The molecular nature of some exotic hadrons

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◆ Quark model hadrons vs. exotic hadrons

◆ Baryons interpreted as meson-baryon “molecules” in SU(3). (the Λ(1405), some N*’s)

◆ Extension to SU(4)
  (the new Ω_c states seen recently at LHCb, prediction of Ξ_{cc}’s)

◆ Conclusions
Although the basic constituents in QCD are quarks and gluons (permitting very complicated structures for mesons and baryons), the *conventional quark model* (Gell-Mann, 1964; Zweig, 1964) is probably one of the most successful approaches to hadron structure.

“50 Years of Quarks,” edited by H. Fritzsch and M. Gell-Mann (World Scientific, 2015)

**Mesons:** $q\bar{q}$ states

**Baryons:** $qqq$ states
Light meson spectrum

\[ \nu = n + L - 1 \approx m(\text{GeV}) \]

\( ^{3}\text{P}_2 = 2^{++} \quad ^{1}\text{P}_1 = 1^{++} \quad ^{3}\text{D}_3 = 3^{--} \quad ^{3}\text{D}_2 = 2^{--} \)

\begin{align*}
\pi(1800) & \quad K(1830) & \quad \eta(1760) \\
\frac{1}{2}s_0 = 0^{-+} & \quad \frac{1}{2}s_1 = 1^{-+} & \\
^{3}\text{P}_2 = 2^{++} & \quad ^{1}\text{P}_1 = 1^{++} & \quad ^{3}\text{D}_3 = 3^{--} \quad ^{3}\text{D}_2 = 2^{--} \\
\pi(1300) & \quad \rho(1450) & \quad \eta(1295) \\
K(1460) & \quad K'(1410) & \quad \phi(1480) \\
\eta(1440) & \quad \phi(1680) & \\
\frac{1}{2}s_1 = 1^{-+} & \\
\end{align*}

\( ^{3}\text{P}_0 = 0^{++} \quad ^{1}\text{P}_1 = 1^{-+} \)

\( nL_J = j^{PC} \)

\[ q'q \]


N and \( \Delta \) spectra

\[ \text{Mass [MeV]} \]

\( J^\pi, \Delta J/2^+ \quad \Delta 3/2^+ \quad \Delta 5/2^+ \quad \Delta 7/2^+ \quad \Delta 9/2^+ \quad \Delta 11/2^+ \quad \Delta 1/2^- \quad \Delta 3/2^- \quad \Delta 5/2^- \quad \Delta 7/2^- \quad \Delta 9/2^- \quad \Delta 11/2^- \)

In spite of the success of the conventional quark model, there are many (excited) hadrons that do not accommodate to the $q\bar{q}$ or $qqq$ description:

**Mesons**

<table>
<thead>
<tr>
<th>$f_0(500)$</th>
<th>$a_0(980)$</th>
<th>$f_0(980)$</th>
<th>$f_1(1420)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^+(0^{++})$</td>
<td>$1^{-}(0^{++})$</td>
<td>$0^+(0^{++})$</td>
<td>$0^+(1^{++})$</td>
</tr>
</tbody>
</table>

\[ \rightarrow \text{the same orbital excitation (only different isospin): } (u\bar{u} \pm d\bar{d})/\sqrt{2} \]

\[ \rightarrow \text{s}\bar{s} \]

**Baryons**

<table>
<thead>
<tr>
<th>$N(1440)$</th>
<th>$N(1535)$</th>
<th>$\Lambda(1405)$</th>
<th>$\Lambda(1670)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1/2^+$</td>
<td>$1/2^-$</td>
<td>$1/2^-$</td>
<td>$1/2^-$</td>
</tr>
</tbody>
</table>

\[ \rightarrow \text{radial excitation (too low mass)} \]

\[ \rightarrow \text{orbital excitation (too high mass)} \]

\[ \rightarrow \text{orbital excitation (too low mass)} \]
Exotic hadrons
(anything that goes beyond $q\bar{q}$ and $qqq$)

Mesons

Tetraquarks
($q\bar{q}q\bar{q}$)

Glueballs

compact 4q system

meson-meson bound state
(or molecule)
Exotic hadrons
(anything that goes beyond $q\bar{q}$ and $qqq$)

Baryons

Pentaquarks
($qqqqq$)

compact 5q system

baryon-meson bound state
(or molecule)
Since the beginning of the millenium, an increasing amount of data covering the charm sector (collected at Belle, BaBar, LHCb and BESIII...), has provided clear evidence for many new exotic states which appear to be inconsistent with the predictions of the conventional quark model.

