New spectrum of negative-parity doubly charmed baryons

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Outline

1. Doubly charmed baryon in observation
2. Heavy antiquark-diquark symmetry
3. Doubly charmed baryon spectrum with $J^P = \frac{1}{2}^-$
4. Summary
5. Backup slides

Doubly charmed baryon in observation

First observation of Ξ_{cc}^{+} in $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$
SELEX, PRL89(2002)

Confirmation of $\Xi_{cc}^{+}(3520)$ via its decay to $pD^{+}K^{-}$
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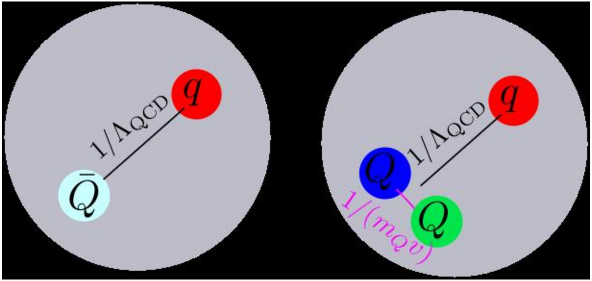
Observation of $\Xi_{cc}^{++}(3621)$ in $\Lambda_c^{+} K^{-} \pi^{+} \pi^{+}$ mass spectrum

LHCb, PRL119(2017)

Heavy anti-quark-diquark symmetry

heavy quark is a static color (anti-)triplet in heavy meson.
$m_Q v \gg \Lambda_{QCD}$, heavy diquark serves as a point-like color anti-triplet source,like a heavy anti-quark in heavy meson.
It relates doubly-heavy baryons to anti-heavy mesons.



Doubly charmed baryon with $J^P = \frac{1}{2}^-$

Following heavy anti-quark-diquark symmetry, there is a bridge between charmed mesons and doubly charmed baryons.

$D^*_{s0}(2317)$

$D^*_{s0}(2317)$ is understood as DK bound state mainly.

T. Barnes et al PRD68(2003); E.E. Kolomeitsev et al PLB582(2004) ; A. Faessler et al PRD76(2007); D. Gamermann et al PRD76(2007) ;F.K. Guo et al PLB(641)(2006), EPJ.A40(2009), PR D87 (2013); L.S. Geng et al PRD89(2014);

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Extended to doubly charmed baryon,
Prediction: $\Omega_{cc}\,(1/2^-)$ with mass $m_{\Xi_{cc}} + m_{D^*_{s0}(2317)} - m_D \approx 4.1\text{GeV}$.
While SU(3) multiplet calculated for GBs scattering off ground states of doubly charmed baryons.
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Does inner structure of heavy diquark contribute to spectrum?

Doubly charmed baryon with $J^P = \frac{1}{2}^-$

Size of doubly charmed baryon

$r_d \approx 1/(m_Q v_Q) \approx\ 0.25$ fm with $m_Q v_Q \approx\ 800$ MeV
$r_q \approx\ 1/\Lambda_{QCD} \approx\ 0.8$ fm with $\Lambda_{QCD} \approx\ 250$ MeV.
$\frac{r_d}{r_q} \approx\ 0.3$
Value of $m_Q v_Q$ is given in J. Hu and T. Mehen PRD73,054003(2006)

Spin structure in heavy diquark

$\vec{J}_{QQ} =\ \vec{S}_{QQ} + \vec{L}_{QQ}$,
$S_{QQ} = 1, L_{QQ} = 0$ in ground state, $\mathcal{P}(+)$
$S_{QQ} = 0, L_{QQ} = 1$ in P-wave excitation. $\mathcal{P}(-)$

Doubly charmed baryon with $J^P = \frac{1}{2}^-$

Potential of P-wave excitation in heavy diquark:
$V^P(cc) = \frac{1}{2}V^P(c\bar{c})$ is predicted in quark model.
$M_{\psi^P_{cc}} - M_{\psi_{cc}} \approx (M_{h_c} - M_{J/\psi})/2 = 214\ \mathrm{MeV}.$

T.Mehen PRD96 (2017)

Something new?

