Spin-parity assignments of excited Ω_b^--baryons in the Quark-Diquark Model

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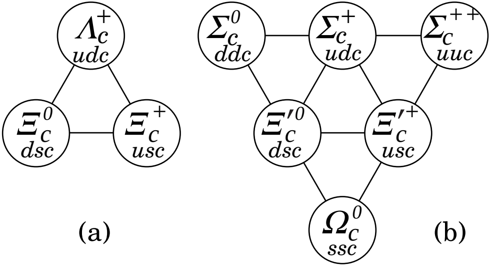
in collaboration with Ahmed Ali, Alexandra Dobrynina, & Elizaveta Oleinik

Outline

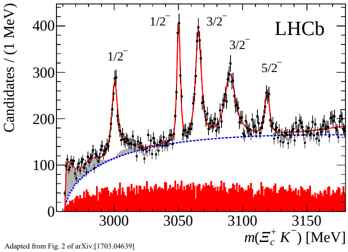
- Charmed baryon multiplets



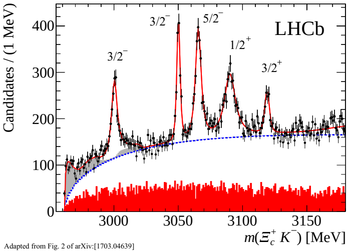
- Similar multiplets exist for bottom baryons after c-quark is replaced by b-quark
- Observation of 5 narrow excited Ω_c baryons in $\Omega_c \to \Xi_c^+ K^-$ [LHCb, PRL 118, 182001 (2017)]
- Plausible quantum numbers, J^P, were suggested assuming the diquark model for $\Omega_c(= css) = c\,[ss]$
  [M. Karliner & J. L. Rosner, PRD 95, 114012 (2017)]

- 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)]

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



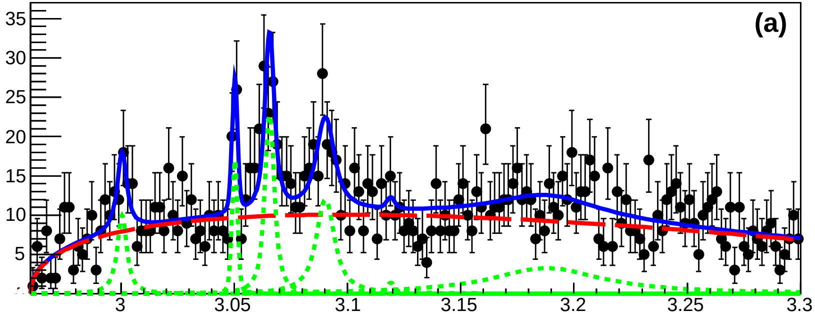
Adapted from Fig. 2 of arXiv:[1703.04639]



Adapted from Fig. 2 of arXiv:[1703.04639]

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

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

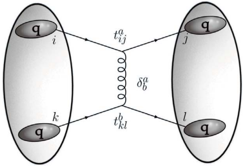


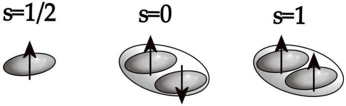
Ω_c^* State Significance	3000 3.9σ	3050 4.6σ	3066 7.2σ	3090 5.7σ	3119 0.4σ	3188 2.4σ
LHCb Mass Belle Mass (with fixed Γ)	$3000.4 \pm 0.2 \pm 0.1$ $3000.7 \pm 1.0 \pm 0.2$	$3050.2 \pm 0.1 \pm 0.1$ $3050.2 \pm 0.4 \pm 0.2$	$3065.5 \pm 0.1 \pm 0.3$ $3064.9 \pm 0.6 \pm 0.2$	$3090.2 \pm 0.3 \pm 0.5$ $3089.3 \pm 1.2 \pm 0.2$	$3119 \pm 0.3 \pm 0.9$ -	3188 ± 5 3199 ± 9

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

$$\text{Scalar:} \quad 0^+ \quad \mathcal{Q}_{i\alpha} = \epsilon_{\alpha\beta\gamma}\left(\bar{c}_c^\beta \gamma_5 q_i^\gamma - \bar{q}_{ic}^\beta \gamma_5 c^\gamma\right)$$

$$\text{Axial-Vector:} \quad 1^+ \quad \vec{\mathcal{Q}}_{i\alpha} = \epsilon_{\alpha\beta\gamma}\left(\bar{c}_c^\beta \vec{\gamma} q_i^\gamma + \bar{q}_{ic}^\beta \vec{\gamma} c^\gamma\right)$$