- Nature gives clues to whether a particular hadron may have an exotic multiquark configuration structure

\[ f_0(500) \rightarrow \text{from analyses of } \pi\pi \text{ scattering data} \]
\[ a_0(980) \]
\[ f_0(980) \]
\[ \Lambda(1405) \rightarrow \text{very close to the } \bar{K}N \text{ threshold} \]

- A lot of activity for more than 20 years! ...
...but disentangling the true nature of a particular hadron is not easy due to the mixing of conventional and exotic components.
Masses do not fit into the $c\bar{c}$ predictions.
Charged $Z_c$ states $\rightarrow$ clearly not $c\bar{c}$!
X(3872)

Discovered at Belle in 2003

*Phys. Rev. Lett. 91 (2003) 262001*

Confirmed by BABAR


and by LHCb,

which settled quantum numbers $J^{PC}=1^{++}$

*R. Aaij et al. (LHCb), PRL 110, 222001 (2013)*

Mass very closes to $D^0\bar{D}^{*0}$ threshold, which was an indication of its possible molecular origin

An impressive amount of experimental and theoretical work has been dedicated to understand the nature of the XYZ states discovered in the last decade.

⇒ (recent) reviews:

- E. Eichten et al., Rev. Mod. Phys. 80 (2008) 1161
- J.M. Richard, Few-Body Syst. 57 (2016) 1185

It is a hot topic! Also in this conference (“Hadrons and particles”)

Monday afternoon: **Stadler**
- García-Ortega
- Takeuchi

Thursday afternoon: **Yamaguchi**
- Montaña
The interpretation of some baryons as being systems of 5 quarks has been revived by the observation of very “highly excited” N* in the reaction $\Lambda_b \rightarrow J/\psi \ p \ K^-$. 

[Diagram showing data from 2015 and 2019, with peaks for identified states: $P_c(4450)$, $P_c(4380)$, $P_c(4440)$, $P_c(4457)$, $P_c(4310)$]
• The flavor content of the $P_c(4310)$, $P_c(4440)$, $P_c(4457)$ states is not exotic (uud) but the high mass and the observation from $J/\psi$ p pairs makes them to be unambiguous pentaquark candidates (c\(\bar{c}\)uud).

These states find a natural explanation as baryon-meson molecules!

Threshold $\Sigma_c^+\bar{D}^0 : 4318$ MeV $\rightarrow P_c(4310)$

Threshold $\Sigma_c^+\bar{D}^*0 : 4460$ MeV ($J=1/2,3/2$) $\rightarrow P_c(4440), P_c(4457)$


• More on heavy baryon spectroscopy in this conference:

Session “Hadrons and particles” Thursday afternoon: → Plessas Yamaguchi
Some examples in SU(3)
The $\Lambda(1405)$

- The $\bar{K}N$ interaction in the isospin I=0 channel is able develop a quasi-bound state, the $\Lambda(1405)$, located only 27 MeV below the $\bar{K}N$ threshold.

- Idea originally proposed by Dalitz and Tuan in the late 1950’s
  

- Reformulated in terms of an effective chiral unitary theory in coupled channels by Kaiser, Siegel and Weise in 1995
  

- Extended to the full coupled-basis by Oset and Ramos in 1998.
  

- For ten more years (up to ~2006), plenty of theoretical work (NLO Lagrangian, s-channel and u-channel Born terms...,) finding similar features.
  