1. $214\ \mathrm{MeV} = \mathcal{O}\left(\mathrm{m}_\pi,\ \mathrm{m}_\mathrm{K},\ \mathrm{m}_\eta\right)$, P-wave excitation in heavy diquark should be a degree of freedom in spectrum of doubly charmed baryon. (s- and u- channel)
2. How to take these P-wave excitations in heavy diquark into consideration?

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$\psi_{cc}^P(\frac{1}{2}^-)$ couples to $\psi_{cc}\phi$ in S-wave

$\mathcal{L}_P = \lambda \bar{\psi}_{cc}^P \gamma^\mu u_\mu \psi_{cc} + h.c.$
This term breaks HQSS and λ is expected to be $\mathcal{O}(\Lambda_{QCD}/m_c) = \mathcal{O}(0.2) \ll 1$ T. Mehen et al PRD73,054003(2006), PRD96,094028(2017)

Doubly charmed baryon with $J^P = \frac{1}{2}^-$

$$V_s = \frac{2\lambda^2}{F^2}\mathcal{C}^{(s)}\bar{u}^f(p_3,\sigma^f)\not{p}_4\frac{1}{\not{P}-\mathring{M}_{\psi_{cc}^P}}\not{p}_2 u^i(p_1,\sigma^i),$$

Born terms in s-channels are considered and the contribution from u-channel Born terms is small.

$$\begin{pmatrix} 2 & -\frac{2}{\sqrt{3}} \\ -\frac{2}{\sqrt{3}} & \frac{2}{3} \end{pmatrix}_{I=0}, \quad \begin{pmatrix} \frac{3}{2} & \frac{1}{2} & \frac{\sqrt{6}}{2} \\ \frac{1}{2} & \frac{1}{6} & \frac{1}{\sqrt{6}} \\ \frac{\sqrt{6}}{2} & \frac{1}{\sqrt{6}} & 1 \end{pmatrix}_{I=1/2}$$

$I=0$: $\Xi_{cc}\bar{K} - \Omega_{cc}\eta$; $\quad$ $I=1/2$: $\Xi_{cc}\pi - \Xi_{cc}\eta - \Omega_{cc}K$

Doubly charmed baryon with $J^P = \frac{1}{2}^-$

The interactions in LO ChPT contain Weinberg-Tomozawa terms and Born terms with ground state of doubly charmed baryons exchanging.

$$\mathcal{L}_{LO} = \bar{\psi}_{cc}(i\not{D} - m_0 + \frac{g_A}{2}\gamma^\mu\gamma_5 u_\mu)\psi_{cc}.$$

with

$$D_\mu = \partial_\mu + \frac{1}{2}\left[u^\dagger\partial_\mu u + u\partial_\mu u^\dagger\right],\ u_\mu = iu^\dagger D_\mu U u^\dagger$$

The axial coupling constant g_A is estimated as, $|g_A| = 0.2$

Doubly charmed baryon with $J^P = \frac{1}{2}^-$

The ground-state doubly charmed baryons are expected to form a flavor triplet of matter fields,

$$\psi_{cc} = \begin{pmatrix} \Xi_{cc}^{++} \\ \Xi_{cc}^{+} \\ \Omega_{cc}^{+} \end{pmatrix}$$

.

The light pseudoscalar mesons (π, K, η) are the Goldstone bosons of QCD,

$$U = u^2 = e^{i\frac{\sqrt{2}\Phi}{F}}$$

with

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

Doubly charmed baryon with $J^P = \frac{1}{2}^-$

NLO terms in ChPT:

$$V^{(2)}(s,t,u) = \frac{4C_0}{F^2}h_0 + \frac{2C_1}{F^2}h_1 - \frac{2C_{24}}{F^2} + \frac{2C_{35}}{F^2}H_{35}(s,t,u)$$

$$c_i = \frac{h_i}{2\bar{M}_D},\ \ i = 0,\ 1,\ 24,\ 35,$$

where $C_{24} = C_2 + C_4'$, $C_{35} = C_3 + C_5'$, $C_4' = C_4\bar{M}^2_{\psi_{cc}}$ and $C_5' = C_5\bar{M}^2_{\psi_{cc}}$. $\bar{M}_D$ and $\bar{M}_{\psi_{cc}}$ are the averaged masses of the ground state charmed mesons and doubly charmed baryons, respectively.
Values of h_i have been fixed from fitting results of lattice calculation.

