Near-threshold charmed baryons: Ξ_c molecular states

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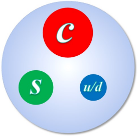
Charmed Baryons: Ξ_c



PDG: $\Xi_c^+(2468)$, $\Xi_c^0(2471)$, $\Xi_c(2645)$, $\Xi_c(2790)$, $\Xi_c(2815)$, $\Xi_c(2970)$ [was $\Xi_c(2980)$], $\Xi_c(3055)$, $\Xi_c(3080)$.

$\Xi_c(2970)$ and $\Xi_c(3080)$ [Belle PRL, 97 (2006) 162001 and BaBar PRD, 77 (2008) 012002].

$\Xi_c(3055)^+$ [BaBar PRD, 77 (2008) 012002 and Belle PRD, 89 (2014) 052003].

$\Xi_c(3055)^0$, $\Xi_c(3055)^+$ and $\Xi_c(3080)^+$ [Belle PRD, 94 (2016) 032002].

J^P have not been determined.

Charmed Baryons: Ξ_c

$\Xi_c(3055)$ is a D-wave state [CPC, 32 (2008) 424].

J^P of the $\Xi_c(3055)$: $\frac{3}{2}^+$, $\frac{5}{2}^+$, $\frac{7}{2}^+$ [PRD, 78 (2008) 056005; PRD, 86 (2012) 034024; PRD, 86 (2012) 034024; EPJA, 51 (2015) 82; PRD, 94 (2016) 114020; PRD, 94 (2016) 114016; PRD, 95 (2017) 074022; NPB, 926 (2018) 467; PRD, 98 (2018) 076015].

$\Xi_c(3055)$ is a $2S$-wave state [PRD, 96 (2017) 114003; PRD, 96 (2017) 114009].

$\Xi_c(3055)$ is a molecular state with $J^P = \frac{1}{2}^-$ [EPJC, 79 (2019) 167].

In this talk (based on [Bo-Lin Huang, Bo Wang, Shi-Lin Zhu, arXiv: 2402. 00460]):

- $\Xi_c(3055)$ is interpreted as a molecular state.
- Identify several molecular states, designated as Ξ_c, within the mass range of 3100 – 3500 MeV.

Chiral Lagrangian

Eight octet-baryon fields in terms of the traceless hermitian 3×3 matrices B:

$$B = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}.$$

The ground state heavy mesons:

$$P = (D^0, D^+, D_s^+), \quad P^*_\mu = (D^{0*}, D^{+*}, D_s^{+*})_\mu,$$

$$H = \frac{1+\not{v}}{2}(P^*_\mu \gamma^\mu + iP\gamma_5), \quad \bar{H} = (P^{*\dagger}_\mu \gamma^\mu + iP^\dagger \gamma_5)\frac{1+\not{v}}{2}.$$

Chiral Lagrangian

The effective chiral Lagrangian:

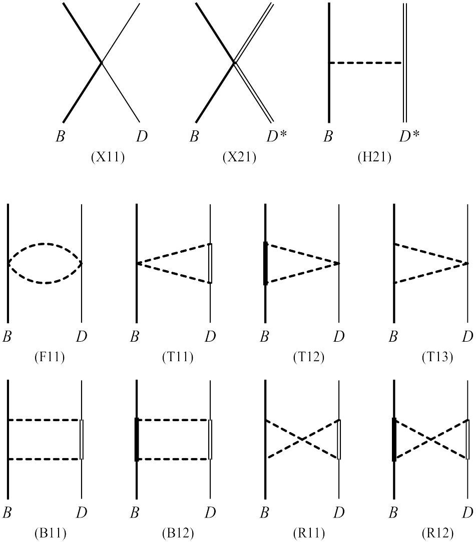
$$\mathcal{L}_{B\phi}^{(1)} = \mathrm{tr}(i\bar{B}[v\cdot D, B]) + 2D\mathrm{tr}(\bar{B}S_\mu\{u^\mu, B\}) + 2F\mathrm{tr}(\bar{B}S_\mu[u^\mu, B]),$$

