A, B, \ldots = 1, \ldots, 2N_F$$

contains two types of contributions, when analyzed in terms of quarks. The first type of contributions corresponds to pure exchange of quarks/antiquarks between meson and baryon, while the second type corresponds to the antiquark annihilation with a quark of the baryon (followed by antiquark-quark creation). Heavy quark-antiquark annihilation violates HQSS and such terms are suppressed in QCD by a factor proportional to the inverse of the heavy quark mass. For simplicity we completely remove those terms, thus guaranteeing exact HQSS of our model. The interaction so obtained enjoys chiral symmetry and full SU(6) × HQSS invariance, however the latter invariance is actually broken in our calculations by using the physical values for the hadron masses and the meson decay constants. The model contains no free parameters. The only freedom lies in the choice of the baryon-meson loop renormalization, for which we apply the prescription in Refs. [4, 5].

An analysis of the allowed interactions consistent with flavor SU(3) and HQSS in the hidden-charm sector (meson-baryon states with exactly one charm quark and one charm antiquark) shows that twelve independent interactions are allowed, corresponding to the Lagrangians:

$$\mathcal{L}_1(x) = g_1 \Sigma_\nu \Sigma^\nu a \text{tr}(\bar{\psi} \overset{\leftrightarrow}{i \partial_\mu} \psi),$$
$$\mathcal{L}_2(x) = g_2 \frac{1}{3!} \Sigma^\mu_{abc} \Delta_{abc} \text{tr}(\bar{\psi} \overset{\leftrightarrow}{i \partial_\mu} \psi),$$
$$\mathcal{L}_3(x) = g_3 \Sigma^\mu \Sigma^\mu a \text{tr}(\bar{\psi} \overset{\leftrightarrow}{i \partial_\mu} \psi),$$
$$\mathcal{L}_4(x) = g_4 \Sigma^\mu_{abc} \Sigma_{abc} \text{tr}(\bar{\psi} \overset{\leftrightarrow}{i \partial_\mu} \psi),$$
$$\mathcal{L}_5(x) = g_5 \frac{1}{2} \Sigma_{abc} \Sigma_{abc} \text{tr}(\bar{\psi} \overset{\leftrightarrow}{i \partial_\mu} \psi),$$
$$\mathcal{L}_6(x) = g_6 \Sigma_{eab} \Sigma_{ca} \text{tr}(\bar{D}_b \overset{\leftrightarrow}{i \partial_\mu} D^b),$$
$$\mathcal{L}_7(x) = g_7 \Sigma_{eab} \Sigma_{ca} \text{tr}(\bar{D}_b \overset{\leftrightarrow}{i \partial_\mu} D^b),$$
$$\mathcal{L}_8(x) = g_8 \Sigma_{eab} \Sigma_{ca} \text{tr}(\bar{D}_b \overset{\leftrightarrow}{i \partial_\mu} D^b),$$
$$\mathcal{L}_9(x) + \mathcal{L}_{10}(x) = \frac{1}{2} \Sigma_{eab} \Sigma_{ca} \text{tr}(\bar{D}_b \overset{\leftrightarrow}{i \partial_\mu} D^b),$$
$$\mathcal{L}_{11}(x) + \mathcal{L}_{12}(x) = \Sigma_{e} \Sigma_{ab} \Sigma_{ca} \text{tr}(\bar{D}_b \overset{\leftrightarrow}{i \partial_\mu} D^b).$$

Our model gives the following values for the parameters (where we have defined $\hat{g}_i = 4f^2 g_i$):

$$\hat{g}_1 = 0, \quad \hat{g}_2 = 0, \quad \hat{g}_3 = \sqrt{\frac{3}{2}}, \quad \hat{g}_4 = \sqrt{\frac{1}{6}}, \quad \hat{g}_5 = -1, \quad \hat{g}_6 = \frac{1}{2},$$
$$\hat{g}_7 = -\frac{1}{2}, \quad \hat{g}_8 = \frac{1}{2}, \quad \hat{g}_9 = 0, \quad \hat{g}_{10} = 0, \quad \hat{g}_{11} = \frac{1}{2}, \quad \hat{g}_{12} = -\frac{1}{2}.$$

### III. SELECTED RESULTS

The extended WT model just described (as well as its bottomed version) has been applied to a number of cases. Here we touch just three topics.

For the hidden-charm sector, we show results in Table I for N-like and Δ-like baryons. The widths are either zero or small in all cases. The dominant channels in each case are also displayed. The group labels are assigned by adiabatic breaking of the symmetries. The states are arranged into HQSS multiplets. Some of these states are also

| States | Widths | Channels |
|--------|--------|----------|
| N-like | Zero   |          |
| Δ-like | Small  |          |
|        |        |          |
found within other approaches with various values for the mass of the resonances. However, at least for the hidden gauge approach, it has been shown in Ref. 43 that the shifts in mass reflect more the different use of renormalization prescriptions than differences in the interactions themselves.

\[ \Delta M_R = M_R - M_{\Lambda_b(g.s)} \]

**FIG. 1:** Predicted bottomed baryonic states. Also shown are the experimentally observed $\Lambda_b^0(5912)$ and $\Lambda_b^0(5920)$ states and some relevant hadronic thresholds.

