Vol. 11 (2018) *Acta Physica Polonica B Proceedings Supplement* No 3

DYNAMICAL HADRONS*

V.R. Debastiani, E. Oset

Departamento de Física Teórica and IFIC
Centro Mixto Universidad de Valencia–CSIC
Institutos de Investigación de Paterna
Aptdo. 22085, 46071 Valencia, Spain

J.M. Dias

Instituto de Física, Universidade de São Paulo
Rua do Matão, 1371, Butantã, CEP 05508-090, São Paulo, Brazil

Wei-Hong Liang

Department of Physics, Guangxi Normal University, Guilin 541004, China

(Received August 6, 2018)

In this paper, we briefly review the theory of resonances dynamically generated from hadron–hadron scattering, sometimes referred to as "molecules". We give some classical examples of meson–meson and meson–baryon systems, as well as a few examples of different approaches to describe the interaction between hadrons. To conclude, we comment on a few recent works that suggest that some of the five new narrow Ω_c states, recently discovered by the LHCb Collaboration, can be interpreted as meson–baryon molecules.

DOI:10.5506/APhysPolBSupp.11.475

1. Introduction

There are many states that can be described from hadron–hadron interaction. Some well-known examples are the scalar mesons obtained from pseudoscalar–pseudoscalar interaction in S-wave and coupled channels: the $a_0(980)$ from $K\bar{K}$ and $\pi\eta$ in isospin 1, the $f_0(980)$ from $K\bar{K}$ and $\pi\pi$ in isospin 0, and the $f_0(500)$ (σ meson) from $\pi\pi$ scattering in isospin 0. In the strange sector, from vector–pseudoscalar interaction, one can describe the

* Presented by V.R. Debastiani at "Excited QCD 2018", Kopaonik, Serbia, March 11–15, 2018.

$f_1(1285)$ as a $K^*\bar{K}+$ c.c. molecule. In the charm–strange sector, there is the $D^*_{s0}(2317)$, which can be described as a DK bound state. Similarly, one of the most famous examples in the charm sector is the $X(3872)$ which can be explained as a $D\bar{D}^*+$ c.c. molecule.

These are just a few cases from meson–meson interaction. On the other hand, in meson–baryon interaction, the best example would be the $\Lambda(1405)$, which is widely accepted [1] as a quasi-bound state between the $\bar{K}N$ and $\pi\Sigma$ thresholds, generated mostly from the $\bar{K}N$ scattering. In the charm sector, the $\Lambda_c(2595)$ shows a similar pattern, lying between the DN and $\pi\Sigma_c$ thresholds. Another good example is the $N^*(1535)$, which is also well-described from ηN and πN interaction. In this context, one could wonder if the new Ω_c states [2] could be described from the interaction of $\Xi_c\bar{K}$ and its coupled channels.

2. Chiral Unitary approach and the Local Hidden Gauge

Assuming the on-shell factorization of the Bethe–Salpeter equation, we can obtain a unitarized scattering amplitude, using an effective interaction V where the hadrons are the degrees of freedom,

$$T(s) = [1 - V(s)G(s)]^{-1}V(s)\,, \tag{1}$$

with G the meson–meson or meson–baryon loop function. Then we can look for poles of the amplitude in the complex energy plane, which are related with the mass and width of the resonances by $z_{\mathrm{R}} = M_{\mathrm{R}} - i\Gamma_{\mathrm{R}}/2$.

The meson–baryon interaction in the SU(3) sector can be described by the chiral Lagrangian

$$\begin{aligned}
\mathcal{L}^B &= \frac{1}{4f_\pi^2}\left\langle \bar{B}i\gamma^\mu\Big[(\Phi\,\partial_\mu\Phi - \partial_\mu\Phi\,\Phi)B - B(\Phi\,\partial_\mu\Phi - \partial_\mu\Phi\,\Phi)\Big]\right\rangle\,, \\
\Phi &= \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}\,, \\
B &= \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}\,.
\end{aligned} \tag{2}$$

At energies close to threshold, one can consider only the dominant contribution coming from ∂_0 and γ^0, such that the interaction is given by

$$V_{ij} = -C_{ij}\frac{1}{4f_\pi^2}\left(k^0 + k'^0\right)\,, \tag{3}$$

where k^0 and k'^0 are the energies of the incoming and outgoing mesons, respectively. This framework was used to described the $\Lambda(1405)$ with coupled channels in $\bar{K}N$ scattering [3].

