Dynamical Hadrons

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From Hadron-Hadron scattering new states can be \textit{dynamically generated}.

\textbf{Resonances} and \textbf{bound states} manifest as \textit{poles} in the $T$ matrix. These poles are associated with the \textit{mass} and \textit{width} of the resonances,

\[ z_R = M_R + i \frac{\Gamma_R}{2}. \]  

(1)

They can be seen as \textbf{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 $\sigma$, $D_{s0}^*(2317)$, $f_1(1285)$, ...
- meson-baryon $\rightarrow \Lambda(1405)$, $N^*(1535)$, ...
- baryon-baryon $\rightarrow$ deuteron!

These states can be described using effective approaches where \textbf{the hadrons are the degrees of freedom}.

In this picture these states are sometimes called \textit{“molecules”}, even though they are not necessarily loosely bound.
The new $\Omega_c$ states

Introduction

The discovery of five narrow $\Omega_c$ states by the LHCb Collaboration [1] has triggered 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”?


Among many others...
Some classical examples from pseudoscalar-pseudoscalar interaction are the scalar mesons $a_0(980)$, $f_0(980)$, $f_0(500)$ or $\sigma$.

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

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

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

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

Figure: Diagrams representing meson-meson loops.

Chiral Unitary Approach - meson-meson molecular states

\( a_0(980), f_0(980), f_0(500) \) or \( \sigma \)

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.

\[
T_{ij} = V_{ij} + \sum_l V_{il} G_l T_{lj} \quad \Rightarrow \quad T = (1 - VG)^{-1} V ,
\]

(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 \( q_{\text{max}} \sim 600 \text{ MeV} \). After the integration in \( q^0 \) and \( \cos \theta \) we have

\[
G_l = \int_0^{q_{\text{max}}} \frac{q^2 dq}{(2\pi)^2 \omega_1 \omega_2 [(P^0)^2 - (\omega_1 + \omega_2) + i\epsilon]} ,
\]

(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 \( \sigma \) is essentially \( \pi\pi \) in \( I = 0 \).
**Chiral Unitary Approach - meson-meson molecular states**

$a_0(980), f_0(980), f_0(500)$ or $\sigma$

---

**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].

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(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.


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

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

We have recently studied the reactions

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

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

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

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

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


\[
\tilde{t}_{\pi^+ \pi^-} = V_p \left( 2\sqrt{3} \ G_{\pi^0 \eta} \ t_{\pi^0 \eta \rightarrow \pi^+ \pi^-} \right. \\
+ \frac{3}{\sqrt{2}} \ G_{K^+ K^-} \ t_{K^+ K^- \rightarrow \pi^+ \pi^-} \\
- \frac{3}{\sqrt{2}} \ G_{K^0 \bar{K}^0} \ t_{K^0 \bar{K}^0 \rightarrow \pi^+ \pi^-} \right). \quad (6)
\]
$a_0(980) - f_0(980)$ mixing in $\chi_{c1} \to \pi^0\pi^+\pi^- (\pi^0\eta)$

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

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

<table>
<thead>
<tr>
<th></th>
<th>$\Gamma(\chi_{c1} \to \pi^0\pi^+\pi^-) / \Gamma(\chi_{c1} \to \pi^0\pi^0\eta)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BESIII [1]</td>
<td>$(0.31 \pm 0.16\text{ (stat)} \pm 0.14\text{ (sys)} \pm 0.03\text{ (para)})%$</td>
</tr>
<tr>
<td>BESIII [2]</td>
<td>$(0.40 \pm 0.07\text{ (stat)} \pm 0.14\text{ (sys)} \pm 0.07\text{ (para)})%$</td>
</tr>
</tbody>
</table>

$m_{K^+} \neq m_{K^0}$ only in $T$ and $G$

$m_{K^+} \neq m_{K^0}$ only in $T$

$m_{K^+} \neq m_{K^0}$ only in $G$

$M_{\pi\eta} \in [885, 1085]$ MeV

0.26 %

0.19 %

0.05 %


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

\[ \mathcal{L}^B = \frac{1}{4 f^2} \left( \bar{B} i \gamma^{\mu} \left( (\Phi \partial_{\mu} \Phi - \partial_{\mu} \Phi \Phi) B - B (\Phi \partial_{\mu} \Phi - \partial_{\mu} \Phi \Phi) \right) \right), \]

