Charm hadron spectroscopy

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June 1st, 2021
CHARM2020/2021
Why studying charm hadrons?

- Two types of exotics:
  - Genuine exotics – no convent. expected
  - **Mixture** – the conventional states are influenced particle interaction. Mass shift towards the strongly-coupled threshold.

- $b/c$ hadrons are narrow

- Level-splitting hierarchy due to $1/m_Q$
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Baryons

- Quark-diquark picture
- Many deeply connected sectors, e.g.
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- Level-splitting hierarchy due to $1/m_Q$
Lattice QCD: 5 $\lambda$ modes and 2 $\rho$ modes

$\Xi(ssu)$

$\Omega_c$

$\Xi'_c K$

$\Xi_c K$

$\Omega^+_c(ssc)$

[PRD87 (2013) 054506]

[PRL 119 (2017) 4, 042001]
Heavy-quark-diquark system

Charm-baryon sectors

- Heavy quark is **static** and **spinless** in the limit $m_Q \to \infty$.
- Excitations of $Qqq$ are governed by the light diquark $q \uparrow(J^P=\frac{1}{2}^+) \otimes q \uparrow(J^P=\frac{1}{2}^+) \Rightarrow \uparrow\downarrow(J^P=0^+)$ and $\uparrow\uparrow(J^P=1^+)$

- Excitation pattern is different for “good” and “bad” diquarks

\[
\begin{align*}
\Lambda_c & \quad \text{“good”} \\
\Sigma_c & \quad \text{“bad” (isospin)} \\
\Xi_c & \quad \text{“good” + “bad”} \\
\Omega_c & \quad \text{“bad” (identity)}
\end{align*}
\]
Excitation spectrum of baryons with “bad” diquark

Structure:
- Radial and orbital excitations

Light d.o.f.: Spin-Orbit splitting
“Hyperfine” doublets: heavy-quark spin

Counting of states – model independent
Size of splitting, the order – differs from model to model
Excitation spectrum of baryons with “bad” diquark

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Size of splitting, the order
- differs from model to model
Phenomenological models

- Agree on the general pattern
- Agree on relation between the sectors

\[ \Sigma_b \]

\[ \Lambda_b \]

\[ \Lambda_b (5815) \]

\[ \Sigma_b (5825) \]

\[ \Lambda_b (5912) \]

\[ \Sigma_b (6097) \]

\[ \Lambda_b (5920) \]

\[ \Sigma_b (5835) \]

\[ \Lambda_b (5620) \]

\[ \Sigma_b \]

\[ \Lambda_b (5620) \]

\[ \Sigma_b (5815) \]

- Often neglect the diquark excitation
- Disagree on the splitting and the order

[Bing Chen et al., PRD98 (2018) 074032]

[Faustov-Galkin, EPJ Web Conf. 204 (2019) 08001]
[Shah-Thakkar-Rai-Vinodkumar, EPJA 52 (2016) 10, 313]
Phenomenological models

- Agree on the general pattern
- Agree on relation between the sectors

Mass (in GeV)

- $\Xi_b$
- $\Xi'_b$
- $\Xi_b(5795)$$^-$
- $\Xi_b(5935)$$^-$
- $\Xi_b(6227)$$^-$$^+$

1P states in QM

- FG
- RP
- STRV

[Faustov-Galkin, EPJ Web Conf. 204 (2019) 08001]
[Shah-Thakkar-Rai-Vinodkumar, EPJA 52 (2016) 10, 313]

- Often neglect the diquark excitation
- Disagree on the splitting and the order

[Bing Chen et al., PRD98 (2018) 031502]
Strong transitions to a baryon and a pseudoscalar

\[
\begin{align*}
\Omega_{c}^{**0} & \rightarrow \Xi_{c}^{+} K^- \\
\Omega_{b}^{**-} & \rightarrow \Xi_{b}^{0} K^- \\
\Xi_{c}^{**0} & \rightarrow \Lambda_{c}^{+} K^- \\
\Xi_{b}^{**-} & \rightarrow \Lambda_{b}^{0} K^- \\
\Sigma_{c}^{**0} & \rightarrow \Lambda_{c}^{+} \pi^- \\
\Sigma_{b}^{**-} & \rightarrow \Lambda_{b}^{0} \pi^- 
\end{align*}
\]

HQSS \((m_Q \rightarrow \infty)\) gives the selection rule based on the light d.o.f. [Chiladze, Falk, PRD 56 (1997)] Can be applied to the decay to ground-state baryon and pseudoscalar \((B + P)\):

