Chinese Physics C

Charmed baryon resonances with heavy-quark symmetry[*]

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Abstract   We study charmed baryon resonances that are generated dynamically from a coupled-channel unitary approach that implements heavy-quark symmetry. Some states can already be identified with experimental observations, such as $\Lambda_c(2595)$, $\Lambda_c(2660)$, $\Sigma_c(2902)$ or $\Lambda_c(2941)$, while others need a compilation of more experimental data as well as an extension of the model to include higher order contributions. We also compare our model to previous $SU(4)$ schemes.

Key words   charmed baryon resonances, heavy-quark symmetry, $SU(8)$ and $SU(4)$ spin-flavor symmetry

PACS   14.20.Lq, 11.10.St, 12.38.Lg

1   Introduction

Charmed baryon resonances have received recently a lot of attention in connection with the discovery of some new states by the CLEO, Belle and BABAR collaborations[1—4]. In fact, one of the challenges in hadron physics over the last years is to establish whether a resonance has the usual q$\bar{\text{q}}$ or qqq structure, or it better qualifies as being dynamically generated via unitarized meson-baryon scattering processes. The extension to the charm sector of the unitarized meson-baryon method in coupled channels was initially attempted in Ref. [5], where the free space amplitudes were constructed from a set of separable coupled-channel interactions obtained from chirally motivated lagrangians upon replacing the s quark by the c quark. A different approach resulting from the scattering of Goldstone bosons off the ground state $1/2^+$ charmed baryons was pursued in[6], but the substantial improvement in construct-

ing the meson-baryon interaction in the charm sector came from exploiting the universal vector-meson coupling hypothesis to break the $SU(4)$ symmetry[7]. The t-channel exchange of vector mesons (TVME) between pseudoscalar mesons and baryons preserved chiral symmetry in the light meson sector keeping the Weinberg-Tomozawa (WT) type of interaction. An extension to d-wave $J = 3/2^-$ resonances was developed in Ref. [8], while some modifications over the model of Ref. [7] were implemented in Ref. [9], both in the kernel and in the renormalization scheme. More recently, there have been attempts to construct the DN and $\bar{\text{D}}$N interaction by incorporating the charm degree of freedom in the $SU(3)$ meson-exchange model of the Jülich group[10].

However, those $SU(4)$ TVME inspired models are not consistent with heavy-quark symmetry (HQS), which is a proper QCD spin-flavor symmetry that appears when the quark masses, such as the charm mass, become larger than the typical confinement scale. As a consequence of this symmetry, the spin in-

teractions vanish for infinitely massive quarks. Thus, heavy hadrons come in doublets (if the spin of the light degrees of freedom is not zero), which are degenerated in the infinite quark-mass limit. First attempts were done in the strange sector by means of a scheme that starts from a $SU(6)$ spin-flavor symmetry Lagrangian and that incorporates some symmetry breaking corrections determined by physical masses and meson decay constants[11—13]. The corresponding Bethe-Salpeter equation reproduces the previous $SU(3)$-flavor WT results for the lowest-lying s- and d-wave, negative parity baryon resonances and gives new information on more massive states, as for example the $\Lambda(1800)$ or $\Lambda(2325)$ resonances.

In this paper, we extend this scheme to four flavors, incorporating the charm degree of freedom[14]. This approach automatically incorporates HQS in the charm sector improving in this respect on the $SU(4)$ TVME models. We focus on non-strange single charmed resonances close to their relevant thresholds and compare our results to the previous $SU(4)$ models. Of several novelties, we find that the dynamics of the lowest lying resonance $\Lambda_c(2595)$ is completely dominated by the DN channel in the $SU(4)$ TVME model[7], while it turns out be largely a D*N state within the $SU(8)$ scheme[14].