\[ \Phi = \begin{pmatrix} \frac{1}{\sqrt{2}} \pi^0 + \frac{1}{\sqrt{6}} \eta \\ \pi^- \\ K^- \end{pmatrix}, \quad \Phi = \begin{pmatrix} \frac{1}{\sqrt{2}} \pi^0 + \frac{1}{\sqrt{6}} \eta \\ \pi^+ \\ K^+ \end{pmatrix}, \]

\[ \begin{pmatrix} \frac{1}{\sqrt{2}} \Sigma^0 + \frac{1}{\sqrt{6}} \Lambda \\ \Sigma^- \\ \Xi^- \end{pmatrix}, \quad \begin{pmatrix} \frac{1}{\sqrt{2}} \Sigma^0 + \frac{1}{\sqrt{6}} \Lambda \\ \Sigma^+ \\ \Xi^0 \end{pmatrix}, \quad \begin{pmatrix} \frac{1}{\sqrt{2}} \Sigma^0 + \frac{1}{\sqrt{6}} \Lambda \\ \Sigma^0 + \frac{1}{\sqrt{6}} \Lambda \\ \Lambda \end{pmatrix}. \]

At energies close to threshold one can consider only the dominant contribution coming from \( \partial_0 \) and \( \gamma^0 \), such that the interaction is given by

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

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

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

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

\[ \begin{array}{ccc}
K^- & K^- & K^+ \\
\downarrow & \downarrow & \downarrow \\
\rho, \omega & K^* & \rho, \omega, \phi \\
p & p & \Sigma^+ \\
(a) & (b) & (c)
\end{array} \]

Figure: Vector exchange in the meson-baryon interaction.

The ingredients needed are the $VPP$ Lagrangian

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

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

\[ V^\mu = \begin{pmatrix}
\rho^0 \sqrt{2} + \omega \sqrt{2} \\
\rho^- \\
\rho^+ \\
K^{*-} \\
K^{-} \sqrt{2} + \omega \sqrt{2} \\
\rho^0 \sqrt{2} + \omega \sqrt{2} \\
K^{*0} \\
K^0 \\
\phi
\end{pmatrix}^\mu, \]

with $g = m_V / 2f_\pi$ and $m_V$ the mass of the vector mesons ($\sim 800$ 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 $\pi N$ and $\eta N$.
- The new $\Omega_c$ states from $\Xi_c\bar{K}$?

And many others...
We can use the **unitarized** scattering amplitude, with **effective interaction** $V$:

$$ T = \frac{V}{1 - VG}, \quad (7) $$

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

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

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

$$ \text{det}[1 - VG^{\prime\prime}] = 0, \quad \rightarrow \quad z_R = M_R + i\frac{\Gamma_R}{2}. \quad (9) $$

**→ Resonances appear as poles in the second Riemann sheet of the complex energy plane.**

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

$$ G_i^{\prime\prime} = G_i' + i\frac{p}{4\pi\sqrt{s}}, \quad p = \frac{\lambda^{1/2}(s, m_{1i}^2, m_{2i}^2)}{2\sqrt{s}}, \text{ and Im}(p) > 0. \quad (10) $$

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

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

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

The new $\Omega_c$ states in the Molecular Picture

Introduction

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

$\rightarrow$ **three** states: the $\Omega_c(3050)$, $\Omega_c(3090)$ and $\Omega_c(3119)$,

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**.


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

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

where we include the mixing between $\eta$ and $\eta'$, and

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

- Heavy quark as a spectator $\rightarrow$ SU(3) content of SU(4).
- Respects heavy quark spin symmetry,
- Except for non diagonal transitions like $\Xi_c \bar{K} \rightarrow \Xi D$
  - Exchange a $D_s^* \rightarrow$ 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 $\rho^0$, $\omega$ and $\phi$ (which can be extended to $K^*$, $\rho^\pm$, ...)

$$
\rho^0 = \frac{1}{\sqrt{2}} (u\bar{u} - d\bar{d}),
$$

$$
\omega = \frac{1}{\sqrt{2}} (u\bar{u} + d\bar{d}),
$$

$$
\phi = s\bar{s}.
$$

- $\gamma_\mu \rightarrow \gamma^0$ 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 $\phi_{MS}$, $\phi_{MA}$, $\chi_{MS}$, $\chi_{MA}$ 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:

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

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

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

- $\Xi^+$: $\frac{1}{\sqrt{2}} c(us - su) \uparrow \frac{1}{\sqrt{2}} (\uparrow\downarrow - \downarrow\uparrow)$, (Antisymmetric for the two light quarks, and $\chi_{MA}$).

