Heavy (charm) excited baryons with heavy-quark spin symmetry

Laura Tolós
Rafael Pavao
Juan M. Nieves
**Experimental scenario and theoretical predictions $\Omega_c$:**

- five $\Omega_c$ with masses between 3 and 3.1 GeV are detected by LHCb analyzing the $\Xi^+_c K^-$ spectrum in pp collisions  
  Aaij et al '17
- four of them are seen by Belle in $e^- e^+$ collisions  
  Yelton et al '18

<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 ± 0.2 ± 0.1 ± 0.3</td>
<td>4.5 ± 0.6 ± 0.3</td>
</tr>
<tr>
<td>$\Omega_c (3050)^0$</td>
<td>3050.2 ± 0.2 ± 0.1 ± 0.3</td>
<td>0.8 ± 0.2 ± 0.1</td>
</tr>
<tr>
<td>$\Omega_c (3066)^0$</td>
<td>3065.6 ± 0.1 ± 0.3 ± 0.3</td>
<td>3.5 ± 0.4 ± 0.2</td>
</tr>
<tr>
<td>$\Omega_c (3090)^0$</td>
<td>3090.2 ± 0.3 ± 0.5 ± 0.3</td>
<td>8.7 ± 1.0 ± 0.8</td>
</tr>
<tr>
<td>$\Omega_c (3119)^0$</td>
<td>3119.1 ± 0.3 ± 0.9 ± 0.3</td>
<td>1.1 ± 0.8 ± 0.4</td>
</tr>
<tr>
<td>$\Omega_c (3188)^0$</td>
<td>3188 ± 5 ± 13</td>
<td>&lt;2.6 MeV, 95% C.L.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\Omega_c$ Excited State</th>
<th>Yield</th>
<th>Significance</th>
<th>LHCb Mass</th>
<th>Belle Mass (with fixed $\Gamma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_c (3000)$</td>
<td>37.7 ± 11.0</td>
<td>3.9 $\sigma$</td>
<td>3000.4 ± 0.2 ± 0.1</td>
<td>3000.7 ± 1.0 ± 0.2</td>
</tr>
<tr>
<td>$\Omega_c (3050)$</td>
<td>28.2 ± 7.7</td>
<td>4.6 $\sigma$</td>
<td>3050.2 ± 0.1 ± 0.1</td>
<td>3050.2 ± 0.4 ± 0.2</td>
</tr>
<tr>
<td>$\Omega_c (3066)$</td>
<td>81.7 ± 13.9</td>
<td>7.2 $\sigma$</td>
<td>3065.5 ± 0.1 ± 0.3</td>
<td>3064.9 ± 0.6 ± 0.2</td>
</tr>
<tr>
<td>$\Omega_c (3090)$</td>
<td>86.6 ± 17.4</td>
<td>5.7 $\sigma$</td>
<td>3090.2 ± 0.3 ± 0.5</td>
<td>3089.3 ± 1.2 ± 0.2</td>
</tr>
<tr>
<td>$\Omega_c (3119)$</td>
<td>3.6 ± 6.9</td>
<td>0.4 $\sigma$</td>
<td>3119 ± 0.3 ± 0.9</td>
<td>-</td>
</tr>
<tr>
<td>$\Omega_c (3188)$</td>
<td>135.2 ± 43.0</td>
<td>2.4 $\sigma$</td>
<td>3188 ± 5 ± 13</td>
<td>3199 ± 9 ± 4</td>
</tr>
</tbody>
</table>

Aaij et al '17  
Yelton et al '18
\( \Xi_c \):

