Revision of $K^-^3He \rightarrow \Lambda p n$ and the $K^- pp$ bound state. Recent $\Omega_c$ and Pentaquark states

IFIC, Universidad de Valencia

The $K^-^3He \rightarrow \Lambda p n$ reaction and the $K^- pp$ bound state revisited

$\Omega_c$ states

New pentaquarks in the $\Lambda_b \rightarrow J/\psi pK^-$ reaction
Kaon rescattering from the chiral unitary approach

Input for $T_1$ from experiment

Klab = 1 GeV
Options A and B for two different ways to estimate the intermediate K energy to account for nucleon binding
Novelty: In the previous work $T_1$ was parametrized as a real amplitude taken at $k_{\text{lab}} = 1$ GeV, neglecting Fermi motion of the nucleons. Now Fermi motion is considered and we take a more complete amplitude

$$T_1(w_1, p_{\text{out}}, p_{\text{in}}) = g(w_1, p_{\text{out}}, p_{\text{in}}, x) - i h(w_1, p_{\text{out}}, p_{\text{in}}, x) \frac{(p_{\text{out}} \times p_{\text{in}}) \cdot \sigma}{p_{\text{out}} p_{\text{in}}}$$

$$g(w, p_{\text{out}}, p_{\text{in}}, x) = \sum_{L=0}^{\infty} [(L+1)T_{L+}(w, p_{\text{out}}, p_{\text{in}}) + L T_{L-}(w, p_{\text{out}}, p_{\text{in}})] P_L(x),$$

$$h(w, p_{\text{out}}, p_{\text{in}}, x) = \sum_{L=1}^{\infty} [T_{L+}(w, p_{\text{out}}, p_{\text{in}}) - T_{L-}(w, p_{\text{out}}, p_{\text{in}})] P'_L(x),$$

$T_L$ is taken up to $L=4$ from


based on dynamical coupled channels with SU(3) phenomenological Lagrangians
The low energy amplitudes of the kaons are the same, based on the chiral unitary approach, which lead to a $K^{-}\Lambda p$ bound state of about 20 MeV and width of about 80 MeV.

Fig. 3. Comparison between theoretical and experimental results of the $\Lambda p$ invariant mass spectrum $d\sigma/dM_{\Lambda p}$ for the $K^{-3}\text{He} \rightarrow \Lambda pn$ reaction in the momentum transfer window $350 \text{ MeV}/c < q_{\Lambda p} < 650 \text{ MeV}/c$. For the experimental data we subtract the background contribution in the experimental analysis [9].

Molecular $\Omega_c$ states generated from coupled meson-baryon channels

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The $\Xi_c K$ mass spectrum is studied with a sample of pp collision data by LHCb, PRL 017

Five clean narrow peaks are obtained

$\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV)</th>
<th>$\Gamma$ (MeV)</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>
</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>
</tr>
<tr>
<td>$\Omega_c(3066)^0$</td>
<td>$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$</td>
<td>$&lt;1.2$ MeV, 95% C.L.</td>
</tr>
<tr>
<td>$\Omega_c(3090)^0$</td>
<td>$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$</td>
<td>$3.5 \pm 0.4 \pm 0.2$</td>
</tr>
<tr>
<td>$\Omega_c(3119)^0$</td>
<td>$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$</td>
<td>$8.7 \pm 1.0 \pm 0.8$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.1 \pm 0.8 \pm 0.4$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$&lt;2.6$ MeV, 95% C.L.</td>
</tr>
</tbody>
</table>
Chiral Lagrangian

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

\[ \mathcal{L}_{\text{VPP}} = -ig \langle [\Phi, \partial_\mu \Phi] V^\mu \rangle, \quad \mathcal{L}_{\text{BBV}} = g \left( \langle \bar{B} \gamma_\mu [V^\mu, B] \rangle + \langle \bar{B} \gamma_\mu B \rangle \langle V^\mu \rangle \right) \]

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

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

\[ V_\mu = \begin{pmatrix} \frac{1}{\sqrt{2}} \rho^0 + \frac{1}{\sqrt{2}} \omega & \rho^+ & K^{*+} \\ \rho^- & -\frac{1}{\sqrt{2}} \rho^0 + \frac{1}{\sqrt{2}} \omega & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}_\mu \]

Equivalent method:
Local hidden gauge approach
\[\rho^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}),\]
\[\omega = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}),\]
\[\phi = s\bar{s}.
\]

Approximation of taking \(\gamma^\mu \to \gamma^0\)

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

(10)
TABLE I. \( J = 1/2 \) states chosen and threshold mass in MeV.