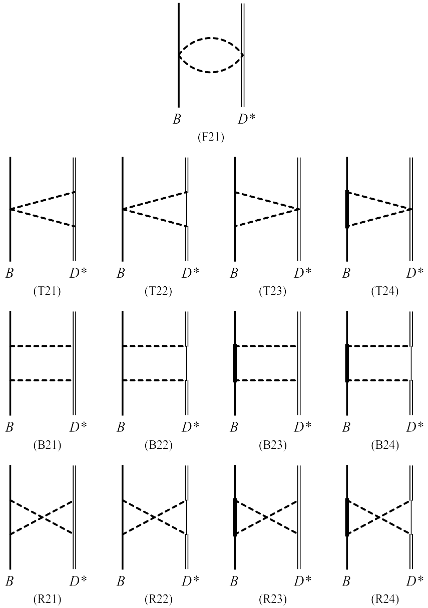
$$\mathcal{L}_{B\phi T}^{(1)} = -\bar{T}^\mu(iv\cdot D - \delta_B)T_\mu + \mathcal{C}(\bar{T}^\mu u_\mu B + \bar{B}u_\mu T^\mu) + 2\mathcal{H}\bar{T}^\mu S\cdot u T_\mu,$$

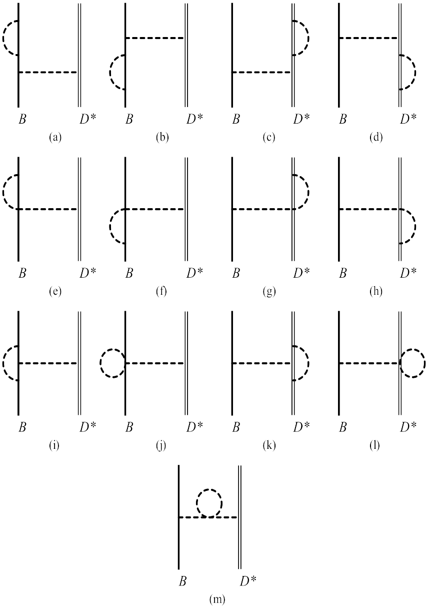
$$\begin{aligned}\mathcal{L}_{H\phi}^{(1)} =& -\left\langle (iv\cdot\partial H)\bar{H}\right\rangle + \left\langle H(iv\cdot\Gamma)\bar{H}\right\rangle - \frac{1}{8}\delta_D\left\langle H\sigma^{\mu\nu}\bar{H}\sigma_{\mu\nu}\right\rangle \\ &+ g\left\langle Hu_\mu\gamma^\mu\gamma_5\bar{H}\right\rangle,\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{BH}^{(0)} =& D_a\mathrm{tr}(\bar{B}B)\left\langle H\bar{H}\right\rangle + D_b\mathrm{tr}(\bar{B}\gamma_\mu\gamma_5 B)\left\langle H\gamma^\mu\gamma_5\bar{H}\right\rangle \\ &+ E_a\mathrm{tr}(\bar{B}\lambda_a B)\left\langle H\lambda_a\bar{H}\right\rangle + E_b\mathrm{tr}(\bar{B}\gamma_\mu\gamma_5\lambda_a B)\left\langle H\gamma^\mu\gamma_5\lambda_a\bar{H}\right\rangle.\end{aligned}$$

Feynman diagrams




B D*
(F21)
B D* B D* B D* B D*
(T21) (T22) (T23) (T24)
B D* B D* B D* B D*
(B21) (B22) (B23) (B24)
B D* B D* B D* B D*
(R21) (R22) (R23) (R24)


B D*
(a)
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(k)
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(l)
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(m)

Effective potentials

The effective potentials for BD and BD^* systems:

$$\mathcal{V}_{BD}^{(\mathrm{X11})} = D_a + \alpha^{(\mathrm{X11})} E_a,$$

$$\mathcal{V}_{BD^*}^{(\mathrm{X21})} = D_a + D_b + \alpha^{(\mathrm{X21})} (E_a + E_b \boldsymbol{\sigma} \cdot \boldsymbol{T}),$$

$$\mathcal{V}_{BD^*}^{(\mathrm{H21})} = \alpha_{\pi}^{(\mathrm{H21})} \frac{g}{f^2} \frac{(\boldsymbol{\sigma} \cdot \boldsymbol{q})(\boldsymbol{T} \cdot \boldsymbol{q})}{\boldsymbol{q}^2 + m_\pi^2} + \alpha_{\eta}^{(\mathrm{H21})} \frac{g}{f^2} \frac{(\boldsymbol{\sigma} \cdot \boldsymbol{q})(\boldsymbol{T} \cdot \boldsymbol{q})}{\boldsymbol{q}^2 + m_\eta^2},$$

$$\mathcal{V}_{BD}^{(\mathrm{F11})} = \alpha_{\pi\pi}^{(\mathrm{F11})} \frac{1}{f^4} J_{22}^F(m_\pi, m_\pi) + \alpha_{KK}^{(\mathrm{F11})} \frac{1}{f^4} J_{22}^F(m_K, m_K),$$