2 $SU(8)$ extension of the WT meson-baryon lagrangian

The WT Lagrangian is not only $SU(3)$ symmetric but also chiral invariant. Symbolically, up to an overall constant, the WT interaction is

$$\mathcal{L}_{\mathrm{WT}} = \mathrm{Tr}([M^\dagger, M][B^\dagger, B]), \qquad (1)$$

where mesons (M) and baryons (B) fall in the $SU(3)$ representation **8**, which is the adjoint representation. The commutator indicates a t-channel coupling to the **8**$_a$ (antisymmetric) representation. Assuming the $SU(8)$ spin-flavor symmetry, the mesons M fall now in the **63** (adjoint representation) and the baryons B are found in the **120**, which is fully symmetric. The group reduction lead to a total of four different t-channel $SU(8)$ singlet couplings[14], that can be used to construct s-wave meson-baryon interactions. However, to ensure that the $SU(8)$ amplitudes will reduce to those deduced from the $SU(3)$ WT Lagrangian in the (**8**$_1$)meson-(**8**$_2$)baryon subspace (denoting the $SU(3)$ multiplets of dimensionality $\boldsymbol{n}$ and spin J by $\boldsymbol{n}_{2J+1}$), we set all the couplings to be zero except for

$$\mathcal{L}_{\mathrm{WT}}^{SU(8)} = \left((M^\dagger \otimes M)_{\mathbf{63}_a} \otimes (B^\dagger \otimes B)_{\mathbf{63}}\right)_1, \qquad (2)$$

which is the natural and unique $SU(8)$ extension of the usual $SU(3)$ WT Lagrangian. To compute the matrix elements of the $SU(8)$ WT interaction, $\mathcal{L}_{\mathrm{WT}}^{SU(8)}$, we use quark model constructions of hadrons with field theoretical methods to express everything in tensor representations as described in Appendix A of Ref. [14]. Since $SU(8)$ spin-flavor symmetry is strongly broken in nature, we implement mass-breaking effects by adopting the physical hadron masses in the tree level interactions and in the evaluation of the kinematical thresholds of different channels. Moreover, we consider the difference between the weak non-charmed and charmed pseudoscalar and vector meson decay constants. Then, our tree level amplitudes read

$$V_{ab}^{IJSC}(\sqrt{s}) =$$
$$D_{ab}^{IJSC} \frac{2\sqrt{s} - M_a - M_b}{4 f_a f_b} \sqrt{\frac{E_a + M_a}{2M_a}} \sqrt{\frac{E_b + M_b}{2M_b}}, \quad (3)$$

where $IJSC$ are the meson-baryon isospin, total angular momentum, strangeness and charm quantum numbers, M_a (M_b) and E_a (E_b) the mass and the CM energy, respectively, of the baryon in the a (b) channel, f_a (f_b) the weak decay constant of the meson in the a (b) channel, and D^{IJSC} a matrix of coefficients in the coupled-channel space[14].

3   Non-strange single charmed baryon resonances

With the kernel of the $SU(8)$ WT meson-baryon interaction given in Eq. (3), we solve the coupled-channel on-shell Bethe-Salpeter equation

$$T^{IJSC}(\sqrt{s}) =$$
$$\frac{1}{1 - V^{IJSC}(\sqrt{s}) G^{0\,(IJSC)}(\sqrt{s})} V^{IJSC}(\sqrt{s}). \quad (4)$$

The loop function for each channel a, $G_a^{0\,(IJSC)}(\sqrt{s})$, is divergent and is regularized by one-subtraction at the subtraction point μ^{ISC}

$$G_a^{0\,(IJSC)}(\sqrt{s} = \mu^I) = 0,$$
$$(\mu^{ISC})^2 = \alpha (m_{\mathrm{th}}^2 + M_{\mathrm{th}}^2), \qquad (5)$$

where m_{th} and M_{th} are the meson and baryon masses of the hadronic channel with lowest mass threshold for a fixed ISC and arbitrary J. The value of $\alpha = 0.9698$ is adjusted to reproduce the position of the well established $\Lambda_c(2595)$ resonance with $IJSC = (0, 1/2, 0, 1)$.