<table>
<thead>
<tr>
<th>States</th>
<th>( \Xi_c \bar{K} )</th>
<th>( \Xi'_c \bar{K} )</th>
<th>( \Xi D )</th>
<th>( \Omega_c \eta )</th>
<th>( \Xi D^* )</th>
<th>( \Xi_c \bar{K}^* )</th>
<th>( \Xi'_c \bar{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 II. \( J = 3/2 \) states chosen and threshold mass in MeV.

<table>
<thead>
<tr>
<th>States</th>
<th>( \Xi'^*_c \bar{K} )</th>
<th>( \Omega'^*_c \eta )</th>
<th>( \Xi'^*D )</th>
<th>( \Xi'^<em>_c \bar{K}^</em> )</th>
<th>( \Xi'^*D )</th>
<th>( \Xi'^<em>_c \bar{K}^</em> )</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>

BARYON WAVE FUNCTIONS

\( \Xi^+_c : \frac{1}{\sqrt{2}} c((us - su) \), and the spin wave function is the mixed antisymmetric, \( \chi_{MA} \), for the two light quarks.

\( \Xi'^0_c : \) the same as \( \Xi^+_c \), changing \( (us - su) \rightarrow (ds - sd) \).

\( \Xi'^+_c : \frac{1}{\sqrt{2}} c'(us + su) \), and now the spin wave function for the three quarks is the mixed symmetric, \( \chi_{MS} \), in the last two quarks,

\( \Xi'^0_c : \) the same as \( \Xi'^*_c \), changing \( (us + su) \rightarrow (ds + sd) \).

\( \Omega'^0_c : css \), and the spin wave function \( \chi_{MS} \) in the last two quarks, like that for \( \Xi'^*_c \).
No need to invoke SU(4)

With light vector exchange the heavy quarks are spectators. Nothing depends upon them. Heavy quark symmetry is automatically implemented.

Upper vertex

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

\[ -it_{K^-K^-} \begin{pmatrix} \rho^0 \\ \omega \\ \phi \end{pmatrix} = gV_\mu(-ip^\mu - ip'^\mu) \begin{pmatrix} 1/\sqrt{2} \\ 1/\sqrt{2} \\ -1 \end{pmatrix}, \]

\[ -it_{K^0\bar{K}^0\rho^-} = gp^+\mu(-ip^\mu - ip'^\mu), \]

\[ g = \frac{m_v}{2 f}, \quad f = 93 \text{ MeV} \]

Lower vertex

\[ \frac{1}{\sqrt{2}} \langle (us - su) \rangle \begin{pmatrix} g \frac{1}{\sqrt{2}} (u\bar{u} - d\bar{d}) \\ g \frac{1}{\sqrt{2}} (u\bar{u} + d\bar{d}) \\ gs\bar{s} \end{pmatrix} \frac{1}{\sqrt{2}} (us - su) \]

\[ = (1/\sqrt{2}g, 1/\sqrt{2}g, g) \]

FIG. 3. Diagrams in the $\bar{K}\Xi_c \rightarrow \bar{K}\Xi'_c$ transition.
We get three states in very good agreement with experiment, both mass and width.
Related work:


Revisions made after experiment to fit some parameter


Uses SU(4): matrix elements exchanging light vectors are equal. Results similar to ours, but only two states, since they study 1/2^- states only.


Better results than in [17] but the widths and the positions not so good as in the works of Montaña and present work.
Run 1 evidence for $P_c^+ \rightarrow J/\psi p$ pentaquarks in $\Lambda_b \rightarrow J/\psi pK^-$

- **Tightly-bound pentaquark**
  - Decays by fall-apart:
    - Wide states?
    - What slows it down to make $P_{c}(4450)^+$ narrow? $L$ between diquarks?
    - $P_{c}(4380)^+$ $S=1,L=0$ broad, $P_{c}(4450)^+$ $S=0,L=1$ narrow
  - Spectrum (confining potential)
    - Many states expected ($n,L,S$)