four \( \Xi_c \) states below 3 GeV

<table>
<thead>
<tr>
<th>Baryon</th>
<th>( J^P )</th>
<th>( M ) (MeV)</th>
<th>( \Gamma ) (MeV)</th>
<th>Decay channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Xi_c(2790)^+/\Xi_c(2790)^0 )</td>
<td>1/2(^-)</td>
<td>2792.4 ± 0.5 / 2794.1 ± 0.5</td>
<td>8.9 ± 1 / 10 ± 1.1</td>
<td>( \Xi_c' \pi )</td>
</tr>
<tr>
<td>( \Xi_c(2815)^+/\Xi_c(2815)^0 )</td>
<td>3/2(^-)</td>
<td>2816.73 ± 0.21 / 2820.26 ± 0.27</td>
<td>2.43 ± 0.26 / 2.54 ± 0.25</td>
<td>( \Xi_c' \pi, \Xi_c^* \pi )</td>
</tr>
<tr>
<td>( \Xi_c(2930)^+/\Xi_c(2930)^0 )</td>
<td>?</td>
<td>2942 ± 5 / 2929.7(^{+2.8}_{-5})</td>
<td>15 ± 9 / 26 ± 8</td>
<td>( \Lambda_c^+ K^- , \Lambda_c^+ K_S^0 )</td>
</tr>
<tr>
<td>( \Xi_c(2970)^+/\Xi_c(2970)^0 )</td>
<td>?</td>
<td>2969.4 ± 0.8 / 2967.8(^{+0.9}_{-0.7})</td>
<td>20.9(^{+2.4}<em>{-3.5}) / 28.1(^{+3.4}</em>{-4})</td>
<td>( \Lambda_c^+ K\pi, \Sigma_c K, \Xi_c 2\pi, \Xi_c' \pi, \Xi_c^* \pi )</td>
</tr>
</tbody>
</table>

\( \Xi_c(2930) \) recently discovered in its decay to \( K^- \Lambda_c^+ \) in 
\( B^- \rightarrow K^- \Lambda_c^+ \Lambda_c^- \) by Belle
Earlier predictions were reported within different approaches, but this discovery has triggered a large activity revisiting conventional quark models, QCD sum-rule schemes, quark-soliton models, lattice QCD and molecular models. Some recent examples of molecular models are:

**Ω_c**

- Montana, Feijoo and Ramos ‘18
  - two states with J=1/2- identified with Ω_c(3050) and Ω_c(3090)

- Debastiani, Dias, Liang and Oset ‘18
  - two states with J=1/2- identified with Ω_c(3050) and Ω_c(3090), and one state J=3/2- identified with Ω_c(3119)

- Wang, Liu, Kang and Guo ‘18
  - identification of 1/2- Ω_c(3118) as superposition of two DΞ states

- Chen, Liu, Hosaka ‘18
  - prediction of 3/2- Ω_c(3140) loosely bound state with large Ξ_c^+K component

**Ξ_c**

- Yu, Pavao, Debastiani and Oset ‘18
  - five Ξ_c states with masses around 3 GeV, that can be identified with the experimental Ξ_c(2790), Ξ_c(2930), Ξ_c(2970), Ξ_c(3055) and Ξ_c(3080)
Our molecular model
unitarized coupled-channel model with a
SU(6)$_{lsf}$ x HQSS - extended
WT meson-baryon interaction

\[ V = \frac{K(s)}{4f^2} H_{WT} \]

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

typically regularized with one subtraction at certain scale

\[ G_{ij} \text{ regularized with one subtraction at certain scale} \]

\[ \Omega_c : C=1, S=-2, I=0 \]

\[ \Xi_c : C=1, S=-1, I=1/2 \]
Our molecular model unitarized coupled-channel model with a SU(6)lsf x HQSS - extended WT meson-baryon interaction

\[ V = \frac{K(s)}{4f^2} H_{WT} \]

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

coupling constant

\[ T_{ij}(s) \simeq \frac{g_i g_j}{\sqrt{s} - \sqrt{S_R}} \]

mass and width

\( G_{ij} \) regularized with one subtraction at certain scale

\[ \Omega_c : C=1, S=-2, I=0 \]

\[ \Xi_c : C=1, S=-1, I=1/2 \]

too low in mass to be identified experimentally

too low in mass, only two might be identified experimentally

Romanets, LT, Garcia-Recio, Nieves, Salcedo, Timmermans ’12
Regularization schemes (RS) of the loop function

\[ G_i(s) = i 2 M_i \int \frac{d^4q}{(2\pi)^4} \frac{1}{q^2 - m_i^2 + i\epsilon} \frac{1}{(P - q)^2 - M_i^2 + i\epsilon} \]

\[ G_i(s) = \overline{G_i}(s) + G_i(s_{i+}) \quad \text{with} \quad s_{i+} = (m_i + M_i)^2 \]

**One-subtraction regularization**
(one subtraction at certain scale)

\[ G_i(\sqrt{s} = \mu) = 0 \]
\[ G_i^\mu(s) = \overline{G_i}(s) - \overline{G_i}(\mu^2) \]

**Common cutoff regularization**
(use of a common UV cutoff)

\[ G_i^\Lambda(s) = \overline{G_i}(s) + G_i^\Lambda(s_{i+}) \]

