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Heavy-quark spin symmetry for charmed and strange baryon resonances

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Abstract

We study charmed and strange odd-parity baryon resonances that are generated dynamically by a unitary baryon-meson coupled-channels model which incorporates heavy-quark spin symmetry. This is accomplished by extending the SU(3) Weinberg-Tomozawa chiral Lagrangian to SU(8) spin-flavor symmetry plus a suitable symmetry breaking. The model generates resonances with negative parity from the s-wave interaction of pseudoscalar and vector mesons with $1/2^+$ and $3/2^+$ baryons in all the isospin, spin, and strange sectors with one, two, and three charm units. Some of our results can be identified with experimental data from several facilities, such as the CLEO, Belle, or BaBar Collaborations, as well as with other theoretical models, whereas others do not have a straightforward identification and require the compilation of more data and also a refinement of the model.

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1. Introduction

The properties of heavy-flavored hadronic resonances have attracted a lot of attention lately. The study of such states can help in the interpretation of the nature of particles found in past and ongoing experiments (e.g. CLEO, BaBar, Belle, LHCb) [1], as well as in understanding states which will be discovered in future experiments (e.g. PANDA at GSI [2]). It is important to understand whether baryon (meson) resonances can be described as excited three-quark (quark-antiquark) states or rather as hadron molecules; also a combined interpretation of such states is possible.

At present there is a lack of a robust scheme to systematically construct an effective field theory approach to study four flavor physics. Some steps in that direction have been taken by recent studies using coupled-channels models. Among them one can find unitarized coupled-channels models [3, 4, 5, 6], the Jülich meson-exchange model [7] and schemes based on hidden gauge formalism [8]. These models are not fully consistent with the heavy-quark spin symmetry (HQSS) [9], which is a proper symmetry of Quantum Chromodynamics (QCD) in the limit of infinitely heavy quark masses. There have also been some attempts to build a scheme based on chiral perturbation theory for hadrons which contain heavy quarks [10]. Moreover, an effective theory which incorporates heavy-quark, chiral and

hidden local gauge symmetries was developed for studying baryon-baryon interactions [11]. Besides, an SU(8) spin-flavor symmetric unitarized coupled-channels model has been recently developed and used for various numbers of charm and strangeness [12, 13].

In this paper we study dynamically-generated baryon resonances, using the SU(8) spin-flavor model. We have paid special attention to analyze the underlying symmetry of the interaction. In particular, we have studied the original group multiplets from where each of the found baryon resonances originates and obtained the different HQSS multiplets. Our studies covered states with charm and strangeness, and in the following sections we will show and discuss our results for baryon resonances with charm $C = 1$, namely Λ_c (strangeness $S = 0$, isospin $I = 0$), Σ_c ($S = 0$, $I = 1$), Ξ_c ($S = -1$, $I = 1/2$) and Ω_c ($S = -2$, $I = 0$).

2. Theoretical framework

We use the SU(8) spin-flavor model of [12, 13]. The interaction potential is an extension of the SU(3) chiral Weinberg-Tomozawa potential to the SU(8) symmetry. In this model vector mesons are treated on equal footing with pseudoscalar mesons and both spin-1/2 and spin-3/2 baryons are taken into account. We only consider s-wave interaction, which is appropriate close to the meson-baryon thresholds. In this SU(8) scheme the mesons fall in the **63**-plet, and the baryons are placed in the **120**-plet. Consequently, in the s-channel, the baryon-meson space reduces into four SU(8) irreps, three of which (**120**, **168** and **4752**) are attractive. We find that the multiplets **120** and **168** are the most attractive ones, and therefore we have concentrated our study on the states which belong to these two irreps in the SU(8) symmetric limit.

We consider the reduction of the SU(8) symmetry $SU(8) \supset SU(6) \times SU_C(2) \times U_C(1)$, where SU(6) is the spin-flavor group for three light flavors, $SU_C(2)$ is the charm quark rotation group, and $U_C(1)$ is the group generated by the charm quantum number C . The SU(6) multiplets can be reduced under $SU(3) \times SU_I(2)$, where $SU_I(2)$ refers to the spin of the light quarks. We further reduce $SU_I(2) \times SU_C(2) \supset SU(2)$ where SU(2) refers to the total spin J ; in this way we make the connection with the labeling (C, S, I, J) .

The contact tree-level meson-baryon interaction of the extended SU(8) symmetric Weinberg-Tomozawa potential reads

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

Here, i and j are the outgoing and incoming baryon-meson channels; M_i , E_i , and f_i stand, respectively, for the mass and the center-of-mass energy of the baryon and the meson decay constant in the i channel; D_{ij} are the matrix elements for the various $CSIJ$ sectors considered in this work, which can be found in the Appendices of [12, 14].