- $\Xi'^+$: $\frac{1}{\sqrt{2}} c(us + su) \frac{1}{\sqrt{6}} (\uparrow\uparrow\downarrow + \uparrow\downarrow\uparrow - 2 \downarrow\uparrow\uparrow)$, (Symmetric for the two light quarks, and $\chi_{MS}$).

- $\Xi^{*+}$: $\frac{1}{\sqrt{2}} c(us + su) \uparrow\uparrow\uparrow$, (Symmetric for the two light quarks, and $\chi_S$).

Interaction - Example

Formalism

\[
\frac{1}{2} \left( \begin{array}{ccc}
K^- & K^- & K^-\\
\Xi^+_c & \Xi^+_c & \Xi^+_c
\end{array} \right) + \left( \begin{array}{ccc}
K^- & \bar{K}^0 & K^-\\
\Xi^+_c & \Xi^0_c & \Xi^+_c
\end{array} \right) + \left( \begin{array}{ccc}
\bar{K}^0 & K^- & \bar{K}^0\\
\Xi^0_c & \Xi^+_c & \Xi^0_c
\end{array} \right) + \left( \begin{array}{ccc}
\bar{K}^0 & \bar{K}^0 & \rho^0, \omega, \phi\\
\Xi^0_c & \Xi^0_c & \rho^0, \omega, \phi
\end{array} \right)
\]

Figure: Diagrams in the $\bar{K}\Xi_c \rightarrow \bar{K}\Xi_c$ 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

\[
V_{ij} = D_{ij} \frac{2\sqrt{s} - M_{Bi} - M_{Bj}}{4f^2} \sqrt{\frac{M_{Bi} + E_{Bi}}{2M_{Bi}}} \sqrt{\frac{M_{Bj} + E_{Bj}}{2M_{Bj}}},
\]

where $M_{Bi,Bj}$ and $E_{Bi,Bj}$ 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 \( q_{\text{max}} = 650 \) MeV. \( g_i G_i^\| \) is in MeV.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV)</th>
<th>( \Gamma ) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Omega_c(3050)^0 )</td>
<td>3050.2 ± 0.1 ± 0.1^{+0.3}_{-0.5}</td>
<td>0.8 ± 0.2 ± 0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(&lt; 1.2 \text{ MeV, 95% CL})</td>
</tr>
<tr>
<td>( \Omega_c(3090)^0 )</td>
<td>3090.2 ± 0.3 ± 0.5^{+0.3}_{-0.5}</td>
<td>8.7 ± 1.0 ± 0.8</td>
</tr>
</tbody>
</table>

\[ \Rightarrow \text{pseudoscalar}(0^-)-\text{baryon}(1/2^+) \text{ nature with } J^P = 1/2^- \]

- \( \Omega_c(3050)^0 \) mostly \( \Xi'_c \bar{K} \).
- \( \Omega_c(3090)^0 \) mostly \( \Xi D \).
Poles and Couplings - Spin 3/2

Results

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.

<table>
<thead>
<tr>
<th></th>
<th>$\Xi_c^* K$</th>
<th>$\Omega_c^* \eta$</th>
<th>$\Xi^* D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3124.84</td>
<td>1.95</td>
<td>1.98</td>
<td>-0.65</td>
</tr>
<tr>
<td>$g_i$</td>
<td>-35.65</td>
<td>-16.83</td>
<td>1.93</td>
</tr>
<tr>
<td>$g_i G_i^{II}$</td>
<td>0.01 + i0.02</td>
<td>0.31 + i0.01</td>
<td>6.22 - i0.04</td>
</tr>
<tr>
<td>3290.31 + i0.03</td>
<td>-0.62 - i0.18</td>
<td>-5.25 - i0.18</td>
<td>-31.08 + i0.20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV)</th>
<th>$\Gamma$ (MeV)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_c (3119)^0$</td>
<td>3119.1 ± 0.3 ± 0.9$^{+0.3}_{-0.5}$</td>
<td>1.1 ± 0.8 ± 0.4</td>
<td>&lt; 2.6 MeV, 95% CL</td>
</tr>
<tr>
<td>3124.84</td>
<td>0.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

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Results

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.