Note that using channel-dependent cutoffs, the one-subtraction regularization scheme is recovered by choosing \( \Lambda_i \) in each channel such that

\[ G_i^\Lambda(i) (s_{i+}) = - \overline{G_i}(\mu^2) \]
We need to explore the impact of different RS in a control manner: employ common UV cutoff within reasonable limits

first we determine how masses (and widths) of the states change as we adiabatically vary the subtraction constants

\[ G_i(s) = \bar{G}_i(s) - (1 - x)\bar{G}_i(\mu^2) + xG_i^\Lambda(s_i+) \]

\[ x \text{ changes from 0 to 1} \]

- two J=1/2 and one J=3/2 can be identified with three experimental states due to closeness in energy and also because of the important contribution of the experimental channels \( \Xi'_cK, \Xi_cK \) to their dynamical generation

- need to assess the cutoff dependence of our results

\[ \Omega_c: C=1, S=-2, I=0 \]

\[ \Lambda = 1090 \text{ MeV} \]

<table>
<thead>
<tr>
<th>Name</th>
<th>( M_R ) (MeV)</th>
<th>( \Gamma_R ) (MeV)</th>
<th>( J )</th>
<th>( M_R^{exp} )</th>
<th>( \Gamma_R^{exp} )</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>

Nieves, Pavao and LT '18
\( \Omega_c : C=1, S=-2, I=0 \)

- for \( \Lambda < 1000 \) MeV or \( \Lambda > 1300 \) MeV no identification is possible
- a maximum number of three states can be identified
$\Xi_c : C=1, S=-1, I=1/2$

from one-subtraction regularization (DR) to common UV cutoff

assessing dependence on common UV cutoff

Nieves, Pavao and LT (in preparation)
\( \Xi_c : C=1, S=-1, I=1/2 \) \[ \Lambda = 1150 \text{ MeV} \]

