Dynamical Hadrons

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From Hadron-Hadron scattering new states can be **dynamically generated**.

Resonances and **bound states** manifest as **poles** in the T matrix. These poles are associated with the **mass** and **width** of the resonances,

$$z_R = M_R + i\frac{\Gamma_R}{2}. \tag{1}$$

They can be seen as **bumps** in cross sections, invariant mass distributions, Dalitz plots...

These states can be formed from different hadronic systems

- meson-meson $\rightarrow a_0(980)$, $f_0(980)$, $f_0(500)$ or σ, $D^*_{s0}(2317)$, $f_1(1285)$, ...
- meson-baryon $\rightarrow \Lambda(1405)$, $N^*(1535)$, ...
- baryon-baryon $\rightarrow$ deuteron!

These states can be described using effective approaches where **the hadrons are the degrees of freedom**.

In this picture these states are sometimes called "**molecules**", even though they are not necessarily loosely bound.

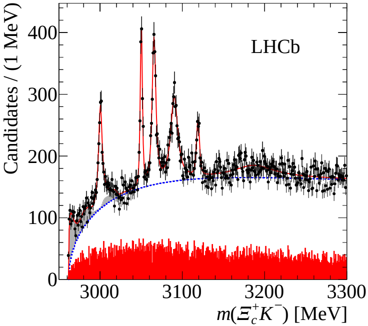
The discovery of five narrow Ω_c states by the **LHCb** Collaboration [1] has trigged a wave of theoretical works with different interpretations.

Their existence was recently confirmed by the **Belle** Collaboration [2].

Quark Models [3] can describe these states as diquark-quark systems $(ss)c$ with orbital and/or radial excitations: $1P$, $2S$.

Some of these states could be exotic **pentaquarks** [4].

Could they also be **meson-baryon "molecules"**?



[1] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **118**, no. 18, 182001 (2017).

[2] J. Yelton *et al.* [Belle Collaboration], arXiv:1711.07927 [hep-ex].

[3] M. Karliner and J. L. Rosner, Phys. Rev. D **95**, no. 11, 114012 (2017).

[4] H. C. Kim, M. V. Polyakov and M. Praszałowicz, Phys. Rev. D **96**, no. 1, 014009 (2017).

Among many others...

Some classical examples from pseudoscalar-pseudoscalar interaction are the **scalar mesons** $a_0(980)$, $f_0(980)$, $f_0(500)$ or σ.

They can be described using an effective chiral Lagrangian where the pseudoscalar mesons are the degrees of freedom:

$$\mathcal{L}_2 = \frac{1}{12\,f_\pi^2}\mathrm{Trace}[\ (\partial_\mu\Phi\,\Phi - \Phi\,\partial_\mu\Phi)^2 + M\Phi^4\ ]\,, \tag{2}$$

$$\Phi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\,\eta_8}{\sqrt{6}} \end{pmatrix}\ ; \quad M = \begin{pmatrix} m_\pi^2 & 0 & 0 \\ 0 & m_\pi^2 & 0 \\ 0 & 0 & 2\,m_K^2 - m_\pi^2 \end{pmatrix}\,, \tag{3}$$

where in M we take the isospin limit $(m_u = m_d)$ and $\eta_8 = \eta$.

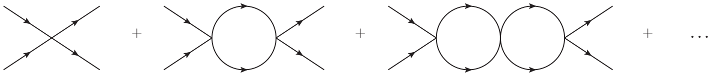


Figure: Diagrams representing meson-meson loops.

[1] J. A. Oller and E. Oset, "Chiral symmetry amplitudes in the S wave isoscalar and isovector channels and the σ, $f_0(980)$, $a_0(980)$ scalar mesons," Nucl. Phys. A **620**, 438 (1997), Erratum: [Nucl. Phys. A **652**, 407 (1999)].

From this Lagrangian we extract the kernel of each channel which are then inserted into on-shell factorized the Bethe-Salpeter equation, summing the contribution of every meson-meson loop.

$$T_{ij} = V_{ij} + \sum_l V_{il} G_l T_{lj} \qquad \Longrightarrow \qquad T = (1 - VG)^{-1} V \,, \tag{4}$$

where G_l is the meson-meson loop-function for the l-channel, which we regularize with a cutoff. In this framework we use $q_{max} \sim 600$ MeV. After the integration in q^0 and $\cos\theta$ we have

$$G_l = \int_0^{q_{max}} \frac{q^2 dq}{(2\pi)^2} \frac{\omega_1 + \omega_2}{\omega_1 \omega_2 [(P^0)^2 - (\omega_1 + \omega_2) + i\epsilon]} \,, \tag{5}$$
$$\omega_i = \sqrt{q^2 + m_i^2}, \quad (P^0)^2 = s.$$

Each contribution is projected in S-wave and a normalization factor is included when identical particles are present.

The matrix T gives us the scattering amplitude and transitions between each channel, which in charge basis are: 1) $\pi^+\pi^-$, 2) $\pi^0\pi^0$, 3) K^+K^-, 4) $K^0\bar{K}^0$, 5) $\eta\eta$ and 6) $\pi^0\eta$.

