Спин и четность возбужденных Ω_Q-барионов в рамках кварк-дикварковой модели

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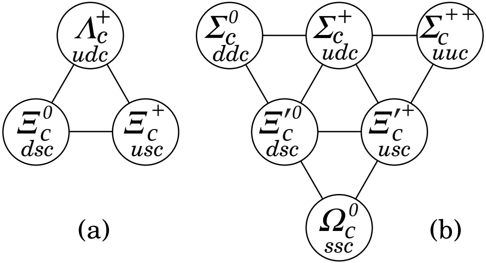
Ω_c-Baryons

Heavy Baryons

- $SU(3)_F$-multiplets of charmed baryons



- Similar multiplets are for bottom baryons after c-quark is replaced by b-quark

Status of Ω_c-Baryons

- Mass of the lowest Ω_c-baryon ($J^P = 1/2^+$) [PDG, 2024]

$$M_{\Omega_c} = (2695.2 \pm 1.7)\ \text{MeV}$$

- Mass of its fine-structure partner ($J^P = 3/2^+$) [PDG, 2024]

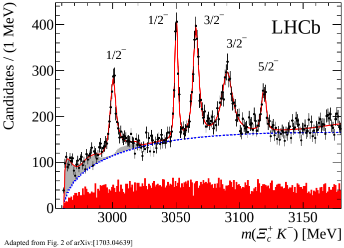
$$M_{\Omega_c^*} = (2765.9 \pm 2.0)\ \text{MeV}$$

- Observation of 5 narrow excited Ω_c-baryons in $\Omega_c^0 \to \Xi_c^+ K^-$: $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, $\Omega_c(3119)^0$ [R. Aaij et al. (LHCb), PRL 118, 182001 (2017)]
- Observation of 2 heavier $\Omega_c(3185)^0$ and $\Omega_c(3327)^0$-baryons in the same $\Omega_c^0 \to \Xi_c^+ K^-$ decay [R. Aaij et al. (LHCb), PRL 131, 131902 (2023)]

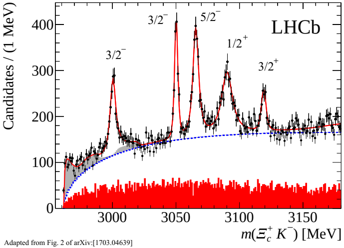
Orbitally Excited Ω_c-Baryons

- Measured masses (in MeV) [LHCb, 2023] and plausible J^P quantum numbers, assuming the quark-diquark model for $\Omega_c(= css) = c\,[ss]$ [M. Karliner & J. L. Rosner, PRD 95, 114012 (2017)]

$$
\begin{aligned}
M(\Omega_c(3000)) &= 3000.4 \pm 0.2 \pm 0.1; \quad J^P = 1/2^- \\
M(\Omega_c(3050)) &= 3050.2 \pm 0.1 \pm 0.1; \quad J^P = 1/2^- \\
M(\Omega_c(3066)) &= 3065.6 \pm 0.1 \pm 0.3; \quad J^P = 3/2^- \\
M(\Omega_c(3090)) &= 3090.2 \pm 0.3 \pm 0.5; \quad J^P = 3/2^- \\
M(\Omega_c(3119)) &= 3119.1 \pm 0.3 \pm 0.9; \quad J^P = 5/2^-
\end{aligned}
$$



Adapted from Fig. 2 of arXiv:[1703.04639]

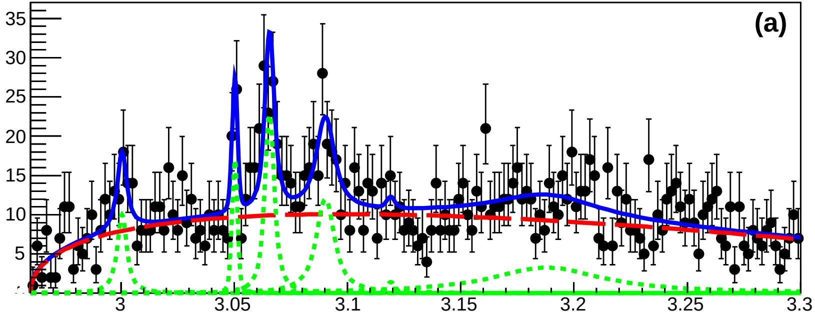


Adapted from Fig. 2 of arXiv:[1703.04639]

Belle Results on Excited Ω_c-Baryons

[J. Yelton et al. [Belle Collab.], Phys.Rev. D97 (2018) 051102]