<table>
<thead>
<tr>
<th>(g_i)</th>
<th>(\Xi D^*)</th>
<th>(\Xi_c K^*)</th>
<th>(\Xi_c' K^*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3221.98</td>
<td>3221.98</td>
<td>0.59</td>
<td>-0.28</td>
</tr>
<tr>
<td>(-29.29)</td>
<td>6.37</td>
<td>-4.66</td>
<td>1.62</td>
</tr>
<tr>
<td>(-0.11 - i0.12)</td>
<td>1.31 - i0.03</td>
<td>0.03 + i0.01</td>
<td></td>
</tr>
<tr>
<td>(2.12 + i0.48)</td>
<td>-26.04 + i0.36</td>
<td>-0.26 - i0.06</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(g_i)</th>
<th>(\Xi D^*)</th>
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<th>(\Xi_c' K^*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-29.29)</td>
<td>6.37</td>
<td>-4.66</td>
<td>1.62</td>
</tr>
<tr>
<td>(-0.11 - i0.12)</td>
<td>1.31 - i0.03</td>
<td>0.03 + i0.01</td>
<td></td>
</tr>
<tr>
<td>(2.12 + i0.48)</td>
<td>-26.04 + i0.36</td>
<td>-0.26 - i0.06</td>
<td></td>
</tr>
<tr>
<td>(-0.84 - i0.23)</td>
<td>0.17 + i0.24</td>
<td>-32.29 - i0.08</td>
<td></td>
</tr>
</tbody>
</table>

- **Degenerated Spin of vector(1\(^-\))-baryon(1/2\(^+\)) nature with** \(J^P = 1/2^-, 3/2^-\).
- New " \(\Omega_c(3222)^0\) " mostly \(\Xi D^*\).
- New " \(\Omega_c(3360)^0\) " mostly \(\Xi_c K^*\).
- New " \(\Omega_c(3465)^0\) " mostly \(\Xi_c' K^*\).
- 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.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV)</th>
<th>$\Gamma$ (MeV)</th>
<th>Yield</th>
<th>$N_\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_c(3000)^0$</td>
<td>$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$</td>
<td>$4.5 \pm 0.6 \pm 0.3$</td>
<td>$1300 \pm 100 \pm 80$</td>
<td>20.4</td>
</tr>
<tr>
<td>$\Omega_c(3050)^0$</td>
<td>$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$</td>
<td>$0.8 \pm 0.2 \pm 0.1$</td>
<td>$970 \pm 60 \pm 20$</td>
<td>20.4</td>
</tr>
<tr>
<td>$\Omega_c(3066)^0$</td>
<td>$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$</td>
<td>$3.5 \pm 0.4 \pm 0.2$</td>
<td>$1740 \pm 100 \pm 50$</td>
<td>23.9</td>
</tr>
<tr>
<td>$\Omega_c(3090)^0$</td>
<td>$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$</td>
<td>$8.7 \pm 1.0 \pm 0.8$</td>
<td>$2000 \pm 140 \pm 130$</td>
<td>21.1</td>
</tr>
<tr>
<td>$\Omega_c(3119)^0$</td>
<td>$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$</td>
<td>$1.1 \pm 0.8 \pm 0.4$</td>
<td>$480 \pm 70 \pm 30$</td>
<td>10.4</td>
</tr>
<tr>
<td>$\Omega_c(3188)^0$</td>
<td>$3188 \pm 5 \pm 13$</td>
<td>$60 \pm 15 \pm 11$</td>
<td>$1670 \pm 450 \pm 360$</td>
<td></td>
</tr>
</tbody>
</table>

$J^P = 1/2^-$  
$3054.05$  
$0.88$  

$J^P = 1/2^-$  
$3091.28$  
$10.24$  

$J^P = 3/2^-$  
$3124.84$  
$0.0$  

$< 1.2\text{MeV}, 95\%\text{ CL}$

$< 2.6\text{MeV}, 95\%\text{ CL}$
The $\Omega^-_b$ baryons have already been measured, most recently by the LHCb Collaboration [1].

The search for the new $\Omega^0_c$ states on the weak decay of the $\Omega^-_b$ was recently proposed in [2].