<table>
<thead>
<tr>
<th>(J^P) (light d.o.f.)</th>
<th>(J^P)</th>
<th>(B + P) (light d.o.f.)</th>
<th>(B + P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0(^-)</td>
<td>1/2(^-)</td>
<td>(S)-wave</td>
<td>(S)-wave</td>
</tr>
<tr>
<td>1(^-)</td>
<td>1/2(^-)</td>
<td>forbidden</td>
<td>(S)-wave</td>
</tr>
<tr>
<td>1(^-)</td>
<td>3/2(^-)</td>
<td>forbidden</td>
<td>(D)-wave</td>
</tr>
<tr>
<td>2(^-)</td>
<td>3/2(^-)</td>
<td>(D)-wave</td>
<td>(D)-wave</td>
</tr>
<tr>
<td>2(^-)</td>
<td>5/2(^-)</td>
<td>(D)-wave</td>
<td>(D)-wave</td>
</tr>
<tr>
<td>1(^-)</td>
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<td>1(^-)</td>
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<td>forbidden</td>
<td>(S)-wave</td>
</tr>
</tbody>
</table>

Four of seven are expected to be suppressed
Experimental observations
LHCb

Muon Stations
Muon ID ~ 97%
p/μ mis ID ~ 1-3%

R_{ing} Imaging

CH_{erenkov}

Kaon ID ~ 95%
p/μ mis ID ~ 5%

Dipole Magnet

H_{adronic} CAL_{orimeter}

Vertex Locator
IP res ~ 20 μm

dp / p = 0.5-1.0%

Tracking stations

pp collider (7+7 TeV)
$\Omega_{c}^{* * 0}$ states in prompt production

[\text{LHCb, PRL 118, 182001 (2017)}]

$\Omega_{c}^{* * 0} \rightarrow \Xi_{c}^{'+} (\rightarrow \Xi_{c}^{+} \gamma) K$

- 5 super-narrow structures
- 1 broad structure
- 3 gray components partially reconstructed

A popular $J^P$ assignment:
the narrow states are $\lambda$ modes
in the natural order $\frac{1}{2}^{-}, \frac{1}{2}^{-}, \frac{3}{2}^{-}, \frac{3}{2}^{-}, \frac{5}{2}^{-}$.


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The new states are

\[ \Omega_b(6315)^- \]
\[ \Omega_b(6330)^- \]
\[ \Omega_b(6340)^- \]
\[ \Omega_b(6350)^- \]
$\Xi_{c}^{**0}$ states in prompt production

$$\Xi_{c}^{**0} \left( \begin{array}{c} c \\ s \\ d \end{array} \right) \rightarrow \Lambda_{c}^{+} \left( \begin{array}{c} c \\ u \\ d \end{array} \right) + K^{-} \left( \begin{array}{c} s \\ \bar{u} \end{array} \right)$$

Four structures are clearly visible
- More cumbersome partially-reconstructed decays
- No fifth narrow state
- The peaks are wider(!)

[LHCb, PRL 124, 222001 (2020)]
$\Xi_{c}^{*0}$ states in prompt production

$$\Xi_{c}^{*0} \begin{pmatrix} c \\ s \\ d \end{pmatrix} \to \Lambda_{c}^{+} \begin{pmatrix} c \\ u \\ d \end{pmatrix} + K^{-} \begin{pmatrix} s \\ \bar{u} \end{pmatrix}$$

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More cumbersome partially-reconstructed decays

No fifth narrow state

The peaks are wider(!)

Same peak spacing as for $\Omega_{c}^{*0}$
\( \Xi^{**-}_b \) states in prompt production

\( \Lambda_b \) is reconstructed in two final states: \( \Lambda_c^+ \pi^- \) and \( \Lambda_c^+ \pi^+ \pi^- \pi^- \)

One clear structure but anomalously broad
$\Xi_b^{**-}$ states in prompt production

$\Lambda_b$ is reconstructed in two final states: $\Lambda_c^+\pi^-$ and $\Lambda_c^+\pi^+\pi^-\pi^-$

One clear structure but anomalously broad

[LHCb, PRD 103, 012004 (2021)]
$\Xi_{b}^{*-}$ states in prompt production

$\Lambda_{b}$ is reconstructed in two final states: $\Lambda_{c}^{+}\pi^{-}$ and $\Lambda_{c}^{+}\pi^{+}\pi^{-}\pi^{-}$