$\cdots$ omitting many more equations $\cdots$

Bound states

The local potentials can be given by

$$V(\boldsymbol{r}) = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} e^{i\boldsymbol{q}\cdot\boldsymbol{r}} \mathcal{V}(\boldsymbol{q}) \mathcal{F}(\boldsymbol{q}),$$

with the regulator function:

$$\mathcal{F}(\boldsymbol{q}) = \exp\left(-\boldsymbol{q}^{2n}/\Lambda^{2n}\right).$$

The Schrödinger equation:

$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + V(\boldsymbol{r})\right]\psi(\boldsymbol{r}) = E\psi(\boldsymbol{r}).$$

Low Energy Constants

SU(2): $D_a = 3c_s, \quad D_b = -c_t, \quad E_a = 3c_s, \quad E_b = -5c_t;$

SU(3): $D_a = 2c_s, \quad D_b = 2c_t/3, \quad E_a = 3c_s, \quad E_b = -5c_t.$

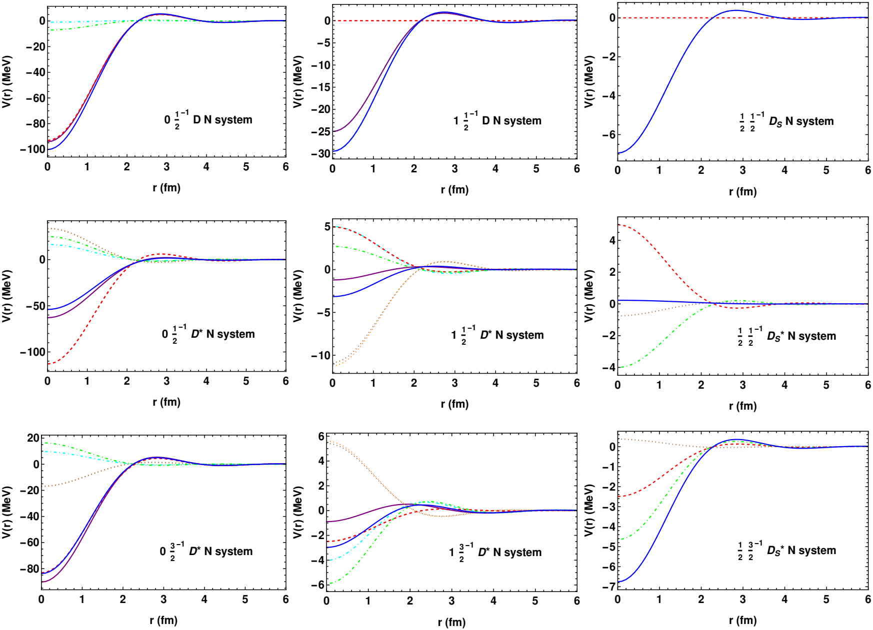
c_s and c_t are determined through quark model [PRD, 101 (2020) 094035] and the $N\bar{N}$ interaction [JHEP, 02 (2014) 113]:

$$c_s = -8.1\,\text{GeV}^{-2}, \quad c_t = 0.65\,\text{GeV}^{-2}.$$

Natural size for NN interaction [EPJA, 51 (2015) 53]:

$$|\widetilde{C}_i| \sim \frac{4\pi}{F_\pi^2} \sim 0.15 \times 10^4\,\text{GeV}^{-2}, \quad |C_i| \sim \frac{4\pi}{F_\pi^2 \Lambda_b^2} \sim 0.6 \times 10^4\,\text{GeV}^{-4}$$