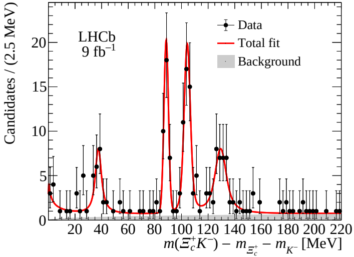
- Decay mode $\Omega_c \to \Xi_c^+ K^-$

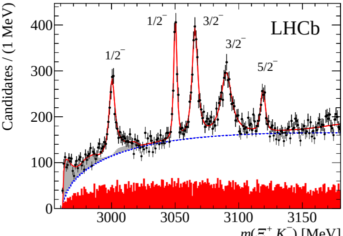


Ω_c^* State Significance	3000 3.9σ	3050 4.6σ	3066 7.2σ	3090 5.7σ	3119 0.4σ	318 2.4
LHCb Mass Belle Mass (with fixed Γ)	$3000.4 \pm 0.2 \pm 0.1$ $3000.7 \pm 1.0 \pm 0.2$	$3050.2 \pm 0.1 \pm 0.1$ $3050.2 \pm 0.4 \pm 0.2$	$3065.5 \pm 0.1 \pm 0.3$ $3064.9 \pm 0.6 \pm 0.2$	$3090.2 \pm 0.3 \pm 0.5$ $3089.3 \pm 1.2 \pm 0.2$	$3119 \pm 0.3 \pm 0.9$ -	3188 ± 5 $3199 \pm$

R. Aaij et al. [LHCb Collab.], PRD 104 (2021) 091102

- Exclusive decay $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ is studied
- Four Ω_c^0 states are found in decay mode $\Omega_c \to \Xi_c^+ K^-$
- The heaviest state is not confirmed

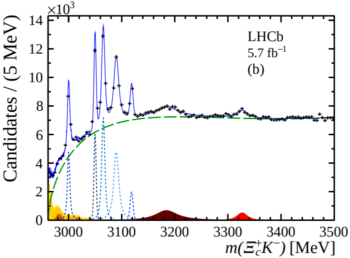


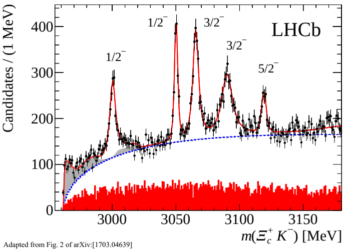


Adapted from Fig. 2 of arXiv:[1703.04639]

R. Aaij et al. [LHCb Collab.], PRL 131, 131902 (2023)

- Decay mode $\Omega_c \to \Xi_c^+ K^-$
- The $\Omega_c(3119)^0$ state is confirmed now
- Observed two new broad baryons, $\Omega_c(3185)^0$ and $\Omega_c(3327)^0$



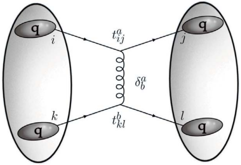


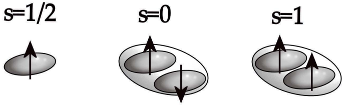
Adapted from Fig. 2 of arXiv:[1703.04639]

Quark-Diquark Model of Hadrons

- Quarks q_i^α and diquarks $\mathcal{Q}_{i\alpha}$ are building blocks of baryons and exotic hadrons
- α is the $SU(3)_C$ index and i is the $SU(3)_F$ index
- Color repres.: $3 \otimes 3 = \bar{3} \oplus 6$; only $\bar{3}$ is attractive

$$t^a_{ij} t^a_{kl} = -\frac{2}{3} \underbrace{(\delta_{ij}\delta_{kl} - \delta_{il}\delta_{kj})/2}_{\text{antisymmetric: projects } \bar{3}} + \frac{1}{3} \underbrace{(\delta_{ij}\delta_{kl} + \delta_{il}\delta_{kj})/2}_{\text{symmetric: projects } 6}$$





- Interpolating diquark operators for the two spin states

$$\text{Scalar:} \quad 0^+ \quad \mathcal{Q}_{i\alpha} = \epsilon_{\alpha\beta\gamma}\left(c_c^{\beta\,T} C\gamma_5 q_i^\gamma - q_{ic}^{\beta\,T} C\gamma_5 c^\gamma\right)$$

$$\text{Axial-Vector:} \quad 1^+ \quad \vec{\mathcal{Q}}_{i\alpha} = \epsilon_{\alpha\beta\gamma}\left(c_c^{\beta\,T} C\vec{\gamma} q_i^\gamma + q_{ic}^{\beta\,T} C\vec{\gamma} c^\gamma\right)$$