- $a_0(980)$ couples to $K\bar{K}$ in $I = 1$ and $\pi\eta$.
- $f_0(980)$ couples to $K\bar{K}$ in $I = 0$, to $\pi\pi$.
- $f_0(500)$ or σ is essentially $\pi\pi$ in $I = 0$.

Chiral Unitary Approach - meson-meson molecular states

$a_0(980)$, $f_0(980)$, $f_0(500)$ or σ

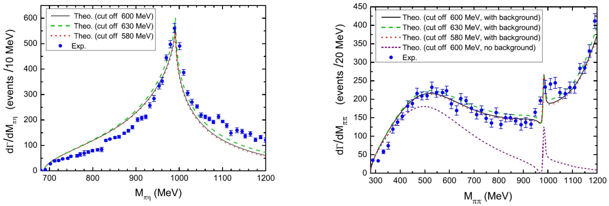
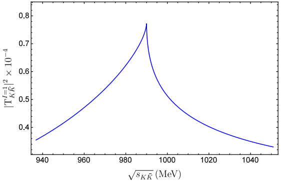
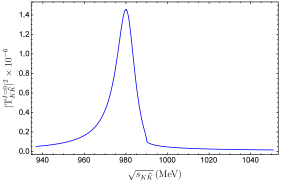


Figure: Results for the $\pi\eta$ (left) and $\pi\pi$ (right) mass distribution in the $\chi_{c1} \to \eta\pi^+\pi^-$ reaction [1], producing $a_0(980)$ (left), $f_0(500)$, $f_0(980)$ (right). Predictions for the analogous reaction $\eta_c \to \eta\pi^+\pi^-$ were done in [2].



(a) $K\bar{K}$ amplitude in $I = 1$; $a_0(980)$.



(b) $K\bar{K}$ amplitude in $I = 0$; $f_0(980)$.

Figure: Comparison between $K\bar{K}$ amplitude squared in isospin 1 and 0.

[1] W. H. Liang, J. J. Xie and E. Oset, Eur. Phys. J. C **76**, no. 12, 700 (2016).

[2] V. R. Debastiani, W. H. Liang, J. J. Xie and E. Oset, Phys. Lett. B **766**, 59 (2017).

→ Both couple to $\mathbf{K\bar{K}}$.
→ Isospin symmetry breaking.
→ Both 0^{++} and similar masses → Mixing.

We have recently studied the reactions

- $\chi_{c1} \to \pi^0 f_0(980) \to \pi^0\pi^+\pi^-$,
- $\chi_{c1} \to \pi^0 a_0(980) \to \pi^0\pi^0\eta$,

and its connection to $K\bar{K}$ loops [1].

These reactions had been proposed in [2], and together with

- $J/\psi \to \phi a_0(980) \to \phi\pi^0\eta$,
- $J/\psi \to \phi f_0(980) \to \phi\pi\pi$,

the mixing was measured by the BESIII Collaboration [3], and recently, with more statistics [4].

[1] M. Bayar and V. R. Debastiani, Phys. Lett. B **775**, 94 (2017).

[2] J. J. Wu and B. S. Zou, Phys. Rev. D **78**, 074017 (2008).

[3] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. D **83**, 032003 (2011).

[4] M. Ablikim *et al.* [BESIII Collaboration], arXiv:1802.00583 [hep-ex].

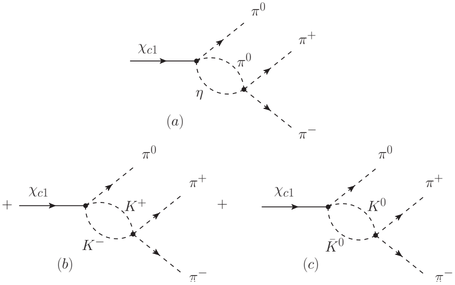
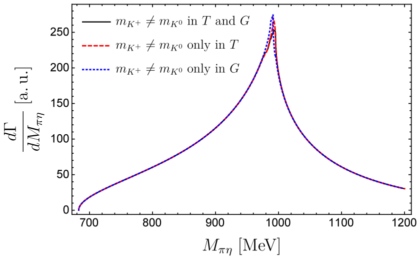


Figure: Diagrams for $f_0(980)$ production in $\chi_{c1} \to \pi^0 f_0(980) \to \pi^0\pi^+\pi^-$.

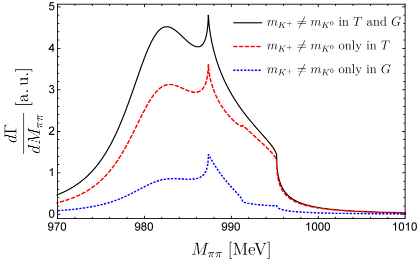
$$t = \vec{\epsilon}_{\chi_{c1}} \cdot \vec{p}_{\pi^0}\ \tilde{t}_{\pi^+\pi^-},$$

$$\begin{aligned} \tilde{t}_{\pi^+\pi^-} &= V_p\ (2\sqrt{3}\ G_{\pi^0\eta}\ t_{\pi^0\eta\to\pi^+\pi^-} \\ &+ \frac{3}{\sqrt{2}}\ G_{K^+K^-}\ t_{K^+K^-\to\pi^+\pi^-} \\ &- \frac{3}{\sqrt{2}}\ G_{K^0\bar{K}^0}\ t_{K^0\bar{K}^0\to\pi^+\pi^-})\,. \end{aligned} \quad (6)$$

$a_0(980) - f_0(980)$ mixing in $\chi_{c1} \to \pi^0\pi^+\pi^-(\pi^0\eta)$



(a) Invariant mass distribution of $\pi^0\eta$ in the $\chi_{c1} \to \pi^0 a_0(980) \to \pi^0\pi^0\eta$ reaction.