<table>
<thead>
<tr>
<th>Irreps</th>
<th>State</th>
<th>( M_R ) (MeV)</th>
<th>( \Gamma_R ) (MeV)</th>
<th>( J )</th>
<th>Couplings</th>
</tr>
</thead>
</table>
| (168, 21_{2,1}, 3_{2}) | c1    | 2773.59         | 10.52                | 1/2  | \( g_{\Xi_c \pi} = 0.53, g_{\Xi_c' \pi} = 0.32, g_{\Lambda_c K} = 1.3, g_{\Sigma_c K} = 0.92, g_{\Lambda_D} = 1.6, \)  
|               |       |                 |                      |      | \( g_{\Sigma D} = 1.5, g_{\Lambda_D'} = 2.9, g_{\Sigma D'} = 1.0, g_{\Xi_c' \rho} = 1.0, g_{\Lambda_c K'} = 0.23 \) |
| (168, 15_{2,1}, 6_{2}) | c2    | 2627.5          | 38.84                | 1/2  | \( g_{\Xi_c \pi} = 1.8, g_{\Xi_c' \pi} = 0.04, g_{\Lambda_c K} = 1.2, g_{\Sigma_c K} = 0.09, g_{\Lambda_c K'} = 0.04, \)  
|               |       |                 |                      |      | \( g_{\Sigma D} = 1.2, g_{\Lambda_D'} = 1.0, g_{\Sigma D'} = 1.9 \) |
| (168, 21_{2,1}, 6_{2}) | c3    | 2791.24         | 17.31                | 1/2  | \( g_{\Xi_c \pi} = 0.37, g_{\Xi_c' \pi} = 0.8, g_{\Lambda_c K} = 0.26, g_{\Sigma_c K} = 1.6, g_{\Sigma D} = 2.6, \)  
|               |       |                 |                      |      | \( g_{\Lambda_D'} = 2.7, g_{\Xi_c' \eta} = 1.1, g_{\Lambda_c K'} = 1.1, g_{\Sigma D'} = 2.5, g_{\Xi_c' \rho} = 1.8 \) |
| (168, 21_{2,1}, 6_{4}) | c4    | 2850.89         | 6.76                 | 3/2  | \( g_{\Xi_c \pi} = 0.57, g_{\Xi_c' \bar{K}} = 2.2, g_{\Lambda_c K} = 1.5, g_{\Xi_c' \eta} = 1.1, g_{\Sigma D} = 1.1, \)  
|               |       |                 |                      |      | \( g_{\Sigma D'} = 1.5, g_{\Sigma_c \bar{K}}' = 1.8 \) |
| (168, 15_{2,1}, 3_{2}) | c5    | 2715.23         | 12.28                | 1/2  | \( g_{\Xi_c \pi} = 0.21, g_{\Xi_c' \pi} = 1.8, g_{\Lambda_c K} = 0.49, g_{\Sigma_c K} = 1.2, g_{\Lambda_D} = 3.1, \)  
|               |       |                 |                      |      | \( g_{\Lambda_c K'} = 0.07, g_{\Sigma D} = 1.5 \) |
| (120, 21_{2,1}, 3_{2}) | c6    | 2806.89         | 0                    | 1/2  | \( g_{\Xi_c \pi} = 0.15, g_{\Xi_c' \pi} = 0.03, g_{\Lambda_c K} = 0.16, g_{\Sigma_c K} = 0.06, g_{\Lambda_D} = 1.8, \)  
|               |       |                 |                      |      | \( g_{\Sigma D} = 1.4, g_{\Lambda_D'} = 1.7, g_{\Lambda_c K'} = 1.2, g_{\Sigma D'} = 1.5, g_{\Xi_c' \rho} = 1.2, \)  
|               |       |                 |                      |      | \( g_{\Sigma D'} = 3.7, g_{\Xi_c' \eta} = 1.1, g_{\Xi_c' \rho} = 1.0, g_{\Xi_c' \rho} = 1.9 \) |
| (120, 21_{2,1}, 6_{2}) | c7    | 2922.5          | 2.48                 | 1/2  | \( g_{\Xi_c \pi} = 1.7, g_{\Xi_c' \bar{K}} = 1.1, g_{\Lambda_D} = 2.4, g_{\Sigma D'} = 1.2, g_{\Lambda_c K'} = 0.23 \)  
|               |       |                 |                      |      | \( g_{\Sigma D} = 2.8, g_{\Xi_c' \eta} = 3.4, g_{\Xi_c' \rho} = 1.4, g_{\Xi_c' \rho} = 1.8 \) |
| (168, 15_{2,1}, 3_{2}) | c8    | 2792.06         | 22.79                | 3/2  | \( g_{\Xi_c \pi} = 0.2, g_{\Sigma_c K} = 0.19, g_{\Lambda_c K'} = 0.4, g_{\Lambda_D'} = 2.7, g_{\Sigma D'} = 2.2, \)  
|               |       |                 |                      |      | \( g_{\Sigma D} = 2.8, g_{\Xi_c' \eta} = 3.4, g_{\Xi_c' \rho} = 1.4, g_{\Xi_c' \rho} = 1.8 \) |
| (120, 21_{2,1}, 6_{4}) | c9    | 2942.05         | 1.46                 | 3/2  | \( g_{\Xi_c \pi} = 1.7, g_{\Xi_c' \bar{K}} = 1.1, g_{\Lambda_D} = 2.4, g_{\Sigma D'} = 1.2, g_{\Lambda_c K'} = 0.23 \)  
|               |       |                 |                      |      | \( g_{\Sigma D} = 2.8, g_{\Xi_c' \eta} = 3.4, g_{\Xi_c' \rho} = 1.4, g_{\Xi_c' \rho} = 1.8 \) |

Nieves, Pavao and LT (in preparation)

**Experimental identification based on energy position and couplings**

\( \Xi_c (2790) \): \( c_1, c_3 \) or \( c_6 \) (coupling to \( \Xi_c' \pi \)), different assignment using DR

\( \Xi_c (2930) \): \( c_7 \) (assuming 1/2- and given coupling to \( \Lambda_c \bar{K} \))

\( \Xi_c (2815) \): \( c_4 \) or \( c_8 \) (coupling to \( \Xi_c' \pi \)), different assignment using DR

\( \Xi_c (2970) \): \( c_9 \) (assuming 3/2-) and given coupling to \( \Lambda_c \bar{K} \rightarrow \Lambda_c \bar{K} \pi \)

and \( \Xi_c' \pi \rightarrow \Xi_c \pi \pi \)
Experimental identification based on SU(3)_{2J+1} classification of Λ_c and Ξ_c

Ξ_c(2815)
- Considering Λ_c(2625)* and c_8 SU(3) siblings with 1- Idof (Σ^*_c π/ Ξ^*_c π)
- Taking Ξ_c(2815) as c_8 state with mixing of c_4 to obtain Γ=2-3 MeV,
then Ξ_c(2815) and Λ_c(2625)* SU(3) siblings (same 3^*_4 multiplet)