  Oller, Meissner, Lutz, Garcia-Recio, Borasoay, Jido, ...
Recently, the more precise SIDDHARTA measurement of the energy shift \( \Delta E \) and width \( \Gamma \) of the 1s state in kaonic hydrogen, clarifying the inconsistency between earlier KEK and DEAR experiments, has injected a renovated interest in the field.


\[
\begin{array}{c|c|c}
\Delta E [\text{eV}] & \Gamma [\text{eV}] \\
\hline
283 \pm 36 \pm 6 & 541 \pm 89 \pm 22 \\
\end{array}
\]

→ the parameters of the NLO meson-baryon Lagrangian can be better constrained
→ better knowledge of the KbarN interaction

1. Meson-baryon effective chiral Lagrangian:

**Lowest order (LO), O(q)**

\[ \mathcal{L}_{MB}^{(1)}(B,U) = \langle \bar{B} i \gamma^\mu \nabla_\mu B \rangle - M_B \langle \bar{B} B \rangle + \frac{1}{2} D \langle \bar{B} \gamma^\mu \gamma_5 \{ u_\mu, B \} \rangle + \frac{1}{2} F \langle \bar{B} \gamma^\mu \gamma_5 [ u_\mu, B ] \rangle \]

\[ \nabla_\mu B = \partial_\mu B + [\Gamma_\mu, B] \]

\[ \Gamma_\mu = \frac{1}{2} \left( u^\dagger \partial_\mu u + u \partial_\mu u^\dagger \right) \]

\[ U = u^2 = \exp \left( \frac{i \sqrt{2} \Phi}{f} \right) \]

\[ u_\mu = i u^\dagger \partial_\mu U u^\dagger \]

\[ \Phi = \begin{pmatrix} \frac{1}{\sqrt{2}} \pi^0 + \frac{1}{\sqrt{6}} \eta_8 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}} \pi^0 + \frac{1}{\sqrt{6}} \eta_8 & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}} \eta_8 \end{pmatrix} \]

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

\[ \rightarrow \text{LO meson-baryon potential in s-wave (contact term)}: \]

\[ V_{ij} = -C_{ij} \frac{1}{4f^2} \bar{u}(p) \gamma^\mu u(p) (k_\mu + k'_\mu) \]

One parameter: \( f \)
Next to leading order (NLO), $O(q^2)$

\[ \mathcal{L}_{MB}^{(2)}(B, U) = b_D \langle \bar{B} \{ \chi_+, B \} \rangle + b_F \langle \bar{B} [\chi_+, B] \rangle + b_0 \langle \bar{B} B \rangle \langle \chi_+ \rangle + d_1 \langle \bar{B} \{ u_\mu, [u_\mu, B] \} \rangle + d_2 \langle \bar{B} \{ u_\mu, [u_\mu, B] \} \rangle = d_3 \langle \bar{B} u_\mu \rangle \langle u_\mu B \rangle + d_4 \langle \bar{B} B \rangle \langle u_\mu u_\mu \rangle \]

explicit chiral symmetry breaking terms: $b_D, b_F, b_0$

\[ \chi_+ = -\frac{1}{4f^2} \{ \Phi, \{ \Phi, \chi \} \} \]

derivative terms: $d_1, d_2, d_3, d_4$

\[ \chi = \begin{pmatrix} m_\pi^2 & 0 & 0 \\ 0 & m_\pi^2 & 0 \\ 0 & 0 & 2m_K^2 - m_\pi^2 \end{pmatrix} \]

$\Rightarrow$ NLO contribution to the meson-baryon potential:

\[ \tilde{V}_{ij} = \frac{1}{f^2} \left( D_{ij} - 2(k_\mu k'_\mu) L_{ij} \right) \sqrt{\frac{M_i + E_i}{2M_i}} \sqrt{\frac{M_j + E_j}{2M_j}} \]

$D_{ij}, L_{ij}$: matrices which depend on the 7 NLO parameters: $b_D, b_F, b_0, d_1, d_2, d_3, d_4$
2. Unitarization:

\[ T_{ij} = V_{ij} + V_{il} G_l T_{lj} \]

N/D, Bethe-Salpeter...