(b) Invariant mass distribution of $\pi^+\pi^-$ in the $\chi_{c1} \to \pi^0 f_0(980) \to \pi^0\pi^+\pi^-$ reaction.

Table: Comparison between experiment and theoretical results for the $a_0(980) - f_0(980)$ mixing in the $\chi_{c1} \to \pi^0\pi^+\pi^-$ and $\chi_{c1} \to \pi^0\pi^0\eta$ reactions.

	$\Gamma(\chi_{c1} \to \pi^0\pi^+\pi^-) \,/\, \Gamma(\chi_{c1} \to \pi^0\pi^0\eta)$
BESIII [1]	$(0.31 \pm 0.16(\text{stat}) \pm 0.14(\text{sys}) \pm 0.03(\text{para}))\%$
BESIII [2]	$(0.40 \pm 0.07(\text{stat}) \pm 0.14(\text{sys}) \pm 0.07(\text{para}))\%$
$m_{K^+} \neq m_{K^0}$	$M_{\pi\eta} \in [885, 1085]$ MeV
in T and G	0.26 %
only in T	0.19 %
only in G	0.05 %

[1] M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. D **83**, 032003 (2011).
[2] M. Ablikim *et al.* [BESIII Collaboration], arXiv:1802.00583 [hep-ex].

Meson-Baryon interaction in $SU(3)$ - Chiral Lagrangian

The meson-baryon interaction in the $\mathrm{SU}(3)$ sector can be described by the chiral Lagrangian

$$\mathcal{L}^B = \frac{1}{4f_\pi^2} \left\langle \bar{B} i\gamma^\mu \Big[(\Phi\, \partial_\mu \Phi - \partial_\mu \Phi\, \Phi\,) B - B(\Phi\, \partial_\mu \Phi - \partial_\mu \Phi\, \Phi\,) \Big] \right\rangle ,$$

$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix} ,$$

$$B = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix} .$$

This framework was used to described the $\Lambda(1405)$ with coupled channels in $\bar{K}N$ scattering [1].

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

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

$$V_{ij} = -C_{ij}\frac{1}{4f^2}(k^0 + k'^0) ,$$

where k^0, k'^0 are the energies of the incoming and outgoing mesons, respectively.

However, the extension to the charm sector is complicated particularly in the baryon sector.

In the LHGA the meson-baryon interaction in $\mathrm{SU}(3)$ is obtained exchanging vector mesons

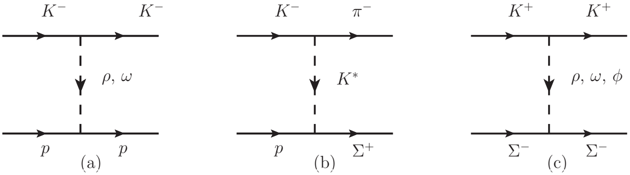


Figure: Vector exchange in the meson-baryon interaction.

The ingredients needed are the *VPP* Lagrangian

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

with

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

and the *VBB* Lagrangian

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

with $g = m_V / 2 f_\pi$ and m_V the mass of the vector mesons (~ 800 MeV).

Taking $q^2/m_V^2 \to 0$ in the propagator of the exchanged vector gives rise to the same interaction of the Chiral Lagrangian.

There are many states that can be described from hadron-hadron interaction.

Meson-Meson:

- $a_0(980)$ from $K\bar{K}$ and $\pi\eta$.
- $f_0(980)$ from $K\bar{K}$ and $\pi\pi$.
- $f_0(500)$ (σ) from $\pi\pi$.
- $D^*_{s0}(2317)$ is predominantly a DK bound state.
- $f_1(1285)$ from $K^*\bar{K}$ + c.c.
- $X(3872)$ from $D\bar{D}^*$ + c.c.

Meson-Baryon

- $\Lambda(1405)$ as quasi-bound state between $\bar{K}N$ and $\pi\Sigma$ threshold from $\bar{K}N$ scattering.
- $\Lambda_c(2595)$ has a similar pattern, lying between the DN and $\pi\Sigma_c$ thresholds.
- $N^*(1535)$ from πN and ηN.
- The new Ω_c states from $\Xi_c\bar{K}$?

And many others...

Poles and Couplings

We can use the **unitarized** scattering amplitude, with **effective interaction** V:

$$T = \frac{V}{1 - VG}, \tag{7}$$

with G the loop function. In the most general form for **meson-meson** we have

$$G_i = i \int \frac{d^4q}{(2\pi)^4} \frac{1}{q^2 - m_{1i}^2 + i\epsilon} \frac{1}{(P-q)^2 - m_{2i}^2 + i\epsilon}, \tag{8}$$

where m_{1i}, m_{2i} are the masses of each meson in the i-channel and P is the center-of-mass energy.