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

- $\Omega^-_b \rightarrow (\Xi D) \pi^-$
- $\Omega^-_b \rightarrow (\Xi_c K) \pi^-$
- $\Omega^-_b \rightarrow (\Xi'_c K) \pi^-$

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

**Figure:** $\Omega^-_b$ decay at quark level with emission of a $\pi^-$ and subsequent hadronization.


V. R. Debastiani, J. M. Dias, Wei-Hong Liang, E. Oset
The transition $\Xi D \rightarrow \Xi c \bar{K}$ 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.

$$t_{\Omega b \rightarrow \pi \Xi c \bar{K}} = V_P \frac{2}{\sqrt{3}} G_{\Xi D}[M_{\text{inv}}(\Xi c \bar{K})] t_{\Xi D \rightarrow \Xi c \bar{K}}[M_{\text{inv}}(\Xi c \bar{K})].$$  \hspace{1cm} (13)\hspace{1cm} \hspace{1cm} \hspace{1cm} \text{Figure: } \Xi c \bar{K} \text{ invariant mass distribution in } \Omega b \rightarrow \pi \Xi c \bar{K}.

We can predict the following rate of production:

$$\frac{\Gamma_{\Omega b \rightarrow \pi \Omega_c(3050)}}{\Gamma_{\Omega b \rightarrow \pi \Omega_c(3090)}} \approx 10\%. \hspace{1cm} (14)$$

Figure: $\Omega b \rightarrow \pi \Xi c \bar{K}$ process through $\Xi D$ rescattering.
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 Λ(1405).

The $a_0(980) - f_0(980)$ mixing appears naturally in the molecular picture through isospin symmetry breaking in $K\bar{K}$ loops.

We can explain three of the recently measured new $\Omega_c$ states as meson-baryon molecular states with $C = +1$, $S = -2$, with remarkable agreement!

$\Omega_c(3050)^0$ and $\Omega_c(3090)^0$ with $J^P = 1/2^-$, pseudoscalar($0^-$)-baryon($1/2^+$) nature.

$\Omega_c(3119)^0$ with $J^P = 3/2^-$, pseudoscalar($0^-$)-baryon($3/2^+$) nature.

Most important channels are $\Xi_c' \bar{K}$, and $\Xi D$ and $\Xi^*_c \bar{K}$, respectively.

NEXT STEPS: Measure the Spin-Parity of the $\Omega_c$ states,

and search for them in other reactions, like the $\Omega_b^- \rightarrow (\Xi_c^+ K^-) \pi^-$ 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.

<table>
<thead>
<tr>
<th>States</th>
<th>$\Xi_c K$</th>
<th>$\Xi'_c K$</th>
<th>$\Xi D$</th>
<th>$\Omega_c \eta$</th>
<th>$\Xi D^*$</th>
<th>$\Xi_c K^*$</th>
<th>$\Xi'_c K^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold</td>
<td>2965</td>
<td>3074</td>
<td>3185</td>
<td>3243</td>
<td>3327</td>
<td>3363</td>
<td>3472</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>States</th>
<th>$\Xi^*_c K$</th>
<th>$\Omega^*_c \eta$</th>
<th>$\Xi D^*$</th>
<th>$\Xi_c K^*$</th>
<th>$\Xi^* D$</th>
<th>$\Xi'_c K^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold</td>
<td>3142</td>
<td>3314</td>
<td>3327</td>
<td>3363</td>
<td>3401</td>
<td>3472</td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>(J = 1/2)</th>
<th>(\Xi_c K)</th>
<th>(\Xi'_c K)</th>
<th>(\Xi D)</th>
<th>(\Omega_c \eta)</th>
<th>(\Xi D^*)</th>
<th>(\Xi_c K^*)</th>
<th>(\Xi'_c K^*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Xi_c \bar{K})</td>
<td>-1</td>
<td>0</td>
<td>(-\frac{1}{\sqrt{2}}\lambda)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(\Xi'_c \bar{K})</td>
<td>-1</td>
<td>(\frac{1}{\sqrt{6}}\lambda)</td>
<td>(-\frac{4}{\sqrt{3}})</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>(\Xi D)</td>
<td>-2</td>
<td>(\frac{\sqrt{2}}{3}\lambda)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>(\Omega_c \eta)</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\Xi D^*)</td>
<td>-2</td>
<td>(-\frac{1}{\sqrt{2}}\lambda)</td>
<td>(\frac{1}{\sqrt{6}}\lambda)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\Xi_c \bar{K}^*)</td>
<td></td>
<td></td>
<td>-1</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\Xi'_c \bar{K}^*)</td>
<td></td>
<td></td>
<td>-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

\[
\frac{1}{q^0 - |q|^2 - m_{D^*}^2} \approx \frac{1}{(m_D - m_K)^2 - m_{D^*}^2},
\]

and the ratio to the propagator of the light vectors is

\[
\lambda \equiv \frac{-m_V^2}{(m_D - m_K)^2 - m_{D^*}^2} \approx 0.25.
\]
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 \(J^P = 3/2^-\).