One clear structure but anomalously broad

Splitting from $\Omega_{b}^{**-}$ indicates that it will be hard to resolve.
The first exclusive observation of $\Omega_c^{*0}$

In $\Omega_b^- \rightarrow \Xi_c^+ K^- \pi^-$ decay

- Strict exclusivity cut $\Rightarrow$ No feed down!
- Same four peaks (no clear fifth)
- $+$ the threshold structure $(5.3\sigma)$
The first exclusive observation of $\Omega_{c}^{**0}$

In $\Omega_{b}^{-} \rightarrow \Xi_{c}^{+} K^{-} \pi^{-}$ decay

- Strict exclusivity cut $\Rightarrow$ No feed down!
- Same four peaks (no clear fifth)
- + the threshold structure ($5.3\sigma$)

![Graphical representation of the data and analysis](image-url)
Angular analysis of $\Omega_b^- \rightarrow \Omega_{c}^{**0}(\rightarrow \Xi_c^+ K^-)\pi^-$

- Spin of $\Omega_b^-$ is $1/2$
- $\Omega_{c}^{**0}$ cannot have spin projection $> 1/2$
- $\Rightarrow$ non-trivial angular dependence for $J = 3/2$, $J = 5/2$.
- Noticeable inefficiency at $\cos \theta = 1$ (soft $K^-$).

3.6σ: $J(\Omega_c(3065)^0)! = 1/2$
2.2σ: $J(\Omega_c(3050)^0)! = 1/2$

Preliminary
Angular analysis of $\Omega_b^- \rightarrow \Omega_c^{**0}(\rightarrow \Xi_c^+ K^-) \pi^-$

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2.2$\sigma$: $J(\Omega_c(3050)^0)! = 1/2$
Spin hypotheses testing

- 2d Log Likelihood ratio as a test statistics

\[ t_{J|J'} = \frac{1}{N} \sum_{i=1}^{N} \log \left( \frac{I_J(\cos \theta_i)}{I'_J(\cos \theta_i)} \right) \]

\[ \Omega_c(3050)^0 \]

\[ \Omega_c(3065)^0 \]

Preliminary
Combined spin test

[LCb-PAPER-2021-012, in preparation]

Preliminary

LHCb 9 fb$^{-1}$

\[ J \neq 1/2 (2.2\sigma) \]

\[ J \neq 1/2 (3.6\sigma) \]
Combined spin test

Preliminary

LHCb 9 fb⁻¹

$J \neq 1/2 (2.2\sigma)$

$J \neq 1/2 (3.6\sigma)$

Excluded by 3.6σ

Candidates / (2.5 MeV)

$\Omega^{0}_{c}$ Non-background

$\Omega^{0}_{c}$ Non-background

$\Omega^{0}_{c}$ Non-background

Adapted from Fig. 2 of arXiv:1703.04639

to be revisited!
Combined spin test

Preliminary

Excluded by 3.6\sigma

One plausible assignments to be revisited!

Adapted from Fig. 2 of arXiv:1703.04639

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The threshold structure

[LHCb-PAPER-2021-012, in preparation]

- Exclusively explained in the prompt analysis by the partially reconstructed \( \Omega_c^{+}(3065) \rightarrow \Xi_c^{'+}K^- \) with anomalously large coupling.

- Exclusive analysis: no feed down is possible

- Other non-physical sources are excluded

- Singinifance in the nominal fit is 5.3\( \sigma \), 4.3\( \sigma \) including systematics

- No model sensitivity due to the low statistics

Further investigation in needed!
Summary

1P multiplet of “bad” diquark – a fundamental piece of the baryon spectroscopy puzzle

- 7 states: five $\lambda$-modes and two $\rho$-modes
- In common for $\Xi, \Sigma_{b/c}, \Omega_{b/c}, \Xi_{b/c}, \Xi_{cc}$
- State splittings indicate spin-orbit and “hyperfine” interaction
- Charm (beaty) baryons are narrow – good chance to resolve it:
  - Assign quantum numbers, reveal the light quark dynamics
  - Identify diquark excitation for the first time

The threshold structure

- Is a state?
- Compact / Molecular component?
- Present at other sectors?

The fifth narrow state

- Why only seen in inclusive $\Xi_c^+ K^-$
- The first manifestation of the diquark excitation? 2S states?