We can look for **poles** when

$$\det[1 - VG^{II}] = 0, \qquad \rightarrow \qquad z_R = M_R + i\frac{\Gamma_R}{2}. \tag{9}$$

$\rightarrow$ **Resonances appear as poles in the second Riemann sheet of the complex energy plane**.

For that we define G_i^{II} for $\mathrm{Re}(\sqrt{s}) > m_{1i} + m_{2i}$ (threshold mass of the i channel)

$$G_i^{II} = G_i^{I} + i\frac{p}{4\pi\sqrt{s}}, \qquad p = \frac{\lambda^{1/2}(s, m_{1i}^2, m_{2i}^2)}{2\sqrt{s}}, \text{ and } \mathrm{Im(p)} > 0\,. \tag{10}$$

To calculate the **couplings** we can use the fact that **close to the pole** the amplitude goes like

$$T_{ij} \approx \frac{g_i g_j}{\sqrt{s} - z_R} \qquad \rightarrow \qquad g_i^2 = \mathrm{Res}(T_{ii}) = \frac{1}{2\pi i}\int_0^{2\pi} T_{ii}(z_R + re^{i\theta}) re^{i\theta} i d\theta. \tag{11}$$

- $g_i G_i^{II}$: Strength of the wave function at the origin (for S-wave) [1].

[1] D. Gamermann, J. Nieves, E. Oset and E. Ruiz Arriola, Phys. Rev. D **81**, 014029 (2010).

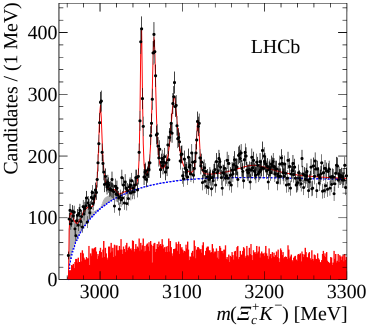
In our work [1] we investigated **meson-baryon molecular states** with $C = +1$, $S = -2$, $I = 0$ and we get

$\rightarrow$ three states: the $\mathbf{\Omega_c(3050)}$, $\mathbf{\Omega_c(3090)}$ and $\mathbf{\Omega_c(3119)}$,

in agreement with the experiment [2].

Another work [3] also found the $\Omega_c(3050)$ and $\Omega_c(3090)$, in agreement with our results.

In Ref. [4] three states were associated with experiment, but with **different nature** and **quantum numbers**.



[1] V. R. Debastiani, J. M. Dias, W. H. Liang and E. Oset, arXiv:1710.04231 [hep-ph].

[2] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **118**, no. 18, 182001 (2017).

[3] G. Montaña, A. Feijoo and A. Ramos, arXiv:1709.08737 [hep-ph].

[4] J. Nieves, R. Pavao and L. Tolos, arXiv:1712.00327 [hep-ph].

Among others...

We use the Lagrangian of the Local Hidden Gauge Approach, $\mathcal{L}_{VPP} = -ig \langle\, [\,\Phi,\, \partial_\mu \Phi\,]\, V^\mu \,\rangle$.

Extending the VPP Lagrangian to the charm sector is simple. We take the same structure with

$$P = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{3}}\eta + \frac{1}{\sqrt{6}}\eta' & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{3}}\eta + \frac{1}{\sqrt{6}}\eta' & K^0 & D^- \\ K^- & \bar{K}^0 & -\frac{1}{\sqrt{3}}\eta + \sqrt{\frac{2}{3}}\eta' & D_s^- \\ D^0 & D^+ & D_s^+ & \eta_c \end{pmatrix},$$

where we include the mixing between η and η', and

$$V = \begin{pmatrix} \frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & -\frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & K^{*0} & \bar{D}^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}.$$

- Heavy quark as a spectator $\rightarrow \mathrm{SU}(3)$ content of $\mathrm{SU}(4)$.
- Respects heavy quark spin symmetry,
- Except for non diagonal transitions like $\Xi_c \bar{K} \rightarrow \Xi D$
  - Exchange a $D_s^* \rightarrow \mathrm{SU}(4)$ is used,
  - Suppressed: heavy quark propagator $\sim (1/m_{D_s^*})^2$.

Extending the VBB Lagrangian to charm sector is not so easy.

- We look at the quark structure of the ρ^0, ω and ϕ (which can be extended to K^*, $\rho^{\pm}$, ...)

$$\begin{aligned} \rho^0 &= \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})\,, \\ \omega &= \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\,, \\ \phi &= s\bar{s}\,. \end{aligned}$$

- $\gamma_\mu \to \gamma^0$ approximation $\Rightarrow$ No spin dependence.

- We consider an operator at the quark level, for instance, for $\rho^0 pp$ vertex

$$\langle p|g\,\rho^0\,|p\rangle \equiv \frac{1}{\sqrt{2}}\frac{1}{\sqrt{2}}\langle \phi_{MS}\,\chi_{MS} + \phi_{MA}\,\chi_{MA}|g\,\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})|\phi_{MS}\,\chi_{MS} + \phi_{MA}\,\chi_{MA}\rangle\,,$$

  where ϕ_{MS}, ϕ_{MA}, χ_{MS}, χ_{MA} are the flavor and spin mixed symmetric and mixed antisymmetric wave functions for the proton.

- Same result as using $\mathcal{L}_{VBB}$ in $SU(3)$.