<table>
<thead>
<tr>
<th>(J = 3/2)</th>
<th>(\Xi_c^* K)</th>
<th>(\Omega_c^* \eta)</th>
<th>(\Xi D^*)</th>
<th>(\Xi_c K^*)</th>
<th>(\Xi^* D)</th>
<th>(\Xi'_c K^*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Xi_c^* K)</td>
<td>-1</td>
<td>(-\frac{4}{\sqrt{3}})</td>
<td>0</td>
<td>0</td>
<td>(\frac{2}{\sqrt{6}}\lambda)</td>
<td>0</td>
</tr>
<tr>
<td>(\Omega_c^* \eta)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>(-\frac{\sqrt{2}}{3}\lambda)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>(\Xi D^*)</td>
<td>-2</td>
<td>(-\frac{1}{\sqrt{2}}\lambda)</td>
<td>0</td>
<td>(\frac{1}{\sqrt{6}}\lambda)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\Xi_c K^*)</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\Xi^* D)</td>
<td>-2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\Xi'_c K^*)</td>
<td></td>
<td></td>
<td></td>
<td>-1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Same diagonals matrix elements of Ref. [1], non diagonal not the same.
- Heavy baryons wave functions are not eigenstates of \(SU(4) \rightarrow \) 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.


Pion Exchange in $VP \rightarrow VB$ Transition

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

\[
\frac{1}{2} \begin{pmatrix}
D^+ & D^{*+} \\
\Xi^- & \Xi^-
\end{pmatrix}
- \begin{pmatrix}
D^+ & D^{*0} \\
\Xi^- & \Xi^0
\end{pmatrix}
- \begin{pmatrix}
D^0 & D^{*+} \\
\Xi^0 & \Xi^-
\end{pmatrix}
+ \begin{pmatrix}
D^0 & D^{*0} \\
\Xi^0 & \Xi^0
\end{pmatrix}
\]

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

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

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

Another work on Meson-Baryon coupled channels
Comparisons

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

Table: Ω_c and Ω_c^* resonances found using α = 1.16

<table>
<thead>
<tr>
<th>Name</th>
<th>M_R (MeV)</th>
<th>Γ_R (MeV)</th>
<th>J</th>
<th>M^exp_R</th>
<th>Γ^exp_R</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>2922.2</td>
<td>0</td>
<td>1/2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>b</td>
<td>2928.1</td>
<td>0</td>
<td>3/2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>c</td>
<td>2941.3</td>
<td>0</td>
<td>1/2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>d</td>
<td>2999.9</td>
<td>0.06</td>
<td>1/2</td>
<td>3000.4</td>
<td>4.5</td>
</tr>
<tr>
<td>e</td>
<td>3036.3</td>
<td>0</td>
<td>3/2</td>
<td>3050.2</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table: Ω_c and Ω_c^* resonances found using the sharp cutoff Λ = 1090 MeV

<table>
<thead>
<tr>
<th>Name</th>
<th>M_R (MeV)</th>
<th>Γ_R (MeV)</th>
<th>J</th>
<th>M^exp_R</th>
<th>Γ^exp_R</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>2963.95</td>
<td>0.0</td>
<td>1/2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>c</td>
<td>2994.26</td>
<td>1.85</td>
<td>1/2</td>
<td>3000.4</td>
<td>4.5</td>
</tr>
<tr>
<td>b</td>
<td>3048.7</td>
<td>0.0</td>
<td>3/2</td>
<td>3050.2</td>
<td>0.8</td>
</tr>
<tr>
<td>d</td>
<td>3116.81</td>
<td>3.72</td>
<td>1/2</td>
<td>3119.1/3090.2</td>
<td>1.1/8.7</td>
</tr>
<tr>
<td>e</td>
<td>3155.37</td>
<td>0.17</td>
<td>3/2</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>


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:

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

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

In this framework [1], the transitions $VB \rightarrow VP$, vector$(1^-)$-baryon$(1/2^+)$ → pseudoescalar$(0^-)$-baryon$(3/2^+)$, like $\Xi D^* \rightarrow \Xi^* D$ 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 $\Xi D$. (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]!