The mass and widths of the dynamically generated baryon resonances are determined by the pole position, z_R, in the second Riemann sheet of the

corresponding scattering amplitudes, namely $M_R = \mathrm{Re}(z_R)$ and $\Gamma_R = -2\,\mathrm{Im}(z_R)$. The coupling constants of each resonance to the various baryon-meson states are obtained from the residues by fitting the amplitudes to

$$T_{ij}^{IJSC}(z) = \frac{g_i e^{i\phi_i} g_j e^{i\phi_j}}{(z - z_R)} \ , \qquad (6)$$

for complex energy values z close to the pole, where the complex couplings are written in terms of the absolute value, g_k, and phase, ϕ_k. We will examine the ij-channel independent quantity

$$\tilde{T}^{IJSC}(z) \equiv \max_j \sum_i |T_{ij}^{IJSC}(z)| \ , \qquad (7)$$

which allows us to identify all the resonances within a given sector at once. Among all dynamically generated baryon resonances of Ref. [14], we focus on nonstrange ($S = 0$) and singly charmed ($C = 1$) baryon resonances in the $I = 0$ and $I = 1$ sectors that have or might have experimental confirmation[15] and compare to $SU(4)$ results[6, 7, 9]. Note that the spin-parity of some resonances, such as the $\Sigma_c(2800)$ and $\Lambda_c(2940)$, are not determined yet experimentally.

3.1 $I = 0$, $J = 1/2$

In the $I = 0$, $J = 1/2$ sector we obtain the $\Lambda_c(2595)$ resonance with a width of 0.58 MeV, that is smaller than the experimental one of $\Gamma = 3.6^{+2.0}_{-1.3}$[15]. This can be explained by the fact that in our calculation we have not included the three-body decay channel $\Lambda_c\pi\pi$, which represents one-third of the decay events[15]. We also observe a second resonance, $\Lambda_c(2610)$, very close to $\Lambda_c(2595)$, which seems to follow the double-pole pattern of the strange counterpart $\Lambda(1405)$[16]. In our $SU(8)$ scheme we find that the $\Lambda_c(2595)$ resonance is a predominantly ND* quasibound state as compared to $SU(4)$ models where it emerges as ND quasibound state.

Other dynamically generated resonances at higher energies are the $\Lambda_c(2822)$ and $\Lambda_c(2938)$ resonances. The first one is a $\Xi_c K$ which does not correspond to the experimental $\Lambda_c(2880)$[15] because of different spin-parity, but it is not incompatible with the pD^0 histogram[4]. On the other hand, the $\Lambda_c(2938)$ cannot correspond to the experimental $\Lambda_c(2940)$[15] because it does not couple to ND states or not preferentially to ND*, as discussed in[17].

3.2 $I = 1$, $J = 1/2$

In this sector we do not find any resonance between 2800 MeV and 3000 MeV which could correspond to the experimental $\Sigma_c(2800)$[15], because all the dynamically generated resonances in this energy region within the $SU(8)$ scheme[14] fail to decay primarily in $\Lambda_c\pi$ states although they couple quite significantly to ND ones. Also our $\Sigma_c(3096)$ resonance cannot be identified with the experimental $\Sigma_c(2800)$ because this resonant state lies too high in mass to be moved to lower energies by changing the subtraction point. Likewise our $\Sigma_c(3035)$ resonance would be too narrow if it were moved to lower energies to make it compatible with the experimental $\Sigma_c(2800)$, even if the $\Lambda_c\pi\pi$ decay is allowed.

Our $\Sigma_c(2974)$ resonance might correspond to the observed enhancement in the $I = 1$ D$^+$p histogram around 2860 MeV with a width of 10 MeV[4], if we lower its mass by changing the subtraction point as it will also reduce its width due to the closing of two out of three decaying channels.

3.3 $I = 0$, $J = 3/2$

The experimental $\Lambda_c(2625)$ and $\Lambda_c(2940)$[15] might be seen in the $I = 0$, $J = 3/2$ sector. The $\Lambda_c(2625)$ with a width less than 2 MeV is the counterpart in the charm sector of the $\Lambda(1520)$. This resonance can be identified with our $\Lambda_c(2660)$ with a width of 38 MeV, which couples very strongly to the $\Sigma_c^*\pi$ channel. Changes in the subtraction point will move this resonance downwards and it will become substantially narrower as soon as it is relocated below the $\Sigma_c^*\pi$ threshold. On the other hand, the dynamically generated $\Lambda_c(2941)$ might be the experimental $\Lambda_c(2940)$ if we implement p-wave interactions in our $SU(8)$ scheme in order to account for the D^{0}p decay[4].