The scattering amplitudes are calculated by solving the on-shell Bethe-Salpeter equation in the coupled channels:

$$T(s) = \frac{1}{1 - V(s)G(s)} V(s). \quad (2)$$

Here $G(s)$ is a diagonal matrix containing the baryon-meson propagator for each channel, and D , T and V are matrices in coupled-channels space.

The bare loop function $G_{ii}^0(s)$ is logarithmically ultraviolet divergent and needs to be renormalized. We have renormalized our amplitudes by using a subtraction point regularization, with a subtraction point $\sqrt{s} = \mu_i = \sqrt{m_{\text{th}}^2 + M_{\text{th}}^2}$, where m_{th} and M_{th} are, respectively, the masses of the meson and the baryon of the channel with the lowest threshold in the given CSI sector,

$$G_{ii}(s) = G_{ii}^0(s) - G_{ii}^0(\mu_i^2). \quad (3)$$

In order to get a better fine-tuning with the experimental data, one can define the subtraction point as $\mu_i = \sqrt{\alpha(m_{\text{th}}^2 + M_{\text{th}}^2)}$, with α being slightly different from one.

The baryon resonances are obtained as poles of the scattering amplitude on the complex-energy plane. The mass m_R and the width Γ_R of the state can be obtained from the coordinate $\sqrt{s_R}$ of the corresponding pole on the complex energy \sqrt{s} plane, $\sqrt{s_R} = m_R - \frac{i}{2}\Gamma_R$, and the couplings to the meson-baryon channels can be found from the residues of the T -matrix around the pole.

The matrix elements D_{ij} display exact SU(8) invariance, but this symmetry is severely broken in nature. Therefore we implement symmetry-breaking mechanisms. It should be mentioned here that we have removed the channels with the $c\bar{c}$ pairs to be consistent with the HQSS. In the present work we use physical values for the masses of the hadrons and for the decay constants of the mesons. The symmetry is broken following the chain $SU(8) \supset SU(6) \supset SU(3) \supset SU(2)$, where the last group SU(2) refers to isospin. This symmetry breaking was performed by adiabatic change of the hadron masses and meson weak decay constants. In this way we can label each baryon resonance with the original group multiplet and define the HQSS multiplets.

3. Dynamically generated baryon resonances

Let us begin with the Λ_c states. Our model generates four Λ_c baryon resonances, three with spin $J = 1/2$ and one with $J = 3/2$. By comparing the dominant channels with the decay channels of the experimental states, two of our Λ_c 's have been identified with experimentally known states. We identify the experimental $\Lambda_c(2595)$ resonance with the state that we found around $2618.8 - i0.6$ MeV. The experimental value of the width of $\Lambda_c(2595)$ $3.6_{-1.3}^{+2.0}$ MeV is not reproduced, due to the fact that we have not included the three-body decay channel $\Lambda_c\pi\pi$, which already represents almost one third of the decay events [15]. Our result for $\Lambda_c(2595)$ agrees with the results from t -channel vector-meson exchange (TVME) models [4, 5], but, as it was first pointed out in Ref. [12], we claim a dominant ND^* component in its structure, whereas in the TVME model the $\Lambda_c(2595)$ is generated mostly as a ND bound state. We also obtain a broad resonance with a mass very close to the $\Lambda_c(2595)$, namely at 2617.3 MeV. It couples strongly to the open channel $\Sigma_c\pi$. The other pole with $J = 1/2$ that we find around $2828 - i0.4$ MeV has not been identified with any known experimental state.

In the $J = 1/2$ sector there are 16 coupled channels, which can generate Λ_c resonances. Every found baryon resonance couples strongly only to some of the coupled channels, see [14]. Therefore, we study how the features (masses, widths and couplings) of the Λ_c resonances change, when we consider only the dominant meson-baryon coupled channels. It turns out that the masses and widths, as well as couplings do not change drastically when we only consider the restricted coupled-channels space. The width of the $\Lambda_c(2617.3)$ resonance increases from 89.8 to 97.3 MeV, whereas the mass and the coupling to the $\Sigma_c\pi$ stay unchanged. The $\Lambda_c(2618.8)$ resonance slightly increases its mass by 2.6 MeV, and the width decreases from 1.2 to 1.1 MeV, while the coupling to ND^* channel remains almost the same. Finally, the mass of the $\Lambda_c(2828.4)$ state raises by 8.6 MeV, and its width is now 1.0 MeV; the couplings to the dominant $\Lambda_c\eta$ and $\Sigma_c^*\rho$ channels slightly vary.