Alternatively, one can use the Local Hidden Gauge Approach (LHGA), where the meson–baryon interaction in SU(3) is obtained exchanging vector mesons. The ingredients needed are the VPP and VBB Lagrangians

$$\mathcal{L}_{VPP} = -ig \langle \, [\Phi, \partial_\mu \Phi] \, V^\mu \, \rangle \,, \tag{4}$$

$$\mathcal{L}_{VBB} = g \left(\left\langle \bar{B}\gamma_\mu [V^\mu, B] \right\rangle + \left\langle \bar{B}\gamma_\mu B \right\rangle \langle V^\mu \rangle \right) \,, \tag{5}$$

where

$$V^\mu = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}^\mu \,, \tag{6}$$

and $g = m_{\mathrm{V}}/2f_\pi$, with m_{V} the mass of the vector mesons (~ 800 MeV).

Taking $q^2/m_{\mathrm{V}}^2 \to 0$ in the propagator of the exchanged vector gives rise to the same interaction of the Chiral Lagrangian.

In our work [4], we have studied meson–baryon molecular states with $C = +1$, $S = -2$, $I = 0$ to investigate if some of the recently discovered Ω_c states [2] can be described as dynamically generated resonances.

Inspired by the Lagrangians of the LHGA, the meson–baryon interaction was described through the exchange of vector mesons. Extending the VPP Lagrangian to the charm sector is simple. We take the same structure including a fourth line and column with the charmed pseudoscalars in Φ and with the charmed vector mesons in V^μ.

Extending the VBB Lagrangian to the charm sector is not so easy. Instead of using SU(4) symmetry, we look at the quark structure of the exchanged vectors like ρ^0, ω and ϕ (which can be extended to K^*, $\rho^\pm$, *etc.*)

$$\rho^0 = \left(u\bar{u} - d\bar{d}\right)/\sqrt{2} \,, \qquad \omega = \left(u\bar{u} + d\bar{d}\right)/\sqrt{2} \,, \qquad \phi = s\bar{s} \,. \tag{7}$$

Within the approximation of $\gamma^\mu \to \gamma^0$, we have no spin dependence in the baryon sector related to the exchanged vector, and we can consider an operator at the quark level. This way, applying the vector meson as a number operator in the wave functions of the baryons, we can get the same result as using $\mathcal{L}_{VBB}$ in SU(3).

With that in mind, we have built spin–flavor wave functions for the baryons involved in our calculations, considering the heavy quark as spectator and using SU(3) symmetry in the light quarks. For instance, for the Ξ_c^+, we have a wave function antisymmetric for the two light quarks, both in flavor and spin

$$\Xi_c^+ = c(us - su) \uparrow (\uparrow\downarrow - \downarrow\uparrow)/2 \,. \tag{8}$$

Finally, the coefficients of the V_{ij} matrix can be constructed from the VPP and VBB vertex, taking into account all the diagrams as in Fig. 1.

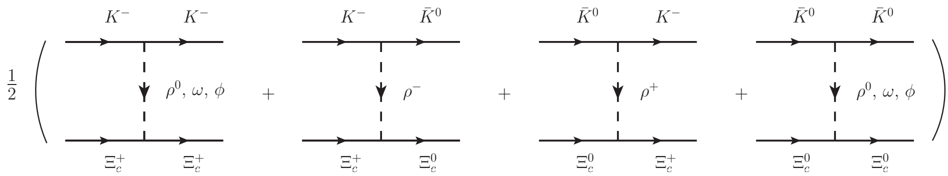

Fig. 1. Diagrams in the $\Xi_c\bar{K} \to \Xi_c\bar{K}$ interaction through vector–meson exchange.

Assuming the heavy quark is a spectator implies that the interactions are dominated by the SU(3) content of SU(4). This has as a consequence that heavy quark spin symmetry is respected, except for a few nondiagonal transitions like $\Xi_c\bar{K} \to \Xi D$, where one has to exchange a D_s^*. In this case, SU(4) is used. However, these terms are suppressed by the heavy-quark propagator that goes like $(1/m_{D_s^*})^2$.

In Tables I and II, we show the poles found from the interaction of pseudoscalar(0^-)–baryon($1/2^+$) and pseudoscalar(0^-)–baryon($3/2^+$), respectively. We also show the coupling g_i of each pole to the channels it couples in our framework, and the quantity $g_i G_i^{II}$, which is proportional to the strength of the wave function at the origin (for S-wave) and is related to the strength of that channel to produce the resonance. In Table III, we compare our results with the measurements of the LHCb Collaboration [2].