3.4 $I = 1$, $J = 3/2$

In this last sector we obtain the $\Sigma_c(2550)$ resonance, which couples strongly to ΔD and ΔD* states. This state could be identified as the counterpart in the charm sector of the $\Sigma(1670)$, which decays primarily to $\Delta\bar{K}$. However, there is no experimental evidence so far. Moreover, our $\Sigma_c(2902)$ state in the $I = 1$, $J = 3/2$ sector of the $SU(8)$ scheme might be identified with the experimental $\Sigma_c(2800)$ if this resonance could also be seen in $\Lambda_c\pi\pi$ states.

4   Comparison with $SU(4)$ models

Compared to $SU(4)$ TVME models[7, 9], the $SU(8)$ scheme includes vector mesons in order to be consistent with heavy-quark symmetry. Another essential difference lies in the fact that the transition amplitudes between states with heavy mesons go as the inverse of a heavy-meson decay constant for each

heavy meson involved, whereas in the $SU(4)$ models the decay constant is kept fixed for all transitions. As a result, we find that the $SU(8)$ model reproduces all resonances generated in the $SU(4)$ approaches that couple strongly to the channels consisting of a pseudoscalar octet meson and a charmed baryon. On the other hand, due to the different pattern of flavor symmetry breaking, resonances in the $SU(4)$ models that couple strongly to baryon-meson states containing a charmed meson and an uncharmed baryon are not necessarily reproduced within our $SU(8)$ approach. However, the enlarged model space in $SU(8)$ due to heavy-quark symmetry compensates largely for the reduced attraction, generating the same resonances as in the $SU(4)$ models but with a quite different composition. This is the case of the $\Lambda_c(2595)$ resonance in the $I = 0$, $J = 1/2$ sector. Within $SU(4)$ models this resonance is dynamically generated mainly from ND states. Instead, the $SU(8)$ scheme interprets this resonance as being mainly a ND* quasibound state.

5 Conclusions and outlook

In this work we study charmed baryon resonances within a coupled-channel unitary approach that implements heavy-quark symmetry. This is achieved by extending the t-channel vector-meson exchange $SU(4)$ models to $SU(8)$ spin-flavor symmetry and, then, implementing a somewhat different way of breaking the flavor symmetry through physical hadron masses and introducing the physical weak decay constants of the mesons involved in the transitions.

The $SU(8)$ model generates a broad spectrum

of baryon resonances with negative parity in all the isospin-spin sectors that one can form from an s-wave interaction between the mesons of the 0^-, 1^- multiplets with the $1/2^+$, $3/2^+$ baryons. We focus in the $S = 0$ and $C = 1$ sector and on those resonances which already have or might have an experimental confirmation. In the $I = 0$, $J = 1/2$ we reproduce the experimental $\Lambda_c(2595)$, while in the $I = 0$, $J = 3/2$ we assign the $\Lambda_c(2660)$ to the experimental $\Lambda_c(2625)$, which is the counterpart of the $\Lambda(1520)$. Similarly, in the $I = 1$, $J = 3/2$ we find the $\Sigma_c(2550)$, as the counterpart of $\Sigma(1670)$. In this sector, we might also identify the experimental $\Sigma_c(2800)$ with our $\Sigma_c(2902)$. This broad spectrum of baryon resonances also includes the resonances that were generated in the previous $SU(4)$ models. However, some of them have different nature, as in the case of the $\Lambda_c(2595)$.

In order to make a more realiable comparison with experiments, future work implies the development of a more realistic model which contains three-body channels and higher-multipolarity interactions. We note that the experimental spectra show a limited amount of counts and, in order to disentagle new resonant structures from data, more statistics is definitely needed. The incorporation of medium modifications on those resonances[18] will also give us some insight into the nature of those states as well as the excitation mechanisms in the medium.

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