Ξ_c(2790)
- Considering Λ_c(2625)* HQSS partner of Λ_c(2595) (wide), then partner of c_5
- Assuming Ξ_c(2815) is the HQSS partner of Ξ_c(2790), then Ξ_c(2790) is
  c_5 state with mixing with c_3 and c_6 to reduce the decay width (3_2 multiplet)

Ξ_c(2930) and Ξ_c(2970)
Taking Ξ_c(2930) and Ξ_c(2970) our c_7 and c_9 states (assuming 1/2- and 3/2-),
then Ξ_c(2930) and Ξ_c(2970) HQSS partners (6_2 and 6_4 multiplets)

| Ξ_c(2790) 1/2- and Ξ_c(2815) 3/2- HQSS partners |
| Ξ_c(2930) (assuming 1/2-) and Ξ_c(2970) (assuming 3/2-) HQSS partners |

Ξ_c(2930) and Ω_c(3090) SU(3) siblings (same 6_2 multiplet) with Σ_c(2800) (?)
Ξ_c(2970) and Ω_c(3119) (!!) SU(3) siblings (same 6_4 multiplet) with Σ_c(2800)(?)

* assuming Λ_c(2625) is a molecular state
Comparison with recent molecular models

\[ \Omega_c : C=1, S=-2, I=0 \]

Montana, Feijoo and Ramos ‘18
- \( t \)-channel vector meson exchange between \( 1/2^+ \) baryons and \( 0^-,1^- \) mesons
- two states with \( J=1/2^- \) identified with \( \Omega_c(3050) \) and \( \Omega_c(3090) \)

Debastiani, Dias, Liang and Oset ‘18
- local hidden gauge model with \( 1/2^+,3/2^+ \) baryons and \( 0^-,1^- \) vector mesons
- two states with \( J=1/2^- \) identified with \( \Omega_c(3050) \) and \( \Omega_c(3090) \), and one state \( J=3/2^- \) identified with \( \Omega_c(3119) \)

Our model identifies \( J=1/2^- \) \( \Omega_c(3000) \), \( \Omega_c(3119/3090) \) and \( J=3/2^- \) \( \Omega_c(3050) \) for \( \Lambda=1090 \) MeV due to a different regularization scheme and different interaction matrices (in particular for \( D, D^* \) and light vector mesons)

Wang, Liu, Kang and Guo ‘18
identification of \( 1/2^- \) \( \Omega_c(3118) \) as superposition of two \( \Xi D \) states

Chen, Liu, Hosaka ‘18
prediction of \( 3/2^- \) \( \Omega_c(3140) \) loosely bound state with large \( \Xi_c^* K \) component

No identification is possible in our model: \( \Omega_c(3118) \) comes from less attractive representation and \( \Omega_c(3140) \) is not seen as we incorporate \( \Xi(\cdot) D(\cdot) \)
Comparison with recent molecular models

$\Xi_c : C=1, S=-1, I=1/2$

Yu, Pavao, Debastiani and Oset ‘18

- local hidden gauge model with $1/2^+, 3/2^+$ baryons and $0^-, 1^-$ vector mesons
- five $\Xi_c$ states with masses around 3 GeV, that can be identified with the experimental $\Xi_c(2790), \Xi_c(2930), \Xi_c(2970), \Xi_c(3055)$ and $\Xi_c(3080)$
- whereas $\Xi_c(2790)$ is obtained with $1/2^-$, $\Xi_c(2930), \Xi_c(2970), \Xi_c(3055)$ and $\Xi_c(3080)$ can be either $1/2^-$ or $3/2^-$ states

our model identifies

$(\Xi_c(2790) \ 1/2^-, \ \Xi_c(2815) \ 3/2^-)$ and
$(\Xi_c(2930) \ 1/2^-, \ \Xi_c(2970) \ 3/2^-)$ as HQSS partners

the differences are due to a different regularization scheme and different interaction matrices (in particular for D, D* and light vector mesons)
We study charm excited baryons ($\Omega_c$ and $\Xi_c$), where several excited states with masses around 3 GeV have been observed.

We use a unitarized coupled-channel approach with a SU(6)$_{lsf} \times$ HQSS - extended WT meson-baryon interaction and analyze the dependence on the regularization scheme, and in particular on the common UV cutoff.

We find that a maximum number of three $\Omega_c$ states can be identified experimentally, whereas the experimental ($\Xi_c(2790)$ 1/2-, $\Xi_c(2815)$ 3/2-) and ($\Xi_c(2930)$ 1/2-, $\Xi_c(2970)$ 3/2-) are found to be HQSS partners.