Coupled channels in S=-1 meson-baryon sector:

\[ K^-p, K^0n, \pi^0\Lambda, \pi^0\Sigma^0, \pi^+\Sigma^-, \pi^-\Sigma^+, \eta\Lambda, \eta\Sigma^0, K^+\Xi^-, K^0\Xi^0 \]

3. Regularization of loop function:

\[ G_l = i2M_l \int \frac{d^4q}{(2\pi)^4} \frac{1}{(P-q)^2 - M_l^2 + i\epsilon} \frac{1}{q^2 - m_l^2 + i\epsilon} \]

Dimensional regularization:

\[ G_l = \frac{2M_l}{16\pi^2} \left\{ a_l(\mu) + \ln \frac{M_l^2}{\mu^2} + \frac{m_l^2 - M_l^2}{2s} \ln \frac{m_l^2}{M_l^2} + \frac{\bar{q}_l}{\sqrt{s}} \left[ \ln(s - (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s}) + \ln(s + (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s}) \right. \right. \\
\left. \left. - \ln(-s + (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s}) - \ln(-s - (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s}) \right] \right\} \]

\[ a_l(\mu) \approx -2 \quad \text{"natural size (}\mu\text{~700 MeV)} \quad \text{J.A. Oller and U.G. Meissner, Phys. Lett. B500 (2001) 263} \]
### Threshold observables

<table>
<thead>
<tr>
<th>$\gamma$</th>
<th>$R_n$</th>
<th>$R_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.36 ± 0.04</td>
<td>0.189 ± 0.015</td>
<td>0.664 ± 0.011</td>
</tr>
</tbody>
</table>

\[
\gamma = \frac{\Gamma(K^- p \rightarrow \pi^+ \Sigma^-)}{\Gamma(K^- p \rightarrow \pi^- \Sigma^+)}
\]

\[
R_n = \frac{\Gamma(K^- p \rightarrow \pi^0 \Lambda)}{\Gamma(K^- p \rightarrow \text{neutral states})}
\]

\[
R_c = \frac{\Gamma(K^- p \rightarrow \pi^+ \Sigma^-, \pi^- \Sigma^+)}{\Gamma(K^- p \rightarrow \text{all inelastic channels})}
\]

### Cross sections

![Cross sections](image)

### Photoproduction data

![Photoproduction data](image)

FIG. 2. (Color online) Fit to photoproduction data with fixed unitary amplitudes of $\alpha_l = 1$ and $\beta_l = 1$. Red: $\pi^0 \Sigma^0$; blue: $\pi^- \Sigma^+$; green: $\pi^+ \Sigma^-$. Experimental data are from Ref. [2].
The two-pole structure of the Λ(1405)

T-matrix poles and couplings to physical states with l=0

\[ T_{ij} = \frac{g_i g_j}{\sqrt{s} - M_R + i \Gamma/2}, \]

\( |g_i| \)

<table>
<thead>
<tr>
<th>Coupling</th>
<th>1390 - 66i</th>
<th>1426 - 16i</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi \Sigma )</td>
<td>2.9</td>
<td>1.5</td>
</tr>
<tr>
<td>( K \Lambda )</td>
<td>2.1</td>
<td>2.7</td>
</tr>
<tr>
<td>( \eta \Xi )</td>
<td>0.77</td>
<td>1.4</td>
</tr>
<tr>
<td>( K \Xi )</td>
<td>0.61</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Magas, Oset, Ramos, PRL 95 (2005) 052301

\( \pi^- p \rightarrow K^0 \pi \Sigma \)


\( M \sim 1385 \) MeV
\( \Gamma \sim 50 \) MeV

\( K^- p \rightarrow \pi^0 \pi^0 \Sigma^0 \)


\( M \sim 1420 \) MeV
\( \Gamma \sim 38 \) MeV

→ The Λ(1405) resonance shows different properties (position, width) in different reactions
→ Success of meson-baryon coupled-channel models!
POLE STRUCTURE OF THE $\Lambda(1405)$ REGION

Written November 2015 by Ulf-G. Meißner (Bonn Univ. / FZ Jülich) and Tetsuo Hyodo (YITP, Kyoto Univ.).