- Colorless combination with the quark results into the baryon

- Measured masses (in MeV) [LHCb] and plausible J^P quantum numbers, assuming the diquark model for $\Omega_c(= css) = c\,[ss]$
[M. Karliner & J. L. Rosner, PRD 95, 114012 (2017)]

$$
\begin{aligned}
M[\Omega_c(3000)] &= 3000.44 \pm 0.07^{+0.07}_{-0.13} \pm 0.23; \quad J^P = 1/2^- \\
M[\Omega_c(3050)] &= 3050.18 \pm 0.04^{+0.06}_{-0.07} \pm 0.23; \quad J^P = 1/2^- \\
M[\Omega_c(3066)] &= 3065.63 \pm 0.06 \pm 0.06 \pm 0.23; \quad J^P = 3/2^- \\
M[\Omega_c(3090)] &= 3090.16 \pm 0.11^{+0.06}_{-0.10} \pm 0.23; \quad J^P = 3/2^- \\
M[\Omega_c(3119)] &= 3118.98 \pm 0.12^{+0.09}_{-0.23} \pm 0.23; \quad J^P = 5/2^-
\end{aligned}
$$

- To get the mass spectrum, effective Hamiltonian is required
- For P states, important to take into account tensor interaction

$$
\begin{aligned}
H_{\rm eff} &= m_c + m_{[ss]} + 2\kappa_{ss}\,(\mathbf{S}_s \cdot \mathbf{S}_s) + \frac{B_{\mathcal{Q}}}{2}\,\mathbf{L}^2 + V_{\rm SD}, \\
V_{\rm SD} &= 2a_1\left(\mathbf{L} \cdot \mathbf{S}_{[ss]}\right) + 2a_2\,(\mathbf{L} \cdot \mathbf{S}_c) + b\,\frac{\langle S_{12}\rangle}{4} + 2c\left(\mathbf{S}_{[ss]} \cdot \mathbf{S}_c\right)
\end{aligned}
$$

- Mass formulae follow from the effective Hamiltonian

$$m_1^{(1/2)} = M_0^{(\Omega_c)} - \frac{1}{2}(6a_1+a_2+b+c) - \frac{1}{6}\sqrt{(2a_1+7a_2+3b-9c)^2+2(4a_1-4a_2-3b)^2}$$

$$m_2^{(1/2)} = M_0^{(\Omega_c)} - \frac{1}{2}(6a_1+a_2+b+c) + \frac{1}{6}\sqrt{(2a_1+7a_2+3b-9c)^2+2(4a_1-4a_2-3b)^2}$$

$$m_1^{(3/2)} = M_0^{(\Omega_c)} - \frac{1}{10}(5a_2-4b+5c) - \frac{1}{30}\sqrt{(40a_1+5a_2-12b-45c)^2+5(20a_1-20a_2+3b)^2}$$

$$m_2^{(3/2)} = M_0^{(\Omega_c)} - \frac{1}{10}(5a_2-4b+5c) + \frac{1}{30}\sqrt{(40a_1+5a_2-12b-45c)^2+5(20a_1-20a_2+3b)^2}$$

$$m^{(5/2)} = M_0^{(\Omega_c)} + 2a_1 + a_2 - \frac{b}{5} + c$$

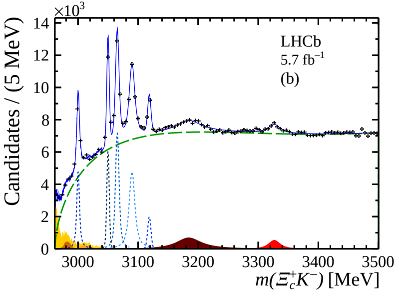
- There are five unknowns $\{M_0^{(\Omega_c)}, a_1, a_2, b, c\}$ and nine measurements
- All unknowns can be fitted by using the χ^2-analysis