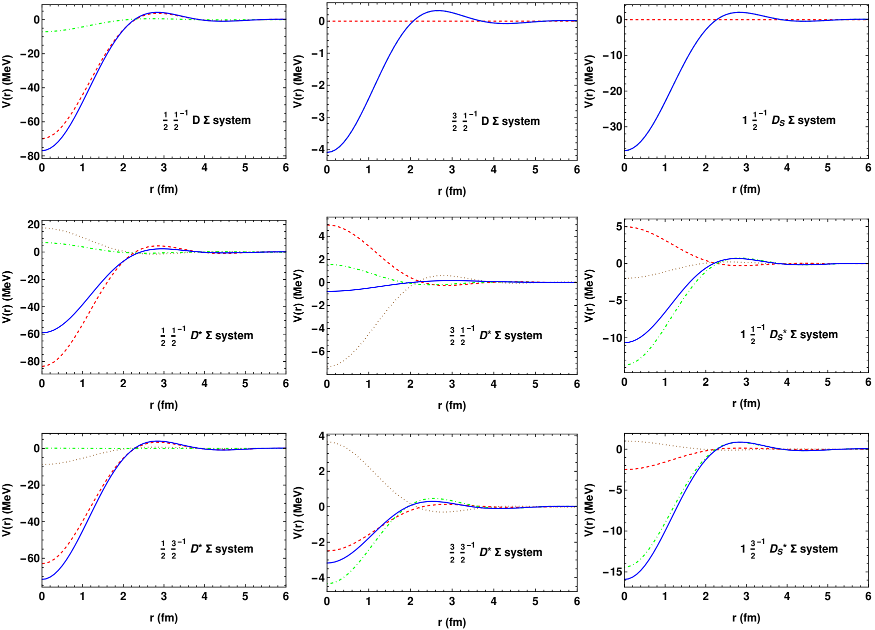
$$|D_i| \sim \frac{4\pi}{F_\pi^2 \Lambda_b^4} \sim 2.5 \times 10^4\,\text{GeV}^{-6}. \quad \Lambda? \qquad \Lambda = 400\,\text{MeV} \to \Lambda_c(2940).$$


V(r) (MeV)
r (fm)
$0\ \frac{1}{2}^{1^{-1}}$ D N system
$1\ \frac{1}{2}^{1^{-1}}$ D N system
$\frac{1}{2}\ \frac{1}{2}^{1^{-1}}$ D_s N system
$0\ \frac{1}{2}^{1^{-1}}$ D^* N system
$1\ \frac{1}{2}^{1^{-1}}$ D^* N system
$\frac{1}{2}\ \frac{1}{2}^{1^{-1}}$ $D_s{}^*$ N system
$0\ \frac{3}{2}^{3^{-1}}$ D^* N system
$1\ \frac{3}{2}^{3^{-1}}$ D^* N system
$\frac{1}{2}\ \frac{3}{2}^{3^{-1}}$ $D_s{}^*$ N system

SU(3)/SU(2)	$[DN]^{I=0}_{J=1/2}$	$[D^*N]^{I=0}_{J=1/2}$	$[D^*N]^{I=0}_{J=3/2}$
ΔE (MeV)	$-12.9/-10.5$	$-1.3/-2.9$	$-6.9/-9.3$
M (MeV)	$2793.2/2795.6$	$2946.2/2944.6$	$2940.5/2938.1$
$\sqrt{\langle r^2\rangle}$ (fm)	$1.7/1.8$	$4.1/3.0$	$2.0/1.9$
States	$\Sigma_c(2800)$?	$\Lambda_c(2940)$	$\Lambda_c(2940)$

PDG: $I(J^P) = 1(?^?)$ for $\Sigma_c(2800)$,

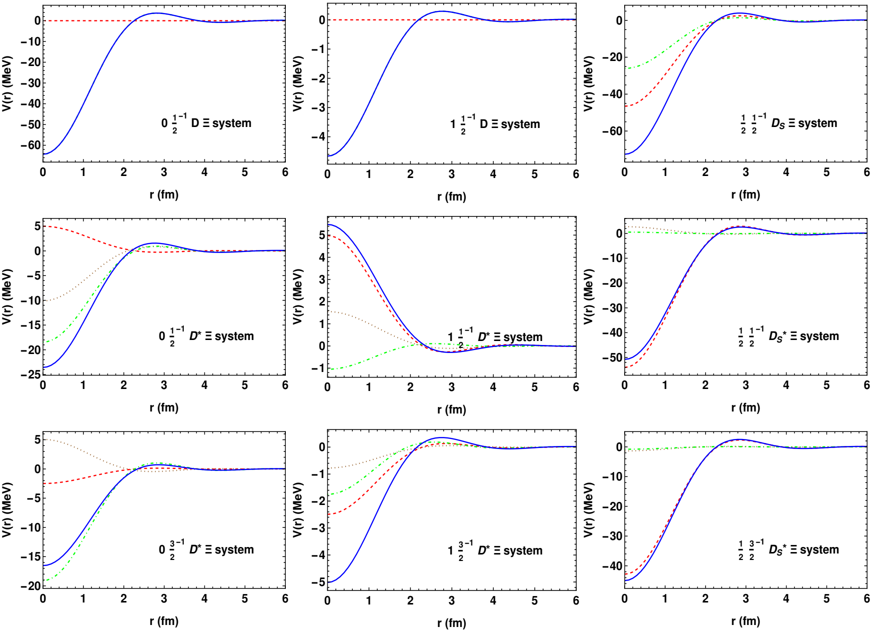
$I(J^P) = 0(\frac{3}{2}^-)$ for $\Lambda_c(2940)$, J^P not certain.