- Colorless combination with the quark results into the baryon

Orbitally Excited Ω_c-Baryons in the Diquark Model

- 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)]

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

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

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

- Mass formulae follow from the effective Hamiltonian

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

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

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

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

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

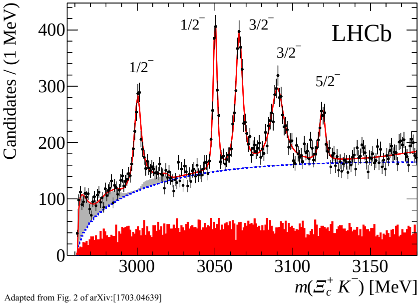
- There are five unknowns $\{M_0^{(\Omega_c)}, a_1, a_2, b, c\}$ and nine measurements
- All unknowns can be fitted with the ξ^2-analysis

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	$M_0^{(\Omega_c)}$
13.45 ± 0.13	12.94 ± 0.36	13.30 ± 0.48	2.01 ± 0.20	3079.80 ± 0.39

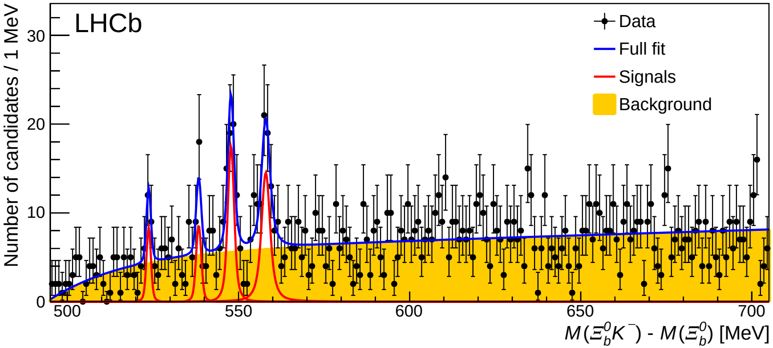
$$M_0^{(\Omega_c)} \equiv m_c + m_{[ss]} + \kappa_{ss}/2 + B_{\mathcal{Q}}$$



Adapted from Fig. 2 of arXiv:[1703.04639]

[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]

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

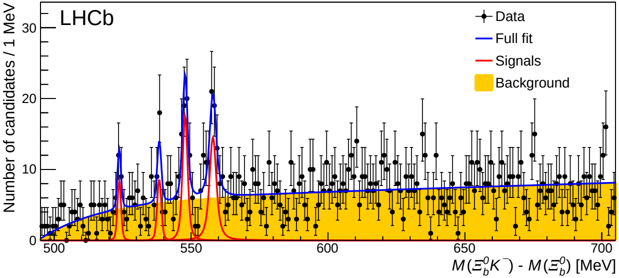
- For Ω_b-baryon mass determination, an effective Hamiltonian is necessary; can be adopted from Ω_c-baryons
  [A. Ali & A. Parkhomenko, JHEP 10 (2019) 256]

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

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

Spin-Parity Assingments for Excited Ω_b-Baryons

- All four Ω_b-baryons — orbitally excited states [M. Karliner & J. L. Rosner, arXiv:2005.12424 [hep-ph]]
  - $J^P = 1/2^-, 1/2^-, 3/2^-, 3/2^-$ more favoured by them
  - $J^P = 1/2^-, 3/2^-, 3/2^-, 5/2^-$
  - Fifth state — 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):
    - I: $M_0^{(\Omega_b)} = 6337.3,\ a_1 = 2.4,\ a_2 = 5.1,\ b = 5.4,\ c = 3.8$
    - II: $M_0^{(\Omega_b)} = 6325.7,\ a_1 = 3.6,\ a_2 = 5.1,\ b = 1.3,\ c = 0.5$

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 $c = 0$
  - I: $M_0^{(\Omega_b)} = 6315.9$ MeV, $a_1 = 10.0$ MeV, $b = 30.2$ MeV
  - II: $M_0^{(\Omega_b)} = 6325.7$ MeV, $a_1 = 4.6$ MeV, $b = -1.1$ MeV
  - Masses of their light $J^P = 1/2^-$ partners:
    $$M_1^{(I)} = 6229 \text{ MeV},\ M_2^{(I)} = 6303 \text{ MeV}$$
    $$M_1^{(II)} = 6304 \text{ MeV},\ M_2^{(II)} = 6317 \text{ MeV}$$
  - Threshold in $\Omega_b^- \to \Xi_b^0 K^-$ decay: $M_{\rm thr} = 6285.6 \pm 0.5$ MeV
- Lowest state with $M_1^{(I)} = 6229$ 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 Sol. II 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 recently
- 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