$SU(3)$ symmetry in light quarks, inspired in Ref. [1]. Heavy quark as spectator.

$$\Xi^0 \equiv \frac{1}{\sqrt{2}}(\phi_{MS}\,\chi_{MS} + \phi_{MA}\,\chi_{MA}),$$

with the Mixed-Symmetric and Mixed-Antisymmetric flavor and spin wavefunctions:

$$\phi_{MS} = \frac{1}{\sqrt{6}}[s(us+su) - 2uss]\,, \quad \phi_{MA} = -\frac{1}{\sqrt{2}}[s(us-su)]\,,$$

$$\chi_{MS} = \frac{1}{\sqrt{6}}(\uparrow\uparrow\downarrow + \uparrow\downarrow\uparrow - 2\downarrow\uparrow\uparrow), \quad \chi_{MA} = \frac{1}{\sqrt{2}}\uparrow(\uparrow\downarrow - \downarrow\uparrow),$$

- Ξ^{*0}: $\frac{1}{\sqrt{3}}(sus + ssu + uss)\uparrow\uparrow\uparrow$, (Symmetric for the three light quarks, ϕ_S and χ_S).

- Ξ_c^+: $\frac{1}{\sqrt{2}}\,c\,(us - su)\uparrow\frac{1}{\sqrt{2}}(\uparrow\downarrow - \downarrow\uparrow)$, (Antisymmetric for the two light quarks, and χ_{MA}).
- $\Xi_c'^+$: $\frac{1}{\sqrt{2}}c(us+su)\frac{1}{\sqrt{6}}(\uparrow\uparrow\downarrow + \uparrow\downarrow\uparrow - 2\downarrow\uparrow\uparrow)$, (Symmetric for the two light quarks, and χ_{MS}).
- Ξ_c^{*+}: $\frac{1}{\sqrt{2}}c(us+su)\uparrow\uparrow\uparrow$, (Symmetric for the two light quarks, and χ_S).

[1] F. E. Close, *"An Introduction to Quarks and Partons,"* Academic Press/London 1979.

Interaction - Example

Formalism

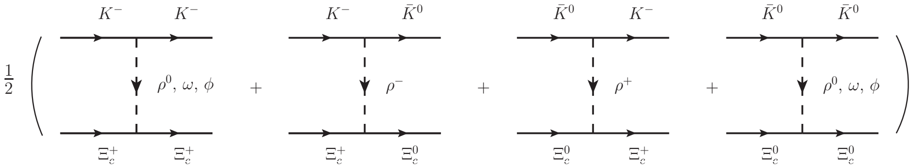


Figure: Diagrams in the $\bar{K}\Xi_c \to \bar{K}\Xi_c$ transition.

We reach the same structure for the meson-baryon interaction

$$V_{ij} = D_{ij}\frac{1}{4f^2}(p^0 + p'^0)\,,$$

and the matrix D_{ij} is constructed from VPP and VBB vertex.

Alternatively, we can use another expression which includes relativistic correction in S-wave

$$V_{ij} = D_{ij}\frac{2\sqrt{s} - M_{B_i} - M_{B_j}}{4f^2}\sqrt{\frac{M_{B_i} + E_{B_i}}{2M_{B_i}}}\sqrt{\frac{M_{B_j} + E_{B_j}}{2M_{B_j}}}\,,$$

where M_{B_i,B_j} and E_{B_i,B_j} stand for the mass and the center-of-mass energy of the baryons.

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

Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
		< 1.2 MeV, 95% CL
	3054.05	**0.88**
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
	3091.28	**10.24**

- $\Rightarrow$ **pseudoescalar(0^-)-baryon($1/2^+$) nature with** $J^P = 1/2^-$
- $\Omega_c(3050)^0$ mostly $\Xi'_c \bar{K}$.
- $\Omega_c(3090)^0$ mostly ΞD.

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

Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$
		$< 2.6\ \mathrm{MeV}, 95\%\ \mathrm{CL}$
	3124.84	**0.0**

- $\Rightarrow$ **pseudoescalar(0^-)-baryon($3/2^+$) nature with** $J^P = 3/2^-$
- $\Omega_c(3119)^0$ mostly $\Xi_c^* \bar{K}$.
- New " $\Omega_c(3290)^0$ " mostly $\Xi^* D$.
- "Spin-Partners" of $\Omega_c(3050)^0$ and $\Omega_c(3090)^0$.

We also make predictions for vector(1^-)-baryon($1/2^+$) states.

Table: The coupling constants to various channels for the poles in $J^P = 1/2^-, 3/2^-$ stemming from vector-baryon interaction with $q_{max} = 650$ MeV. $g_i\, G_i^{II}$ is in MeV.