The $\Lambda(1405)$ resonance emerges in the meson-baryon scattering amplitude with the strangeness $S = -1$ and isospin $I = 0$. It is the archetype of what is called a dynamically generated resonance, as pioneered by Dalitz and Tuan [1]. The most powerful and systematic approach for the low-energy regime of the strong interactions is chiral perturbation theory (ChPT), see e.g. Ref. 2. A perturbative calculation is, however, not applicable to this sector because of the existence of the $\Lambda(1405)$ just below the $\bar{K}N$ threshold. In this case, ChPT has to be combined with a non-perturbative resummation technique, just as in the case of the nuclear forces. By solving the Lippmann-Schwinger equation with the interaction kernel determined by ChPT and using a particular regularization, in Ref. 3 a successful description of the low-energy $K^-p$ scattering data as well as the mass distribution of the $\Lambda(1405)$ was achieved (for further developments, see Ref. 4 and references therein).

The study of the pole structure was initiated by Ref. 5, which finds two poles of the scattering amplitude in the complex energy plane between the $\bar{K}N$ and $\pi\Sigma$ thresholds. The spectrum in experiments exhibits one effective resonance shape, while the existence of two poles results in the reaction-dependent lineshape [6]. The origin of this two-pole structure is attributed

The acceptance of the $\Lambda(1405)$ as a meson-baryon quasibound state is a real success of the chiral unitary models in coupled channels!
Other sectors...

\[ J^P=1/2^- \]

\[ S=0 \rightarrow N^*(1535) \]


\[ S=-2 \rightarrow \Xi(1620), \Xi(1690) \]


\[ J^P=3/2^- \]

\[ \Delta(1700), \Lambda(1520), \Sigma(1670), \Xi(1820) \]

(Interaction of the 0^- pseudoscalar meson octet with the 3/2^+ baryon decuplet)


for \( W < 2 \) GeV
We obtain two resonances, generated from the interaction of baryons with vector mesons.

The state at 1977 MeV couples mostly to $K^*\Lambda$ and $K^*\Sigma$.

Anomaly in the $K^0_\Sigma^+$ photoproduction cross section in $\gamma p \to K^0 \Sigma^+$


$\gamma p \to K^0 \Sigma^+$
Destructive interference between $K^*\Sigma$ and $K^*\Lambda$ amplitudes, of similar size and shape.

$\gamma n \to K^0 \Sigma^0$ (PREDICTION)
$K^*\Sigma$ and $K^*\Lambda$ amplitudes of different size

Fine tuning to data

$J^P = 1/2^-, 3/2^-$

$M_R = 1972 \text{ MeV} \quad \Gamma_R = 64 \text{ MeV}$

VB model adjusted to reproduce downfall:
- $M_R = 2035 \text{ MeV} \quad \Gamma_R = 125 \text{ MeV}$

NEW! $\gamma n \rightarrow K^0 \Sigma^0$ measured by BGO-OD@ELSA

Tom Jude, NSTAR2019 (K. Kohl, PhD thesis)

- N*(2080) (3/2-) and N*(2090) (1/2-) were in earlier PDG versions.
- We find them generated from the coupled channel Vector-Baryon dynamics!
Charm sector
The new $\Omega_c$’s seen at LHCb


C=1, S=-2

<table>
<thead>
<tr>
<th>state</th>
<th>mass</th>
<th>width</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_c(3000)$</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>
</tr>
<tr>
<td>$\Omega_c^0(3050)$</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>
</tr>
<tr>
<td>$\Omega_c^0(3066)$</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>
</tr>
<tr>
<td>$\Omega_c(3090)$</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>
</tr>
<tr>
<td>$\Omega_c^0(3119)$</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>
</tr>
</tbody>
</table>

Similarly as the $P_c$ pentaquarks, it is plausible that some $\Omega_c$’s can be obtained by adding a $uu$ pair to the natural ssc content → the hadronization of the 5q system could lead to *meson-baryon bound states*.

→ Moreover, the $K\Xi_c$ and $K\Xi_c'$ thresholds, 2964 Mev and 3070 MeV, are in the energy range of interest.
Possible interpretation: css states

Quark models have been revisited after the LHCb discovery of the $5 \Omega_c$ states decaying into $K^-\Xi_c^+$ pairs.