Numerical analysis of excited Ω_c states in the Quark-Diquark model

- Coefficients determined from the Ω_c-baryon masses (in MeV) measured by the LHCb and Belle Collaborations [A. Ali & A. Parkhomenko, JHEP 10 (2019) 256]

a_1	a_2	b	c	$M_0^{(\Omega_c)}$
13.46 ± 0.05	12.86 ± 0.13	13.49 ± 0.22	2.03 ± 0.08	3079.88 ± 0.13

$$M_0^{(\Omega_c)} \equiv m_c + m_{[ss]} + \kappa_{ss}/2 + B_{\mathcal{Q}}$$



Ω_b-Baryons

Status of Ω_b-Baryons

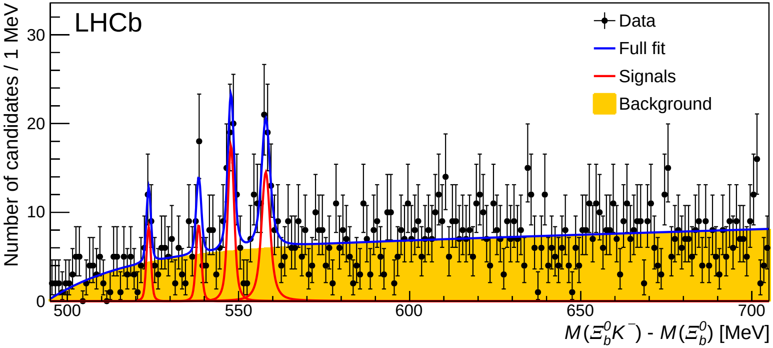
- Mass of the lowest Ω_b-baryon ($J^P = 1/2^+$) [PDG, 2024]

$$M_{\Omega_b} = (6045.8 \pm 0.8)\ \text{MeV}$$

- Its fine-structure partner with $J^P = 3/2^+$ is unknown yet
- Observation of 4 narrow excited Ω_b-baryons in $\Omega_b^- \to \Xi_b^0 K^-$:
  $\Omega_b(6316)^-$, $\Omega_b(6330)^=$, $\Omega_b(6340)^-$, $\Omega_b(6350)^-$
  [R. Aaij et al. (LHCb), PRL 124, 082002 (2020)]

[R. Aaij et al. [LHCb Collab.], PRL 124 (2020) 082002]

- They are found in the decay channel $\Omega_b^- \to \Xi_b^0 K^-$



- Masses: $M_{\Xi_b^0} = 5791.9 \pm 0.5$ MeV; $M_{K^-} = 493.7$ MeV

- Masses (in MeV) for $\Omega_b(= bss) = b\,[ss]$
  [LHCb, PRL 124 (2020) 082002]

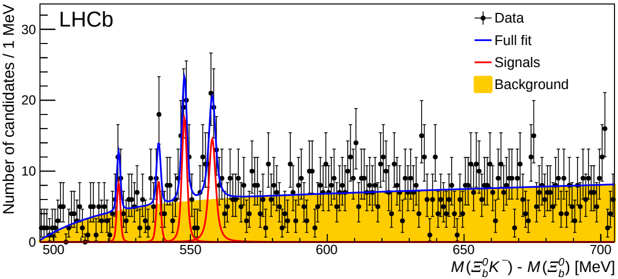
$$
\begin{aligned}
M[\Omega_b(6316)] &= 6315.64 \pm 0.31 \pm 0.07 \pm 0.50 \\
M[\Omega_b(6330)] &= 6330.30 \pm 0.28 \pm 0.07 \pm 0.50 \\
M[\Omega_b(6340)] &= 6339.71 \pm 0.26 \pm 0.05 \pm 0.50 \\
M[\Omega_b(6350)] &= 6349.88 \pm 0.35 \pm 0.05 \pm 0.50
\end{aligned}
$$

- For Ω_b-baryon mass determination, an effective Hamiltonian is necessary; can be adopted from Ω_c-baryons
  [A. Ali & A. Parkhomenko, JHEP 10 (2019) 256]

$$
\begin{aligned}
H_{\rm eff} &= m_b + m_{[ss]} + \kappa_{ss}\,(\mathbf{S}_s \cdot \mathbf{S}_s) + \frac{B_{\mathcal{Q}}}{2}\,\mathbf{L}^2 + V_{\rm SD}, \\
V_{\rm SD} &= a_1\left(\mathbf{L} \cdot \mathbf{S}_{[ss]}\right) + a_2\,(\mathbf{L} \cdot \mathbf{S}_b) + b\,\frac{\langle S_{12} \rangle}{4} + c\left(\mathbf{S}_{[ss]} \cdot \mathbf{S}_b\right)
\end{aligned}
$$

- Four measurements do not allow to fix five coefficients; some reasonable assumptions about coefficients are required