3221.98	$\Xi\, D^*$	$\Xi_c\, \bar{K}^*$	$\Xi_c'\, \bar{K}^*$
g_i	6.37	0.59	-0.28
$g_i\, G_i^{II}$	-29.29	-4.66	1.62
$3360.37 + i0.20$	$\Xi\, D^*$	$\Xi_c\, \bar{K}^*$	$\Xi_c'\, \bar{K}^*$
g_i	$-0.11 - i0.12$	$1.31 - i0.03$	$0.03 + i0.01$
$g_i\, G_i^{II}$	$2.12 + i0.48$	$-26.04 + i0.36$	$-0.26 - i0.06$
$3465.17 + i0.09$	$\Xi\, D^*$	$\Xi_c\, \bar{K}^*$	$\Xi_c'\, \bar{K}^*$
g_i	$-0.01 + i0.06$	$0.01 - i0.01$	$1.75 + i0.01$
$g_i\, G_i^{II}$	$-0.84 - i0.23$	$0.17 + i0.24$	$-32.29 - i0.08$

- **Degenerated Spin of vector(1^-)-baryon($1/2^+$) nature with $J^P = 1/2^-, 3/2^-$.**
- New " $\Omega_c(3222)^0$ " mostly ΞD^*.
- New " $\Omega_c(3360)^0$ " mostly $\Xi_c \bar{K}^*$.
- New " $\Omega_c(3465)^0$ " mostly $\Xi_c' \bar{K}^*$.
- Same pattern in opposite order (due to thresholds mass in opposite order).

Table: Results of the fit to $m(\Xi_c^+ K^-)$ for the mass, width, yield and significance for each resonance. For each fitted parameter, the first uncertainty is statistical and the second systematic. Upper limits are also given for the resonances $\Omega_c(3050)^0$ and $\Omega_c(3119)^0$ for which the width is not significant.
AND COMPARISON WITH OUR RESULTS.

Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		$< 1.2\mathrm{MeV}, 95\%\ \mathrm{CL}$		
$J^P = 1/2^-$	**3054.05**	**0.88**		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$J^P = 1/2^-$	**3091.28**	**10.24**		
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		$< 2.6\mathrm{MeV}, 95\%\ \mathrm{CL}$		
$J^P = 3/2^-$	**3124.84**	**0.0**		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	

The Ω_b^- baryons have already been measured, most recently by the LHCb Collaboration [1].

The search for the new Ω_c^0 states on the weak decay of the Ω_b^- was recently proposed in [2].

Using our molecular description in coupled channels we have just presented predictions for the reactions [3]:

- $\Omega_b^- \to (\Xi\, D)\,\pi^-$
- $\Omega_b^- \to (\Xi_c\, \bar{K})\,\pi^-$
- $\Omega_b^- \to (\Xi_c'\, \bar{K})\,\pi^-$

[1] R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. D **93**, no. 9, 092007 (2016).

[2] I. Belyaev, "Spectroscopy of charm baryons at LHCb", talk presented at the Hadron 2017 Conference, Salamanca, September 2017.

[3] Today on arXiv:1803.03268 [hep-ph] !

V. R. Debastiani, J. M. Dias, Wei-Hong Liang, E. Oset

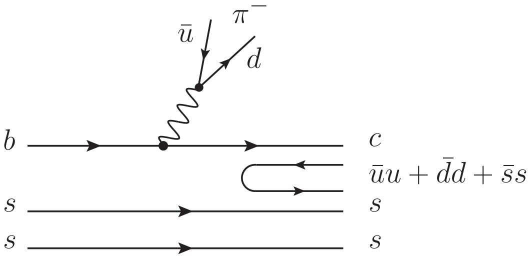


Figure: Ω_b^- decay at quark level with emission of a π^- and subsequent hadronization.

→ The hadronization after the emission of a π^- should produce a ΞD pair in $I = 0$.

$$css \to c\,(\bar{u}u + \bar{d}d + \bar{s}s)\,ss \equiv H,$$

$$H = \sum_i c\,\bar{q}_i q_i\, ss \equiv \sum_i \Phi_{4i}\, q_i ss,$$

$$|H\rangle = -\frac{2}{\sqrt{6}} D^0\,\Xi^0 + \frac{2}{\sqrt{6}} D^+\,\Xi^- = \frac{2}{\sqrt{3}}|\Xi D, I = 0\rangle. \quad (12)$$

$\Omega_b^- \to (\Xi_c^+ K^-)\,\pi^-$ and the Ω_c states

The transition $\Xi D \to \Xi_c \bar{K}$ appears naturally in the coupled channel approach, and we expect to see the **$\Omega_c(3050)$** and **$\Omega_c(3090)$** in the $\Xi_c \bar{K}$ invariant mass distribution.

$$t_{\Omega_b^- \to \pi^- \Xi_c \bar{K}} = V_P \frac{2}{\sqrt{3}} G_{\Xi D}[M_{\rm inv}(\Xi_c \bar{K})]\, t_{\Xi D \to \Xi_c \bar{K}}[M_{\rm inv}(\Xi_c \bar{K})]. \quad (13)$$

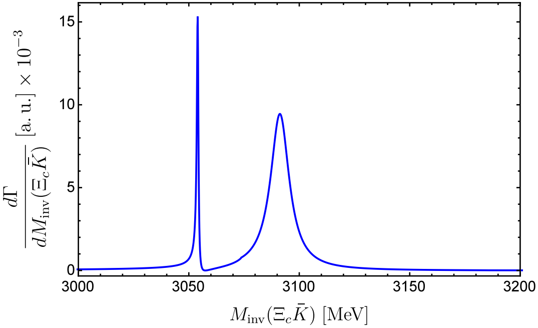


Figure: $\Xi_c \bar{K}$ invariant mass distribution in $\Omega_b^- \to \pi^- \Xi_c \bar{K}$.