1 heavy quark ($c$) and 2 light quarks ($ss$):

1P-wave orbital excitations of the $ss$ pair w.r.t. the $c$ quark

B.Chen and X.Liu [arXiv:1704.02583 [hep-ph]]

$S_{ss} = 1, S_c = 1/2$ and P-wave excitation $\rightarrow J^P = 1/2^- (2), 3/2^- (2), 5/2^- (1)$

Some states 1P-wave orbital excitations and some others 2S radial excitations


Additional $J^P$ possibilities: $1/2^+, 3/2^+$
Some earlier theoretical works already gave predictions for $\Omega_c$ resonances being meson-baryon molecules:

**SU(8) model:** [O. Romanets et al., Phys. Rev. D85 (2012) 114032]

Could some of these states be “molecular?”

<table>
<thead>
<tr>
<th>$M_R$ (GeV)</th>
<th>$\Gamma_R$ (MeV)</th>
<th>Couplings to main channels</th>
<th>$J$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2810.9</td>
<td>0.0</td>
<td>$g_{\Xi D} = 3.3, g_{\Xi D^<em>} = 1.7, g_{\Xi_c\bar{K}^</em>} = 0.9, g_{\Xi^* D^*} = 4.8,$</td>
<td>1/2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$g_{\Omega_c\eta'} = 0.9, g_{\Omega_c D_s^*} = 4.2$</td>
<td></td>
</tr>
<tr>
<td>2814.3</td>
<td>0.0</td>
<td>$g_{\Xi D^<em>} = 3.7, g_{\Xi^</em> D} = 3.1, g_{\Xi^* D^<em>} = 3.8, g_{\Omega D_s^</em>} = 2.7,$</td>
<td>3/2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$g_{\Omega_c\eta'} = 0.9, g_{\Omega_c D_s^*} = 3.4$</td>
<td></td>
</tr>
<tr>
<td>2884.5</td>
<td>0.0</td>
<td>$g_{\Xi_c\bar{K}} = 2.1, g_{\Xi D^<em>} = 1.7, g_{\Xi_c\bar{K}^</em>} = 1.5, g_{\Xi^* \bar{K}^*} = 1.8,$</td>
<td>1/2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$g_{\Omega_c\phi} = 0.9, g_{\Omega_c\phi} = 1.1$</td>
<td></td>
</tr>
<tr>
<td>2941.6</td>
<td>0.0</td>
<td>$g_{\Xi_c\bar{K}} = 1.9, g_{\Xi D} = 1.5, g_{\Omega_c\eta} = 1.7, g_{\Xi_c\bar{K}^*} = 1.4,$</td>
<td>1/2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$g_{\Xi^* \bar{K}^<em>} = 1.1, g_{\Omega_c\phi} = 1.0, g_{\Omega D_s^</em>} = 0.9$</td>
<td></td>
</tr>
<tr>
<td>2980.0</td>
<td>0.0</td>
<td>$g_{\Xi_c\bar{K}} = 1.9, g_{\Omega_c\eta} = 1.6, g_{\Xi D^<em>} = 1.4, g_{\Xi_c\bar{K}^</em>} = 1.6,$</td>
<td>3/2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$g_{\Xi^* \bar{K}^*} = 1.3, g_{\Omega_c\phi} = 1.2$</td>
<td></td>
</tr>
</tbody>
</table>

But these $\Omega_c$ states are much more bound than the LHCb ones.

→ 3 $\Omega_c$ states (below 2953 MeV)

The only model that gives a prediction above 3 GeV!

We have revisited this model to the light of the new states observed in the C=1, S=-2 sector.

**TABLE VI.** Masses, widths, and couplings of the resonances in the $(I, S, C) = (0, -2, 1)$ sector.

|     | $M$ [MeV] | $\Gamma$ [MeV] | $|g_i|$ | $|g_i|$ | $|g_i|$ |
|-----|-----------|-----------------|--------|--------|--------|
| $\bar{K}\Xi_c(2964)$ | 2959 | 0 | 1.36 | 0.43 | 0.51 |
| $\bar{K}\Xi'_c(3070)$ | 2966 | 1.1 | 2.04 | 4.49 | 0.27 |
| $D\Xi(3189)$ | 3117 | 16 | 2.03 | 1.68 | 5.34 |
| $\eta\Omega_c(3246)$ | | | 1.67 | 3.69 | 0.24 |
| $\eta'\Omega_c(3656)$ | | | 0.10 | 0.07 | 0.35 |
| $D_s\Omega_{cc}(5528)$ | | | 0.17 | 1.17 | 0.19 |
| $\eta_c\Omega_c(5678)$ | | | 0.28 | 0.21 | 1.03 |
We consider the following pseudoscalar-baryon coupled channels:

\[ \bar{K}\Xi_c(2964), \bar{K}\Xi'_c(3070), D\Xi(3189), \eta\Omega_c(3246), \eta'\Omega_c(3656), \quad \bar{D}_s\Omega_{cc}(5528), \eta_c\Omega_c(5678) \]

\[
\begin{array}{cccccc}
\bar{K}\Xi_c & \bar{K}\Xi'_c & D\Xi & \eta\Omega^0_c & \eta'\Omega^0_c \\
\hline
\bar{K}\Xi_c & 1 & 0 & \sqrt{\frac{3}{2} \kappa_c} & 0 & 0 \\
\bar{K}\Xi'_c & 1 & \frac{1}{\sqrt{2}} \kappa_c & -\sqrt{6} & 0 \\
D\Xi & 2 & -\frac{1}{\sqrt{3}} \kappa_c & -\sqrt{\frac{2}{3}} \kappa_c \\
\eta\Omega^0_c & 0 & 0 \\
\eta'\Omega^0_c & 0 & 0 \\
\end{array}
\]

\[ \kappa_c \text{ is a reduction factor accounting for the larger mass in heavy vector meson exchange} \]

\[ \text{strong attraction in the } D\Xi \text{ channel} \]

**TABLE I:** The \( C_{ij} \) coefficients for the \( I = 0, C = 1, S = -2 \) sector of the \( PB \) interaction.

\[ V_{ij}(\sqrt{s}) = -C_{ij} \frac{1}{4f^2} (2\sqrt{s} - M_i - M_j) \sqrt{\frac{E_i + M_i}{2M_i}} \sqrt{\frac{E_j + M_j}{2M_j}} \]
Model 1: Subtraction constants in the dimensional regularization loops chosen so as to make it coincide with cut-off loop ($\Lambda=800\text{ MeV}$)

<table>
<thead>
<tr>
<th></th>
<th>$a_K\Xi_c$</th>
<th>$a_K\Xi'_c$</th>
<th>$a_D\Xi$</th>
<th>$a_{\eta}\Omega_c$</th>
<th>$a_{\eta'}\Omega_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>-2.19</td>
<td>-2.26</td>
<td>-1.90</td>
<td>-2.31</td>
<td>-2.26</td>
</tr>
<tr>
<td>$\Lambda$ (MeV)</td>
<td>800</td>
<td>800</td>
<td>800</td>
<td>800</td>
<td>800</td>
</tr>
</tbody>
</table>

$$a_l(\mu) = \frac{16\pi^2}{2M_l} \left(G_l^{\text{cut}}(\Lambda) - G_l(\mu, a_l = 0)\right)$$

The state at 3051 MeV clearly qualifies as a $D\Xi$ bound state.

The state at 3103 MeV mainly composed by $K\Xi'_c$ and $\eta\Omega_c$.

The state at 3103 MeV clearly qualifies as a $D\Xi$ bound state.

$\rightarrow$ 10 MeV too heavy and too wide...

Exp: $M = 3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$ MeV
\[\Gamma = 8.7 \pm 1.0 \pm 0.8\text{ MeV.}\]
Preliminary comparison using:

\[ q_K \left| \Sigma_i T_i \rightarrow K \Xi_c \right|^2 [\text{MeV}^{-2}] \]

- The states at 3050 MeV and 3090 MeV are in very good agreement with experiment.
- If these states are interpreted as pseudoscalar meson-baryon molecules, their spin-parity can be predicted to be $1/2^-$. 
• These results are corroborated by the recent work:
  (with identical diagonal amplitudes)


  but additional decuplet-pseudoscalar channels included!