V(r) (MeV)
r (fm)
$\frac{1}{2}\ \frac{1}{2}^{-1}$ D Σ system
$\frac{3}{2}\ \frac{1}{2}^{-1}$ D Σ system
$1\ \frac{1}{2}^{-1}$ D_s Σ system
$\frac{1}{2}\ \frac{1}{2}^{-1}$ D^* Σ system
$\frac{3}{2}\ \frac{1}{2}^{-1}$ D^* Σ system
$1\ \frac{1}{2}^{-1}$ $D_s{}^*$ Σ system
$\frac{1}{2}\ \frac{3}{2}^{-1}$ D^* Σ system
$\frac{3}{2}\ \frac{3}{2}^{-1}$ D^* Σ system
$1\ \frac{3}{2}^{-1}$ $D_s{}^*$ Σ system

SU(3)	$[D\Sigma]^{I=1/2}_{J=1/2}$	$[D^*\Sigma]^{I=1/2}_{J=1/2}$	$[D^*\Sigma]^{I=1/2}_{J=3/2}$
ΔE (MeV)	-7.5	-3.6	-6.2
M (MeV)	3052.9	3198.1	3195.5
$\sqrt{\langle r^2 \rangle}$ (fm)	1.9	2.5	2.0
States	$\Xi_c(3055)$	$\Xi_c(3196)$	$\Xi_c(3196)$

$\Xi_c(3055)$: $I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$, a molecular state.

$\Xi_c(3196)$ vs $\Lambda_c(2940)$


V(r) (MeV)
r (fm)
0 $\frac{1}{2}^{-1}$ D Ξ system
1 $\frac{1}{2}^{-1}$ D Ξ system
$\frac{1}{2}$ $\frac{1}{2}^{-1}$ D_s Ξ system
0 $\frac{1}{2}^{-1}$ D^* Ξ system
1 $\frac{1}{2}^{-1}$ D^* Ξ system
$\frac{1}{2}$ $\frac{1}{2}^{-1}$ $D_s{}^*$ Ξ system
0 $\frac{3}{2}^{-1}$ D^* Ξ system
1 $\frac{3}{2}^{-1}$ D^* Ξ system
$\frac{1}{2}$ $\frac{3}{2}^{-1}$ $D_s{}^*$ Ξ system

SU(3)	$[D\Xi]^{I=0}_{J=1/2}$	$[D_S\Xi]^{I=1/2}_{J=1/2}$	$[D_S^*\Xi]^{I=1/2}_{J=1/2}$	$[D_S^*\Xi]^{I=1/2}_{J=3/2}$
ΔE (MeV)	-4.1	-7.7	-1.7	-0.4
M (MeV)	3181.4	3279.0	3428.8	3430.1
$\sqrt{\langle r^2 \rangle}$ (fm)	2.3	1.9	3.2	5.7
States	$\Omega_c(3188)$?	$\Xi_c(3279)$	$\Xi_c(3430)$	$\Xi_c(3430)$

$(\Xi_c(3055), [D\Sigma]^{I=1/2}_{J=1/2})$ vs $(\Xi_c(3279), [D_S\Xi]^{I=1/2}_{J=1/2})$

$\Xi_c(3430)$ vs $\Xi_c(3196)$ vs $\Lambda_c(2940)$

Summary and Outlook

- Ξ_c: $\Xi_c(3055)$, $\Xi_c(3196)$, $\Xi_c(3279)$, $\Xi_c(3430)$

  Ξ_c within the mass range of $3100 - 3500$ MeV.

- Outlook
  - Other methods for these states.
  - We look forward with great anticipation to future experimental investigations, which we hope will validate the existence of these states.

Thank you for your attention!