L. Liu et al PRD 87,014508(2013)

Doubly charmed baryon with $J^P = \frac{1}{2}^-$

Bethe-Salpeter equation with on-shell approximation

$$T = (1 - V \cdot G)^{-1} V,$$

where $V = V_{WT} + V_s + V^{(2)}$. V_s is contribution from baryon exchanging with P-wave excitation in heavy diquark.
Neglecting u-channels in Born terms of ground states and excitation states exchanging, contribution of which has been checked and is small.

F-K Guo et al PLB641,278(2006); D.-L. Yao et al EPJC78,310(2018)

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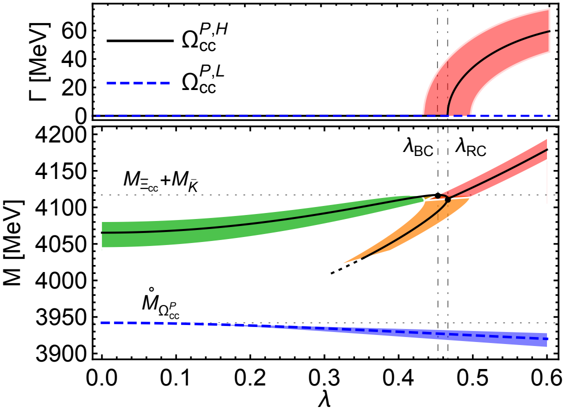
$M_{\Xi_{cc}^{++}} = 3621.4 \text{ MeV}$
$M_{\Omega_{cc}^{+}} - M_{\Xi_{cc}^{+}} = M_{D_s^+} - M_{D^+}$
$M_{\Xi_{cc}^P} = 3838 \text{ MeV}$, bare pole $(\frac{1}{2}^-)$ in quark model.

D.Ebert et al PRD 66,014008(2002)

$M_{\Omega_{cc}^P} \approx M_{\Omega_{cc}} + 217\text{MeV} \approx 3942\text{MeV}.$

Doubly charmed baryon with $J^P = \frac{1}{2}^-$

Sector I=0,S=-1, $\Xi_{cc}\bar{K}$-$\Omega_{cc}\eta$. Thresholds: 4120 MeV and 4273 MeV.



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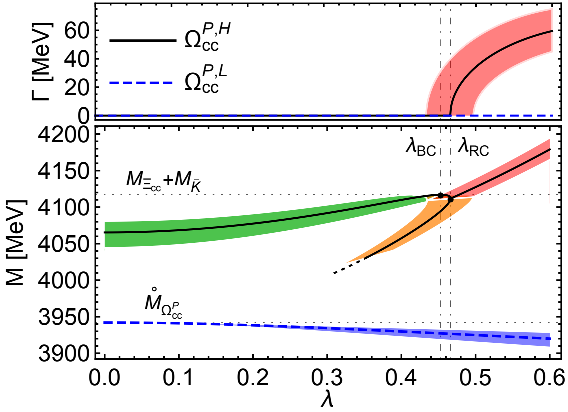

Compositeness: $P = -g^2 \frac{\partial G}{\partial s}\Big|_{s=M^2_{pole}}$.

The higher pole contains 55-80 % of $\Xi_{cc}\bar{K}$.

Doubly charmed baryon with $J^P = \frac{1}{2}^-$

Study on isospin violated decay width is a good way to understand hadronic structure. Mass differences of intermediate particles in loops in particle basis and $\pi^0 - \eta$ mixing contribute to decay width.

$\pi^0 - \eta$ mixing

$$\tilde{\pi}^0 = \pi^0 \cos\epsilon_{\pi^0\eta} + \eta \sin\epsilon_{\pi^0\eta},$$
$$\tilde{\eta} = -\pi^0 \sin\epsilon_{\pi^0\eta} + \eta \cos\epsilon_{\pi^0\eta}.$$

where

$$\epsilon_{\pi^0\eta} = \frac{\sqrt{3}}{4}\frac{m_d - m_u}{m_s - \hat{m}}$$

with $\hat{m} = (m_u + m_d)/2$, $\frac{m_d - m_u}{m_s - \hat{m}} = 0.012 \pm 0.001$

F.K. Guo et al PLB66(2008)