- All four Ω_b-baryons are orbitally excited states [M. Karliner & J. L. Rosner, PRD 102, 014027 (2020)]
  - $J^P = 1/2^-, 1/2^-, 3/2^-, 3/2^-$ more favoured by them
  - $J^P = 1/2^-, 3/2^-, 3/2^-, 5/2^-$
  - Fifth state is wide, not extracted from background
- According to our analysis, these assignments are unrealistic; coefficients in effective Hamiltonian are complex, i. e. unphysical



Alternative Spin-Parity Assignment of Ω_b-Baryons

- All four Ω_b-baryons are orbitally excited states
- Peak $\Omega_b(6330)$ has a double hurmed structure, not yet resolved experimentally
- Assumption: both states are degenerate in mass

$$\begin{aligned}
M(\Omega_b(6316)) &= 6315.64 \pm 0.31 \pm 0.07 \pm 0.50; \quad J^P = 1/2^- \\
M(\Omega_b(6330)) &= 6330.30 \pm 0.28 \pm 0.07 \pm 0.50; \quad J^P = 1/2^- \\
M(\Omega_b(6330)) &= 6330.30 \pm 0.28 \pm 0.07 \pm 0.50; \quad J^P = 3/2^- \\
M(\Omega_b(6340)) &= 6339.71 \pm 0.26 \pm 0.05 \pm 0.50; \quad J^P = 3/2^- \\
M(\Omega_b(6350)) &= 6349.88 \pm 0.35 \pm 0.05 \pm 0.50; \quad J^P = 5/2^-
\end{aligned}$$

- Two physical solutions are exist (in MeV):
  - SI: $M_0^{(\Omega_b)} = 6337.3,\ a_1 = 2.4,\ a_2 = 5.1,\ b = 5.4,\ c = 3.8$
  - SII: $M_0^{(\Omega_b)} = 6325.7,\ a_1 = 3.6,\ a_2 = 5.1,\ b = 1.3,\ c = 0.5$
- Compare with fitted values from Ω_c^0-baryons: $M_0^{(\Omega_c)} = 3079.88,\ a_1 = 13.46,\ a_2 = 12.86,\ b = 13.49,\ c = 2.03$

Other Alternative Interpretation of Ω_b^*-Baryons

- The other set of spin-parities: $J^P = 3/2^-,\ 3/2^-,\ 5/2^-,\ 1/2^+$; three states are orbitally excited and the fourth is radially excited
- Assuming: $a_2 = a_1$ and $c = 0$
    - SI: $M_0^{(\Omega_b)} = 6315.9$ MeV, $a_1 = 10.0$ MeV, $b = 30.2$ MeV
    - SII: $M_0^{(\Omega_b)} = 6325.7$ MeV, $a_1 = 4.6$ MeV, $b = -1.1$ MeV
    - Masses of their light $J^P = 1/2^-$ partners:
      $$M_1^{(SI)} = 6229 \text{ MeV}, \quad M_2^{(SI)} = 6303 \text{ MeV}$$
      $$M_1^{(SII)} = 6304 \text{ MeV}, \quad M_2^{(SII)} = 6317 \text{ MeV}$$
    - Threshold in $\Omega_b^- \to \Xi_b^0 K^-$ decay: $M_{\rm thr} = 6285.6 \pm 0.5$ MeV
- Lowest state with $M_1^{(SI)} = 6229$ MeV is below the threshold
- Both solutions predict a state with the mass $M \simeq 6304$ MeV; not yet seen experimentally; probably a wide state
- Higher mass state in SII is close in mass to $\Omega_b(6316)$; this state may have a double hurmed structure

Summary

- The assignment of spin-parities $J^P = 1/2^-, 3/2^-, 5/2^-$ to Ω_c-baryons observed by the LHCb and Belle Collaborations allows to fix all the coefficients in the effective Hamiltonian relevant for the mass spectrum
- This approach was used for the analysis of four excited Ω_b-baryons observed by the LHCb Collaboration in 2020
- The assignment of spin-parities $J^P = 1/2^-, 3/2^-, 5/2^-$ to Ω_b-baryons with the assumption that the second observed peak can have a double hurmed structure allows to fix all the coefficients in the effective Hamiltonian
- Alternative interpretation that three lowest mass states have spin-parities $J^P = 3/2^-, 3/2^-, 5/2^-$ predict Ω_b-baryon with the mass $M \simeq 6304$ MeV which is not yet seen experimentally
- Further experimental study of excited Ω_b-baryons will allow to test a correctness of quark-diquark model in application to heavy baryons