TABLE I

The coupling constants to various channels for the poles in the $J^P = 1/2^-$ sector, with $q_{\max} = 650$ MeV. $g_i\, G_i^{II}$ is in MeV.

3054.05+i0.44	$\Xi_c\bar{K}$	$\Xi_c'\bar{K}$	ΞD	$\Omega_c\eta$
g_i	$-0.06+i0.14$	$\mathbf{1.94+i0.01}$	$-2.14+i0.26$	$1.98+i0.01$
$g_i\, G_i^{II}$	$-1.40-i3.85$	$\mathbf{-34.41-i0.30}$	$9.33-i1.10$	$-16.81-i0.11$
3091.28+i5.12	$\Xi_c\bar{K}$	$\Xi_c'\bar{K}$	ΞD	$\Omega_c\eta$
g_i	$0.18-i0.37$	$0.31+i0.25$	$\mathbf{5.83-i0.20}$	$0.38+i0.23$
$g_i\, G_i^{II}$	$5.05+i10.19$	$-9.97-i3.67$	$\mathbf{-29.82+i0.31}$	$-3.59-i2.23$

We see that from the pseudoscalar(0^-)–baryon($1/2^+$) interaction, the mass and width of the $\Omega_c(3050)$ and $\Omega_c(3090)$ can be obtained with remarkable agreement with experiment. This implies that both of these states have quantum numbers $J^P = 1/2^-$, and the couplings and wave functions tell us that the $\Omega_c(3050)$ is mostly a $\Xi_c'\bar{K}$ molecule, which also couples strongly to the channels ΞD and $\Omega_c\eta$. The small coupling of the $\Omega_c(3050)$ to $\Xi_c\bar{K}$,

TABLE II

The coupling constants to various channels for the poles in the $J^P = 3/2^-$ sector, with $q_{\max} = 650$ MeV. $g_i\, G_i^{II}$ is in MeV.

3124.84	$\Xi_c^* \bar{K}$	$\Omega_c^* \eta$	$\Xi^* D$
g_i	**1.95**	1.98	-0.65
$g_i\, G_i^{II}$	$\mathbf{-35.65}$	-16.83	1.93
$3290.31 + i0.03$	$\Xi_c^* \bar{K}$	$\Omega_c^* \eta$	$\Xi^* D$
g_i	$0.01 + i0.02$	$0.31 + i0.01$	$\mathbf{6.22 - i0.04}$
$g_i\, G_i^{II}$	$-0.62 - i0.18$	$-5.25 - i0.18$	$\mathbf{-31.08 + i0.20}$

TABLE III

Comparison of our results [4] with the LHCb data [2].

Resonance	Mass [MeV]	Γ [MeV]	
$\Omega_c(3050)$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	< 1.2 MeV, 95% C.L.
This work [4]	**3054.05**	**0.88**	
$\Omega_c(3090)$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	
This work [4]	**3091.28**	**10.24**	
$\Omega_c(3119)$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	< 2.6 MeV, 95% C.L.
This work [4]	**3124.84**	**0**	

the only channel open for strong decay (with a small phase space available), explains its extremely small width. On the other hand, the $\Omega_c(3090)$ is mostly a ΞD molecule, and the small width can also be explained by the small couplings to $\Xi_c \bar{K}$ and $\Xi_c' K$, the former being slightly bigger and with more phase space than for the $\Omega_c(3050)$.

The states from pseudoscalar(0^-)–baryon$(3/2^+)$ interaction present a similar pattern, with a state corresponding to the $\Omega_c(3119)$ made mostly of $\Xi_c^* \bar{K}$. The decay of this state into $\Xi_c \bar{K}$, as seen in the experiment [2], requires the exchange of vector mesons in P-wave, which give raise to its small width. Another state made mostly of $\Xi^* D$ is also found, as well as others from the interaction of vector mesons with baryons, which are presented and discussed in Ref. [4].

The Ω_b^- baryons have already been measured, most recently by the LHCb Collaboration [5]. The search for the new Ω_c^0 states on the weak decay of the Ω_b^- was recently proposed in Ref. [6]. Using our molecular description in coupled channels, we presented predictions for the reactions: $\Omega_b^- \to (\Xi\, D)\, \pi^-$, $\Omega_b^- \to (\Xi_c\, \bar{K})\, \pi^-$ and $\Omega_b^- \to (\Xi_c'\, \bar{K})\, \pi^-$.