Sector I=0,S=-1, $\Xi_{cc}\bar{K}$-$\Omega_{cc}\eta$-$\Omega_{cc}\pi^0$

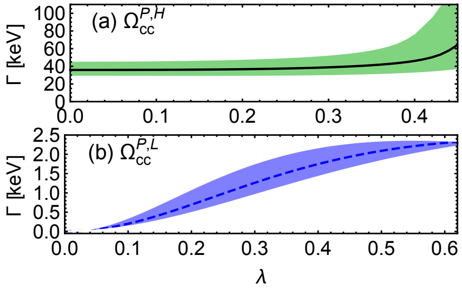

Figure: Decay width of Isospin violated process

Decay width of the lower pole is a few keV and the one of the higher pole is larger than 30 keV.

Doubly charmed baryon with $J^P = \frac{1}{2}^-$

Sector I=1/2,S=0, $\Xi_{cc}\pi$-$\Xi_{cc}\eta$-$\Omega_{cc}K$

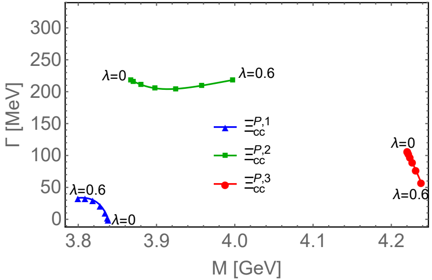

Figure: Trajectories of the three resonant poles in the $(S, I) = (0, 1/2)$ channel vary with λ value. Central values of LECs and $a^{\psi_{cc}\phi}$ are adopted, and $\mathring{M}_{\Xi_{cc}^P} = 3838$ MeV is used.

Thresholds: 3762 MeV, 4176 MeV and 4222 MeV.

Summary

- Analogue of DK hadronic molecule $D_{s0}^*(2317)$: Possibility of two narrow doubly charmed baryons with $J^P = \frac{1}{2}^-$, the lower one corresponds to the normal ccs baryon, while the higher pole to the $\Xi_{cc}\bar{K}$ hadronic molecule.
- The LECs up to NLO are correlated to those for heavy meson-GBs interactions via HADS, the latter ones have been widely studied and fixed by lattice simulation.
- Difference: there is an additional s-channel pole contribution.
- Other analogues: $J^P = \frac{1}{2}^-,\ \frac{3}{2}^-$ doubly heavy baryons.

Thanks

Backup slides

NLO terms in chiral Lagrangian and low energy constants read

$$T^{(2)}(s,t,u) = \frac{4C_0}{F^2}h_0 + \frac{2C_1}{F^2}h_1 - \frac{2C_{24}}{F^2} + \frac{2C_{35}}{F^2}H_{35}(s,t,u) \tag{1}$$

with

$$H_{24}(s,t,u) = 2h_2 p_2 \cdot p_4 + h_4(p_1 \cdot p_2 p_3 \cdot p_4 + p_1 \cdot p_4 p_2 \cdot p_3) \tag{2}$$

$$H_{35}(s,t,u) = h_3 p_2 \cdot p_4 + h_5(p_1 \cdot p_2 p_3 \cdot p_4 + p_1 \cdot p_4 p_2 \cdot p_3) \tag{3}$$

G contains a subtraction, $a(1\mathrm{GeV}) = -2.79^{+0.04}_{-0.05}$.
Matching the value of G at threshold with a regularization of three momentum cut-off, $q_{max} \approx m_\rho$.

Here one makes an analogy to the case of $D^*_{s0}(2317)$ bounded from DK. But the contributions from $m_d - m_u$ and electromagnetic term (virtual photons) go in opposite directions.

Ds(2317)

$(M_{D^+} - M_{D^0})^{strong} = (2.67 \pm 0.30)$ MeV,
$(M_{D^+} - M_{D^0})^{em} = (2.10 \pm 0.32)$ MeV

Ξ_{cc}

$(M_{\Xi_{cc}^{++}} - M_{\Xi_{cc}^{+}})^{strong} = (-2.7 \pm\ 1.5)$ MeV,
$(M_{\Xi_{cc}^{++}} - M_{\Xi_{cc}^{+}})^{em} = (4.2 \pm\ 2.30)$ MeV