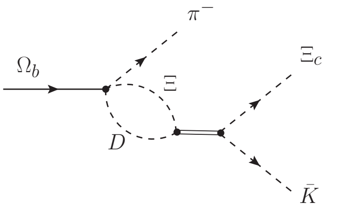


Figure: $\Omega_b^- \to \pi^- \Xi_c \bar{K}$ process through ΞD rescattering.

We can predict the following rate of production:

$$\frac{\Gamma_{\Omega_b^- \to \pi^- \Omega_c(3050)}}{\Gamma_{\Omega_b^- \to \pi^- \Omega_c(3090)}} \approx 10\%. \quad (14)$$

Conclusions

- **Dynamically Generated** states from meson-meson and meson-baryon interaction are of great importance.
- There are many "**molecular**" states measured experimentally which **cannot** be well understood in **quark models** or other approaches, like the **scalar mesons** and the $\mathbf{\Lambda(1405)}$.
- The $\mathbf{a_0(980) - f_0(980)}$ mixing appears naturally in the **molecular** picture through isospin symmetry breaking in $\mathbf{K\bar{K}}$ loops.

- We can explain three of the recently measured new Ω_c states as meson-baryon molecular states with $C = +1$, $S = -2$, with remarkable agreement!
- $\Omega_c(3050)^0$ and $\Omega_c(3090)^0$ with $J^P = 1/2^-$, pseudoescalar(0^-)-baryon($1/2^+$) nature.
- $\Omega_c(3119)^0$ with $J^P = 3/2^-$, pseudoescalar(0^-)-baryon($3/2^+$) nature.
- Most important channels are $\Xi_c'\bar{K}$, and ΞD and $\Xi_c^*\bar{K}$, respectively.

- **NEXT STEPS: Measure the Spin-Parity of the Ω_c states,**
- **and search for them in other reactions, like the $\mathbf{\Omega_b^-} \to (\mathbf{\Xi_c^+ K^-})\,\pi^-$ decay.**

Backup slides

We have chosen the following channels. We neglect channels whose threshold is already too high to generate the experimental states.

We separate spin 1/2 and spin 3/2.

Table: $J = 1/2$ states chosen and threshold mass in MeV. From pseudoscalar-baryon(1/2) and vector-baryon(1/2) interactions.

States	$\Xi_c \bar{K}$	$\Xi'_c \bar{K}$	ΞD	$\Omega_c \eta$	ΞD^*	$\Xi_c \bar{K}^*$	$\Xi'_c \bar{K}^*$
Threshold	2965	3074	3185	3243	3327	3363	3472

Table: $J = 3/2$ states chosen and threshold mass in MeV. From pseudoscalar-baryon(3/2) and vector-baryon(1/2) interactions.

States	$\Xi^*_c \bar{K}$	$\Omega^*_c \eta$	ΞD^*	$\Xi_c \bar{K}^*$	$\Xi^* D$	$\Xi'_c \bar{K}^*$
Threshold	3142	3314	3327	3363	3401	3472

Two blocks: pseudoescalar(0^-)-baryon($1/2^+$) decouples from vector(1^-)-baryon($1/2^+$).

Table: D_{ij} coefficients of Eq. (12) for the meson-baryon states coupling to $J^P = 1/2^-$ in s-wave.

$J=1/2$	$\Xi_c\bar{K}$	$\Xi'_c\bar{K}$	ΞD	$\Omega_c\eta$	ΞD^*	$\Xi_c\bar{K}^*$	$\Xi'_c\bar{K}^*$
$\Xi_c\bar{K}$	-1	0	$-\frac{1}{\sqrt{2}}\lambda$	0	0	0	0
$\Xi'_c\bar{K}$		-1	$\frac{1}{\sqrt{6}}\lambda$	$-\frac{4}{\sqrt{3}}$	0	0	0
ΞD			-2	$\frac{\sqrt{2}}{3}\lambda$	0	0	0
$\Omega_c\eta$				0	0	0	0
ΞD^*					-2	$-\frac{1}{\sqrt{2}}\lambda$	$\frac{1}{\sqrt{6}}\lambda$
$\Xi_c\bar{K}^*$						-1	0
$\Xi'_c\bar{K}^*$							-1

In some non diagonal transitions like $\bar{K}\to D$, the propagator of the exchanged vector

$$\frac{1}{q^0-|\mathbf{q}|^2-m_{D_s^*}^2}\approx\frac{1}{(m_D-m_K)^2-m_{D_s^*}^2},$$

and the ratio to the propagator of the light vectors is

$$\lambda\equiv\frac{-m_V^2}{(m_D-m_K)^2-m_{D_s^*}^2}\approx 0.25\,.$$

Pseudoescalar(0^-)-baryon($3/2^+$) decouples from vector(1^-)-baryon($1/2^+$).

Table: D_{ij} coefficients of Eq. (12) for the meson-baryon states coupling to $J^P = 3/2^-$.