- **Loosely-bound pentaquark**
  - Decays by heavy quarks changing confinement partners, then fall-apart:
    - All states narrow
  - Spectrum (shallow potential well)
    - $n=0,L=0$ between hadron
    - Very few states expected (S)
    - Weak binding: masses a few MeV below the related baryon-meson thresholds

$M_{P_c} = M_{J/\psi p} + M_p + \sim 400$ MeV

$\chi_{c1}p$ Run $1 \sim 3$ fb$^{-1}$ for $LHCb$

- $27k \Lambda_b \rightarrow J/\psi pK^-$ signal events
  - 5.4% background

Amplitude model fit to $m_{J/\psi p}$ [GeV]

$P_{c}(4450)^+$
- $M = 4450 \pm 2 \pm 3$ MeV
- $\Gamma = 39 \pm 5 \pm 19$ MeV
- $F.F. = 4.1 \pm 0.5 \pm 1.1 \%$

$P_{c}(4380)^+$
- $M = 4380 \pm 8 \pm 29$ MeV
- $\Gamma = 205 \pm 18 \pm 86$ MeV
- $F.F. = 8.4 \pm 0.7 \pm 4.2 \%$

27k $\Lambda_b \rightarrow J/\psi pK^-$ signal events
5.4% background
The only thresholds below which molecular bound states are expected in this mass range favor "molecular" pentaquarks with meson-baryon substructure!

However, we need to measure J^P's to confirm molecular hypothesis, find isospin partners, ...

Existence of $\Sigma_c^+ \bar{D}^0$ molecule would imply importance of $\rho$-exchange

$P_c(4312)^+$, $P_c(4440)^+$ not near triangle diagram thresholds, $P_c(4457)^+$ is (see backup slides).

Can diquark substructure separated by a potential barrier [Maiani, Polosa, Riquer, PL,B778, 247 (2018)] produce width suppression?
Are masses near thresholds just by coincidence?
This hypothesis is not ruled out.
Heavy quark spin symmetric molecular states from $\bar{D}^(*)\Sigma_c^(*)$ and other coupled channels in the light of the recent LHCb pentaquarks


$$I = 1/2, \eta_c N, J/\psi N, \bar{D}\Lambda_c, \bar{D}\Sigma_c, \bar{D}^*\Lambda_c, \bar{D}^*\Sigma_c, \bar{D}^*\Sigma^*_c$$ for spin parity $J^P = 1/2^-$

$$J/\psi N, \bar{D}^*\Lambda_c, \bar{D}^*\Sigma_c, \bar{D}\Sigma^*_c, \bar{D}^*\Sigma^*_c$$ for $J^P = 3/2^-$

$$T = [1 - V G]^{-1} V$$

HQSS tells that the interaction cannot depend on the spin of the heavy quarks. Then one rewrites the physical states in terms of a basis of states where the spin of the light quarks and the heavy ones are separated. This produces symmetries in the matrix elements of the interaction.
\[ J = 1/2, \ I = 1/2 \]