**TABLE I:** Odd-parity hidden-charm $N$ and $\Delta$ resonances found within the model, with their group labels, mass, dominant couplings, isospin and spin. Resonances with equal SU(6) $\times$ HQSS and SU(3) $\times$ HQSS labels form HQSS multiplets, and they are collected in consecutive rows.

| SU(6) $\times$ HQSS | SU(3) $\times$ HQSS | $M_R$ [MeV] | Couplings to main channels | $I$ | $J$ |
|---------------------|---------------------|------------|---------------------------|-----|-----|
| $70_{2,0}$ (82)      | $2_0$               | 3918.3     | $g_{\Lambda_b^0} = 3.1$, $g_{\Sigma_b^0} = 2.6$, $g_{\Xi_b^0} = 2.6$ | 1/2 | 1/2 |
| $70_{2,0}$ (82)      | $2_0$               | 3926.0     | $g_{\Lambda_b^0} = 3.0$, $g_{\Sigma_b^0} = 4.2$ | 1/2 | 1/2 |
| $70_{2,0}$ (82)      | $2_0$               | 3946.1     | $g_{\Lambda_b^0} = 3.4$, $g_{\Sigma_b^0} = 3.6$ | 1/2 | 3/2 |
| $70_{2,0}$ (84)      | $2_0$               | 3974.3     | $g_{\Lambda_b^0} = 3.4$, $g_{\Sigma_b^0} = 3.1$ | 1/2 | 1/2 |
| $70_{2,0}$ (84)      | $2_0$               | 3986.5     | $g_{\Lambda_b^0} = 2.7$, $g_{\Sigma_b^0} = 4.3$ | 1/2 | 3/2 |
| $70_{2,0}$ (84)      | $2_0$               | 4005.8     | $g_{\Lambda_b^0} = 3.2$, $g_{\Sigma_b^0} = 4.2$ | 1/2 | 3/2 |
| $70_{2,0}$ (84)      | $2_0$               | 4027.1     | $g_{\Sigma_b^0} = 5.6$ | 1/2 | 5/2 |
| $70_{2,0}$ (10)      | $2_0$               | 4005.8     | $g_{\Sigma_b^0} = 2.7$, $g_{\Xi_b^0} = 4.4$ | 3/2 | 1/2 |
| $70_{2,0}$ (10)      | $2_0$               | 4032.5     | $g_{\Sigma_b^0} = 2.9$, $g_{\Xi_b^0} = 4.1$ | 3/2 | 3/2 |
| $70_{2,0}$ (10)      | $2_0$               | 4050.0     | $g_{\Sigma_b^0} = 1.9$, $g_{\Xi_b^0} = 5.1$ | 3/2 | 1/2 |
| $56_{2,0}$ (10)      | $2_0$               | 4306.2 (cusp) | $g_{\Delta J/\psi} = 1.3$ | 3/2 | 1/2 |
| $56_{2,0}$ (10)      | $2_0$               | 4306.8 (cusp) | $g_{\Delta J/\psi} = 0.8$ | 3/2 | 3/2 |

The negative charm baryons are exotic as they are necessarily pentaquarks rather than three-quark states. In this sector several states are obtained within our model. Of particular interest is the isoscalar strangeless $1/2^-$ baryon at 2805 MeV. This is a bound state of $DN$ with a large component of $D^*N$ (this state is part of a HQSS doublet). The binding energy is just 1 MeV, and the same prediction has been obtained in Ref. 44, also by enforcing HQSS. This state plays an important role in the dynamics of $D$-nucleus systems, including $D^-$ mesic atoms and $D^0$ mesic nuclei. As discussed in Ref. 45, $DN$ is the lightest hadronic channel for those quantum numbers. This means that, after Coulomb and particle-hole cascading, a $D^-$ would remain inside the nucleus, perhaps forming a pentaquark, awaiting for weak decay.

Finally, we present results for $1/2^-$ and $3/2^-$ $\Lambda_b$ baryons. Such states have recently been found by the LHCb Collaboration with masses remarkably close to those predicted by the relativized quark model. The same states are dynamically generated within our model as part of a full SU(3) $\times$ HQSS multiplet which also involves $\Xi_b$ states with $J = 1/2$ and $3/2$, not yet observed. This is displayed in Fig. 1, together with relevant hadronic thresholds. We find a close analogy with the strange and charm sectors. In particular, $\Lambda_b(5912)$ is part of a two-pole structure similar to that present in the $\Lambda(1405)$ and $\Lambda_c(2995)$ resonances.
IV. SUMMARY

We have reviewed a model for dynamically generated odd-parity baryon resonances with charm or bottom, through coupled-channels unitarization. The model is a minimal one based on chiral, spin-flavor and heavy-quark spin invariances and it has no free parameters in the interaction. Results have been reported in several sectors.

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