$J = 3/2$	$\Xi_c^* \bar{K}$	$\Omega_c^* \eta$	ΞD^*	$\Xi_c \bar{K}^*$	$\Xi^* D$	$\Xi_c' \bar{K}^*$
$\Xi_c^* \bar{K}$	-1	$-\frac{4}{\sqrt{3}}$	0	0	$\frac{2}{\sqrt{6}}\lambda$	0
$\Omega_c^* \eta$		0	0	0	$-\frac{\sqrt{2}}{3}\lambda$	0
ΞD^*			-2	$-\frac{1}{\sqrt{2}}\lambda$	0	$\frac{1}{\sqrt{6}}\lambda$
$\Xi_c \bar{K}^*$				-1	0	0
$\Xi^* D$					-2	0
$\Xi_c' \bar{K}^*$						-1

- Same diagonals matrix elements of Ref. [1], non diagonal not the same.
- Heavy baryons wave functions are not eigenstates of $\mathrm{SU}(4) \rightarrow$ Different spin-flavor dependence from Ref. [1].
- Both our coefficients and the ones from Ref. [1] differ from Ref. [2] in some diagonal and non diagonal.

[1] G. Montaña, A. Feijoo and A. Ramos, arXiv:1709.08737 [hep-ph].

[2] O. Romanets, L. Tolos, C. Garcia-Recio, J. Nieves, L. L. Salcedo and R. G. E. Timmermans, Phys. Rev. D **85**, 114032 (2012).

We have also evaluated the diagrams connecting the $VP \to VB$ transitions, like pseudoescalar(0^-)-baryon($1/2^+$) $\to$ vector(1^-)-baryon($1/2^+$), as in $\Xi D \to \Xi D^*$.

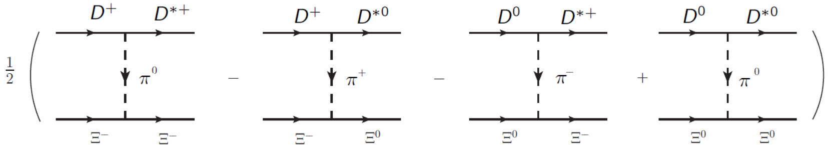


Figure: Example of pion exchange in $VP \to VB$ transition.

However, they are small in comparison to the diagonal channels like $\Xi D \to \Xi D$, $\Xi^* D \to \Xi^* D$ and $\Xi D^* \to \Xi D^*$, and we can safely neglect them [1].

This way pseudoescalar-baryon decouples from vector-baryon states.

[1] W. H. Liang, C. W. Xiao and E. Oset, Phys. Rev. D **89**, no. 5, 054023 (2014).

Based on Ref. [1], an update considering the new experimental data was developed [2]

Table: Ω_c and Ω_c^* resonances found using $\alpha = 1.16$

Name	M_R (MeV)	Γ_R (MeV)	J	M_R^{exp}	Γ_R^{exp}
a	2922.2	0	1/2	—	—
b	2928.1	0	3/2	—	—
c	2941.3	0	1/2	—	—
d	2999.9	0.06	1/2	3000.4	4.5
e	3036.3	0	3/2	3050.2	0.8

Table: Ω_c and Ω_c^* resonances found using the sharp cutoff $\Lambda = 1090$ MeV

Name	M_R (MeV)	Γ_R (MeV)	J	M_R^{exp}	Γ_R^{exp}
a	2963.95	0.0	1/2	—	—
c	2994.26	1.85	1/2	3000.4	4.5
b	3048.7	0.0	3/2	3050.2	0.8
d	3116.81	3.72	1/2	3119.1/3090.2	1.1/8.7
e	3155.37	0.17	3/2	—	—

[1] O. Romanets, L. Tolos, C. Garcia-Recio, J. Nieves, L. L. Salcedo and R. G. E. Timmermans, Phys. Rev. D **85**, 114032 (2012).

[2] J. Nieves, R. Pavao and L. Tolos, arXiv:1712.00327 [hep-ph].

Another work on Meson-Baryon coupled channels

Comparisons

Different V_{ij} from the symmetries $SU(6)$ (spin-flavor in light sector) and $SU(2)$ (spin in heavy sector) and different renormalization of meson-baryon loops:

$$G_l(s) = \bar{G}_l(s) - \bar{G}_l(\mu^2), \qquad \mu = \alpha\sqrt{m_{th}^2 + M_{th}^2},$$

where m_{th} and M_{th} are the masses of the meson and baryon of the lightest channel.

In this framework [1], the transitions $VB \to VP$, vector(1^-)-baryon($1/2^+$) $\to$ pseudoescalar(0^-)-baryon($3/2^+$), like $\Xi D^* \to \Xi^* D$ are sizable due to the symmetry employed.

However, if one look at their couplings, there seem to exist a correspondence with our results [1].

The pattern is the same:

- One pole with $J = 1/2$ is mostly $\Xi_c' \bar{K}$. (Our $\Omega_c(3050)^0$, their $\Omega_c(3000)^0$)
- Another pole with $J = 1/2$ is mostly ΞD. (Our $\Omega_c(3090)^0$, their $\Omega_c(3119)^0$)
- And the pole with $J = 3/2$ is mostly $\Xi_c^* \bar{K}$. (Our $\Omega_c(3119)^0$, their $\Omega_c(3050)^0$)

Our results have a remarkable agreement with experiment and with Ref. [2] !

[1] J. Nieves, R. Pavao and L. Tolos, arXiv:1712.00327 [hep-ph].

[2] G. Montaña, A. Feijoo and A. Ramos, arXiv:1709.08737 [hep-ph].