\[
\begin{pmatrix}
\eta_c N & J/\psi N & \bar{D} \Lambda_c & \bar{D} \Sigma_c & \bar{D}^* \Lambda_c & \bar{D}^* \Sigma_c & \bar{D}^* \Sigma^*_c \\
\mu_1 & 0 & \frac{\mu_{12}}{2} & \frac{3\mu_{13}}{2} & -\frac{\mu_{13}}{2\sqrt{3}} & \sqrt{\frac{2}{3}}\mu_{13} \\
0 & \mu_1 & \frac{\sqrt{3}\mu_{12}}{2} & -\frac{\mu_{13}}{2\sqrt{3}} & -\frac{\mu_{12}}{2} & \frac{5\mu_{13}}{6} & \sqrt{\frac{2}{3}}\mu_{13} \\
\frac{\mu_{12}}{2} & \frac{\sqrt{3}\mu_{12}}{2} & \mu_2 & 0 & 0 & \frac{\mu_{23}}{\sqrt{3}} & \sqrt{\frac{2}{3}}\mu_{23} \\
\frac{\mu_{13}}{2} & -\frac{\mu_{13}}{2\sqrt{3}} & 0 & \frac{1}{3}(2\lambda_2 + \mu_3) & \frac{\mu_{23}}{\sqrt{3}} & \frac{2(\lambda_2 - \mu_3)}{3\sqrt{3}} & \frac{1}{3}\sqrt{\frac{2}{3}(\mu_3 - \lambda_2)} \\
\frac{\sqrt{3}\mu_{12}}{2} & -\frac{\mu_{12}}{2} & 0 & \frac{\mu_{23}}{\sqrt{3}} & \mu_2 & -\frac{2\mu_{23}}{3} & \frac{\sqrt{2}\mu_{23}}{3} \\
-\frac{\mu_{13}}{2\sqrt{3}} & \frac{5\mu_{13}}{6} & \frac{\mu_{23}}{\sqrt{3}} & \frac{2(\lambda_2 - \mu_3)}{3\sqrt{3}} & -\frac{2\mu_{23}}{3} & \frac{1}{9}(2\lambda_2 + 7\mu_3) & \frac{1}{9}\sqrt{2}(\mu_3 - \lambda_2) \\
\sqrt{\frac{2}{3}}\mu_{13} & \sqrt{\frac{2}{3}}\mu_{23} & \frac{1}{3}\sqrt{\frac{2}{3}(\mu_3 - \lambda_2)} & \frac{\sqrt{2}\mu_{23}}{3} & \frac{1}{9}\sqrt{2}(\mu_3 - \lambda_2) & \frac{1}{9}(\lambda_2 + 8\mu_3) & I = 1/2
\end{pmatrix}
\]
• $J = 3/2, I = 1/2$

\[
\begin{pmatrix}
\mu_1 & \mu_1 \mu_2 & \frac{\mu_{13}}{3} & -\frac{\mu_{13}}{\sqrt{3}} & \frac{\sqrt{5} \mu_{13}}{3} \\
\mu_{12} & \mu_2 & \frac{\mu_{23}}{3} & -\frac{\mu_{23}}{\sqrt{3}} & \frac{\sqrt{5} \mu_{23}}{3} \\
\frac{\mu_{13}}{3} & \frac{\mu_{23}}{3} & \frac{1}{9}(8 \lambda_2 + \mu_3) & \frac{\lambda_2 - \mu_3}{3 \sqrt{3}} & \frac{1}{9} \sqrt{5}(\mu_3 - \lambda_2) \\
-\frac{\mu_{13}}{\sqrt{3}} & -\frac{\mu_{23}}{\sqrt{3}} & \frac{\lambda_2 - \mu_3}{3 \sqrt{3}} & \frac{1}{3}(2 \lambda_2 + \mu_3) & \frac{1}{3} \sqrt{\frac{5}{3}}(\lambda_2 - \mu_3) \\
\frac{\sqrt{5} \mu_{13}}{3} & \frac{\sqrt{5} \mu_{23}}{3} & \frac{1}{9} \sqrt{5}(\mu_3 - \lambda_2) & \frac{1}{3} \sqrt{\frac{5}{3}}(\lambda_2 - \mu_3) & \frac{1}{9}(4 \lambda_2 + 5 \mu_3)
\end{pmatrix}
\]

$I = 1/2$

• $J = 5/2, I = 1/2$

$\bar{D}^* \Sigma_c^* : (\lambda_2)_{I=1/2}$
The different terms are evaluated using an extensión of the local hidden gauge approach, with the exchange of vector mesons.

\[ \mu_1 = 0, \quad \mu_{23} = 0, \quad \lambda_2 = \mu_3, \quad \mu_{13} = -\mu_{12}, \]
\[ \mu_2 = \frac{1}{4f^2}(k^0 + k'^0), \quad \mu_3 = -\frac{1}{4f^2}(k^0 + k'^0), \]
\[ \mu_{12} = -\sqrt{6} \frac{m_P^2}{p_{D*}^2 - m_{D*}^2} - \frac{1}{4f^2}(k^0 + k'^0), \]

\( f = f_\pi = 93 \text{ MeV}, \ k^0, k'^0 \) are the energies of the external mesons

The only free parameter is the subtraction constant in the regularization of the meson baryon loops. We take it such that the average mass of our states agrees with experiment.
TABLE I. Dimensionless coupling constants of the \((I = 1/2, J^P = 1/2^-)\) poles found in this work to the different channels.