  ➔ a J^P=3/2^- Ω_c resonance is obtained, which could be identified with the Ω_c(3119)

• Similarly, the SU(8) model was revisited recently, employing “cut-off oriented”
  regularization


  This model treats simultaneously: Pseudoscalar and vector mesons
  1/2^+ and 3/2^+ baryons

  ➔ results are qualitatively similar to the previous works
The doubly charmed (ground state) baryon $\Xi_{cc}^{++}$ has been recently observed by LHCb


$M(\Xi_{cc}^{++}) = 3621.2 \pm 0.7$ MeV

- Are there $\Xi_{cc}$ resonances with these quantum numbers?
- Could they have a dynamical origin (generated from the interaction of mesons with baryons)?

Q. Llorens, A. Ramos (in preparation)
Pseudoscalar-Baryon channels with C=2, S=0 and JP=1/2

<table>
<thead>
<tr>
<th>Channel</th>
<th>πΞ_{cc}</th>
<th>DΛ_{cc}</th>
<th>ηΞ_{cc}</th>
<th>KΩ_{cc}</th>
<th>DΣ_{cc}</th>
<th>D_sΞ_{cc}</th>
<th>D_sΞ'_{cc}</th>
<th>η'Ξ_{cc}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold</td>
<td>3759</td>
<td>4152</td>
<td>4169</td>
<td>4208</td>
<td>4319</td>
<td>4438</td>
<td>4545</td>
<td>4579</td>
</tr>
</tbody>
</table>

C_{ij} coefficients for PB scattering

\[
\begin{array}{cccccccc}
\pi Ξ_{cc} & DΛ_{cc} & ηΞ_{cc} & KΩ_{cc} & DΣ_{cc} & D_sΞ_{cc} & D_sΞ'_{cc} & η'Ξ_{cc} \\
\pi Ξ_{cc} & 2 & \frac{3}{2} \kappa_c & 0 & \sqrt{\frac{3}{2}} & \frac{-1}{2} \kappa_c & 0 & 0 & 0 \\
DΛ_{cc} & 1 - ξ_{cc} & \frac{-1}{2} \kappa_c & 0 & 0 & 1 & 0 & \frac{-1}{\sqrt{2}} \kappa_c \\
ηΞ_{cc} & 0 & \sqrt{\frac{3}{2}} & \frac{-1}{2} \kappa_c & \kappa_c & \frac{1}{\sqrt{3}} \kappa_c & 0 \\
KΩ_{cc} & 1 & 0 & \sqrt{\frac{3}{2}} \kappa_c & \frac{-1}{\sqrt{2}} \kappa_c & 0 \\
DΣ_{cc} & 3 - ξ_{cc} & 0 & \sqrt{3} & \frac{-1}{\sqrt{2}} \kappa_c \\
D_sΞ_{cc} & 1 - ξ_{cc} & 0 & \frac{-1}{\sqrt{2}} \kappa_c \\
D_sΞ'_{cc} & 1 - ξ_{cc} & \frac{1}{\sqrt{6}} \kappa_c \\
η'Ξ_{cc} & & & & & & 0 \\
\end{array}
\]
Amplitude to different final states:

Poles:

Two-narrow resonances are predicted:

\[ \Xi_{cc}(4134) \rightarrow D\Lambda_c \text{ molecule} \]

\[ \Xi_{cc}(4239) \rightarrow D\Sigma_c \text{ molecule} \]
Conclusions

• There are quite a few baryons than can be naturally described as meson-baryon molecules, generated by the interaction of their hadronic constituents (just as the Deuteron is a bound state of two nucleons)
  → The Λ(1405) is a well tested nice example!

• Disentangling their nature can be a difficult task!
  → decay modes provide valuable information
  → but also coupled channel dynamics (naturally associated to molecules) can manifest in some production reactions, as e.g. the N*(20XX)

• The charm sector is offering a plethora of possibly composite states (pentaquarks P_c, charmonia XYZ, ...)
  → In the Ω_c (C=1, S=-2) sector we can identify two states having a pseudoscalar-baryon molecular nature, hence possibly having J^P=1/2^-
  → We also predict molecular states in the doubly-charmed baryon spectrum

A combined theoretical effort (Quark model/Effective theories/Lattice QCD) is necessary to interpret the new data that is becoming available from various B-factories and LHCb (especially in the prolific charm sector).
Thank you for your attention