The transition $\Xi D \to \Xi_c \bar{K}$ appears naturally in the coupled channels approach, and we expect to see the $\Omega_c(3050)$ and $\Omega_c(3090)$ in the $\Xi_c \bar{K}$ invariant mass distribution. As discussed in detail in Ref. [6], the amplitude of the reaction $\Omega_b^- \to (\Xi_c \bar{K})\,\pi^-$ would be of the form of

$$t_{\Omega_b^- \to \pi^- \Xi_c \bar{K}} = V_P \, G_{\Xi D} \left[M_{\rm inv}\left(\Xi_c \bar{K}\right)\right] \, t_{\Xi D \to \Xi_c \bar{K}} \left[M_{\rm inv}\left(\Xi_c \bar{K}\right)\right] . \tag{9}$$

Then we can estimate the invariant mass distribution, as seen in Fig. 2, and we can also predict the following rate of production:

$$\frac{\Gamma_{\Omega_b^- \to \pi^- \Omega_{\mathbf{c}}(\mathbf{3050})}}{\Gamma_{\Omega_b^- \to \pi^- \Omega_{\mathbf{c}}(\mathbf{3090})}} \approx 10\% . \tag{10}$$

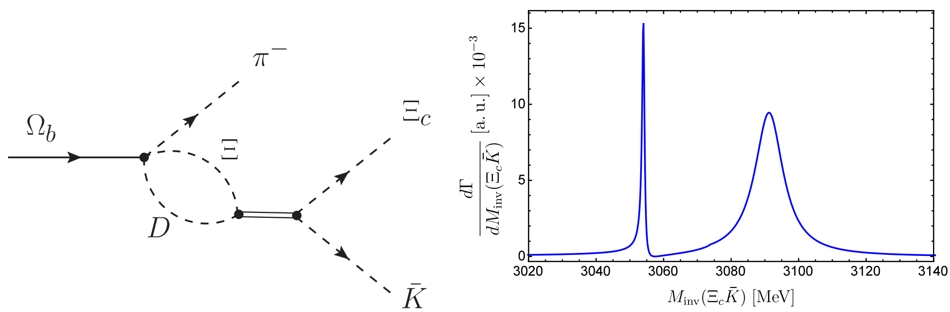

Fig. 2. $\Omega_b^- \to \pi^- \Xi_c \bar{K}$ process through ΞD rescattering. On the right, $\Xi_c \bar{K}$ invariant mass distribution showing the $\Omega_c(3050)$ and $\Omega_c(3090)$.

V.R. Debastiani would like to thank the organizers of the event for the invitation to present this talk and for providing such a nice environment. He is especially grateful to Pedro Bicudo, Marina Marinković and Robert Kamiński for their extra effort in making this event possible. V.R.D. also acknowledges the Programa Santiago Grisolia of Generalitat Valenciana (Exp. GRISOLIA/2015/005). J.M.D. thanks the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) for support by FAPESP grant 2016/22561-2. This work is partly supported by the Spanish Ministerio de Economia y Competitividad and European FEDER funds under the contract numbers FIS2014-57026-REDT, FIS2014-51948-C2- 1-P and FIS2014-51948-C2-2-P, the Generalitat Valenciana in the program Prometeo II-2014/068 (E.O.), and by the National Natural Science Foundation of China under grants Nos. 11565007, 11747307 and 11647309.

REFERENCES

[1] U.-G. Meißner, T. Hyodo, *Chin. Phys. C* **40**, 100001 (2016).

[2] R. Aaij *et al.* [LHCb Collaboration], *Phys. Rev. Lett.* **118**, 182001 (2017).

[3] E. Oset, A. Ramos, *Nucl. Phys. A* **635**, 99 (1998).

[4] V.R. Debastiani, J.M. Dias, W.H. Liang, E. Oset, *Phys. Rev. D* **97**, 094035 (2018) [arXiv:1710.04231 [hep-ph]].

[5] R. Aaij *et al.* [LHCb Collaboration], *Phys. Rev. D* **93**, 092007 (2016).

[6] V.R. Debastiani, J.M. Dias, W.H. Liang, E. Oset, arXiv:1803.03268 [hep-ph].