<table>
<thead>
<tr>
<th></th>
<th>(\eta_cN)</th>
<th>(J/\psi N)</th>
<th>(\bar{D}\Lambda_c)</th>
<th>(\bar{D}\Sigma_c)</th>
<th>(\bar{D}^*\Lambda_c)</th>
<th>(\bar{D}^*\Sigma_c)</th>
<th>(\bar{D}^<em>\Sigma_c^</em>)</th>
</tr>
</thead>
<tbody>
<tr>
<td>((4306.38 + i7.62)) MeV</td>
<td>(g_i)</td>
<td>0.67 + i0.01</td>
<td>0.46 - i0.03</td>
<td>0.01 - i0.01</td>
<td><strong>2.07 - i0.28</strong></td>
<td>0.03 + i0.25</td>
<td>0.06 - i0.31</td>
</tr>
<tr>
<td></td>
<td>(</td>
<td>g_i</td>
<td>)</td>
<td>0.67</td>
<td>0.46</td>
<td>0.01</td>
<td>2.09</td>
</tr>
<tr>
<td>((4452.96 + i11.72)) MeV</td>
<td>(g_i)</td>
<td>0.24 + i0.03</td>
<td>0.88 - i0.11</td>
<td>0.09 - i0.06</td>
<td>0.12 - i0.02</td>
<td>0.11 - i0.09</td>
<td><strong>1.97 - i0.52</strong></td>
</tr>
<tr>
<td></td>
<td>(</td>
<td>g_i</td>
<td>)</td>
<td>0.25</td>
<td>0.89</td>
<td>0.11</td>
<td>0.13</td>
</tr>
<tr>
<td>((4520.45 + i11.12)) MeV</td>
<td>(g_i)</td>
<td>0.72 - i0.10</td>
<td>0.45 - i0.04</td>
<td>0.11 - i0.06</td>
<td>0.06 - i0.02</td>
<td>0.06 - i0.05</td>
<td>0.07 - i0.02</td>
</tr>
<tr>
<td></td>
<td>(</td>
<td>g_i</td>
<td>)</td>
<td>0.73</td>
<td>0.45</td>
<td>0.13</td>
<td>0.06</td>
</tr>
</tbody>
</table>
### TABLE II. Same as Table I for $J^P = 3/2^-$.  

| $g_i$ | $|g_i|$ | $J/\psi N$ | $\bar{D}^*\Lambda_c$ | $\bar{D}^*\Sigma_c$ | $\bar{D}\Sigma_c^*$ | $\bar{D}^*\Sigma_c^*$ |
|---|---|---|---|---|---|---|
| (4374.33 + i6.87) MeV | 0.73 – i0.06 | 0.11 – i0.13 | 0.02 – i0.19 | **1.91 – i0.31** | 0.03 – i0.30 |
| | (4452.48 + i1.49) MeV | 0.30 – i0.01 | 0.05 – i0.04 | **1.82 – i0.08** | 0.08 – i0.02 | 0.01 – i0.19 |
| | (4519.01 + i6.86) MeV | 0.66 – i0.01 | 0.11 – i0.07 | 0.10 – i0.3 | 0.13 – i0.02 | **1.79 – i0.36** |

### TABLE III. Identification of some of the $I = 1/2$ resonances found in this work with experimental states.  

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>4306.4</td>
<td>15.2</td>
<td>$\bar{D}\Sigma_c$</td>
<td>1/2$^-$</td>
<td>$P_c(4312)$</td>
</tr>
<tr>
<td>4453.0</td>
<td>23.4</td>
<td>$\bar{D}^*\Sigma_c$</td>
<td>1/2$^-$</td>
<td>$P_c(4440)$</td>
</tr>
<tr>
<td>4452.5</td>
<td>3.0</td>
<td>$\bar{D}^*\Sigma_c$</td>
<td>3/2$^-$</td>
<td>$P_c(4457)$</td>
</tr>
</tbody>
</table>
Similar conclusions based on single channels.
Conclusions

Improvements on the K⁻⁻³He -> Λ pn, adjusting to the experimental cuts, lead to a very good agreement with experiment. Results compatible with small binding of the K⁻ pp system.

Extension of chiral unitary theory to the heavy sector, using the exchange of vectors in the hidden gauge approach, together with unitarity in coupled channels leads to neat predictions for molecular states.

Recent results for Ωc states and the new pentaquarks states of hidden charm, are giving support to these molecular pictures.