Further, we find one Λ_c resonance with $J = 3/2$ located at $(2666.6 - i26.7)$ MeV. We identify this resonance with the experimental $\Lambda_c(2625)$ [15]. The experimental $\Lambda_c(2625)$ has a very narrow width, $\Gamma < 0.97$ MeV, and decays mostly to $\Lambda_c\pi\pi$. By changing the subtraction point, such that the mass of the resonance is closer to the value of the experimental one, the phase space would be reduced. A similar resonance was found at 2660 MeV in the TVME model of Ref. [6]. However, in our calculation we obtain a non-negligible contribution from the baryon-vector meson channels to the generation of this resonance, as already observed in Ref. [12]. When restricting the number of coupled channels to the four ones, to which $\Lambda_c^*(2666.6)$ couples the most, namely $\Sigma_c^*\pi$, ND^* , $\Sigma_c\rho$ and $\Sigma_c^*\rho$, the resonance features are changed as follows. The mass somewhat increases by 1.2 MeV, while the width grows by 8.2 MeV, and couplings remain almost unchanged.

We obtain three spin-1/2 Σ_c resonances, with masses 2571.5, 2622.7 and 2643.4 MeV. These states are predictions of our model, since there is no experimental data in this energy region. In the SU(4) model of Ref. [5] two Σ_c spin-1/2 resonances are predicted. In this reference, the first Σ_c resonance has a mass 2551 MeV and a width of 0.15 MeV, and it can be associated with the $\Sigma_c(2572)$ state of our model which we generate with the width $\Gamma = 0.8$ MeV. However, in our model this resonance couples most strongly to the channels which incorporate vector mesons, whereas in Ref. [5] it is not the case. The other resonance predicted in Ref. [5] cannot be compared to any of our results. Further, we obtain two spin-3/2 Σ_c resonances. The first one, a bound state at 2568.4 MeV, lies below the threshold of any possible decay channel and is thought to be the charmed counterpart of the hyperonic $\Sigma(1670)$ resonance. The second state at $2692.9 - i33.5$ MeV has no direct comparison with the available experimental data.

Our model generates six Ξ_c states with $J = 1/2$ and three ones with $J = 3/2$. In this sector there are two negative-parity experimentally known resonances that can be identified with some of our dynamically-generated states, namely experimental $\Xi_c(2790)$ $J^P = 1/2^-$ and $\Xi_c(2815)$ $J^P = 3/2^-$ [15]. The state $\Xi_c(2790)$ has a width of $\Gamma < 12 - 15$ MeV and it decays to $\Xi_c'\pi$, with $\Xi_c' \rightarrow \Xi_c\gamma$. We assign it to the $2804.8 - i13.5$ MeV state found in our model because of the

large $\Xi_c'\pi$ coupling. A slight modification of the subtraction point can lower the position of our resonance to 2790 MeV and most probably reduce its width as it will get closer to the $\Xi_c'\pi$ channel. It could be also possible to identify our pole at 2733 MeV with the experimental $\Xi_c(2790)$ state. In that case, one would expect that if the resonance position gets closer to the physical mass of 2790 MeV, its width will increase and it will easily reach values of the order of 10 MeV. The full width of the experimental Ξ_c resonance with $J^P = 3/2^-$ is expected to be less than 3.5 MeV for $\Xi_c^+(2815)$ and less than 6.5 MeV for $\Xi_c^0(2815)$, and the decay modes are $\Xi_c^+\pi^+\pi^-$, $\Xi_c^0\pi^+\pi^-$. We obtain two resonances at $2819.7 - i16.2$ MeV and $2845.2 - i22.0$ MeV, respectively, that couple strongly to $\Xi_c^*\pi$, with $\Xi_c^* \rightarrow \Xi_c\pi$. Allowing for this possible indirect three-body decay channel, we might identify one of them to the experimental result. This assignment is possible for the state at 2845.2 MeV if we slightly change the subtraction point, which will lower its position and reduce its width as it gets closer to the threshold of the open $\Xi_c^*\pi$ channel.

We obtain three Ω_c bound states with masses 2810.9, 2884.5 and 2941.6 MeV. There is no experimental information on those excited states. However, our predictions can be compared to recent calculations of Ref. [5]. In this work three Ω_c resonances are predicted, with masses higher than the ones of our resonances by approximately 100 MeV. Further, we obtain two spin-3/2 bound states Ω_c with masses 2814.3 and 2980.0 MeV, which mainly couple to ΞD^* and $\Xi^* D^*$, and to $\Xi_c^* \bar{K}$, respectively. As in the $J = 1/2$ sector, no experimental information is available here.

4. Summary

Charmed baryon resonances, in particular Λ_c , Σ_c , Ξ_c and Ω_c odd-parity states have been studied within a coupled-channels unitary approach that implements HQSS. For this purpose the SU(8) spin-flavor symmetric model of Ref. [12] has been used. We have obtained four Λ_c baryon resonances, two of which can be identified with the experimental $\Lambda_c(2595)$ and $\Lambda_c(2625)$ states. When the number of coupled channels is reduced to the dominant ones, the features (mass, width, coupling constants) of the corresponding resonance do not change significantly. Further, five Σ_c and nine Ξ_c resonances are obtained. Some of our resonances can be identified with experimentally known Σ_c and Ξ_c states, while others require the compilation of more data and a refinement of the model.

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