Possible molecular bound states: $\Lambda_c N$ & $\Lambda_c \Lambda_c$

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Content

- Hadronic molecule: loosely bound state of hadrons
  [inter-hadron distance]>[confinement size]

  [e.g. deuteron(NN), triton(NNN), hypertriton(Λpn) ]

- Exotic heavy quark mesons (near-threshold states):
  $D_{sJ}(2317)$, $X(3872)$, $Y(3940)$, $X(4260)$, $Z^{+}(4430)$, ...
  $\Rightarrow$ heavy quark molecule problem
  e.g. DK, $D\bar{D}^{*}$, $D^{*}\bar{D}^{*}$, DD_1, $D^{*}D_1$, ...

- Kinetic term vs. potential

$$H = \frac{p^2}{2\mu} + V(r)$$

  μ larger $\Rightarrow$ advantageous for bound states.

- Hidden charm hadron-hadron states
  - Possible two-body bound states
    $(c\bar{q})(\bar{c}q)$, $(\bar{c}\bar{q}\bar{q})(cqq)$, $(\bar{c}q)(cqq)$: $D\bar{D}^*$, $\Lambda_c\bar{\Lambda}_c$, $\bar{D}\Lambda_c$, ...
    $(c\bar{c})(q\bar{q})$..., $(c\bar{c})(qqq)$...: $J/\psi\omega$, $J/\psi N$, ...
  - Nuclear-bound charmonium or hadro-charmonium
- Charmed bound states:
  - $\bar{D}-N$, $D-N$: Yasui, X. Liu, J. He, Haidenbauer, Meissner, ...
  - Λ_c/Σ_c hypernuclei: Dover, Bando, Tsushima, ...
  - Two body $\Sigma_c N$, $\Xi_{cc}N$, $\Sigma_c\Sigma_c$, ...: Riska [NPA 750, 337 (2005)]
- Λ_c: lowest charmed baryon
- Detailed studies of $\Lambda_c N$ and $\Lambda_c\Lambda_c$:
  $\Lambda_c N - \Sigma_c N - \Sigma_c^* N$ & $\Lambda_c\Lambda_c - \Sigma_c\Sigma_c - \Sigma_c^*\Sigma_c^* - \Sigma_c\Sigma_c^*$:
  heavy quark spin symmetry $\Rightarrow$ coupled channel effects may be important

The systems ($\Lambda_c N$ & $\Lambda_c\Lambda_c$)

- Λ_c: 2286.46 MeV, N: 938 MeV
  Σ_c: 2453 MeV, ~~Δ: 1232 MeV~~
  Σ_c^*: 2518 MeV

Channels	1	2	3	4	5	6	7
$J^P = 0^+$	$\Lambda_c N(^1S_0)$	$\Sigma_c N(^1S_0)$	$\Sigma_c^* N(^5D_0)$				
$J^P = 1^+$	$\Lambda_c N(^3S_1)$	$\Sigma_c N(^3S_1)$	$\Sigma_c^* N(^3S_1)$	$\Lambda_c N(^3D_1)$	$\Sigma_c N(^3D_1)$	$\Sigma_c^* N(^3D_1)$	$\Sigma_c^* N(^5D_1)$

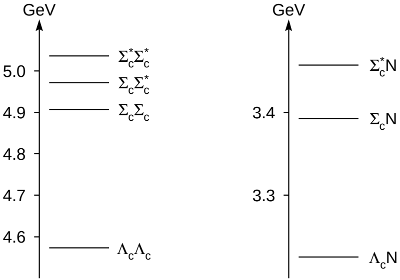
TABLE I: The S-wave $\Lambda_c N$ states and the channels which couple to them.

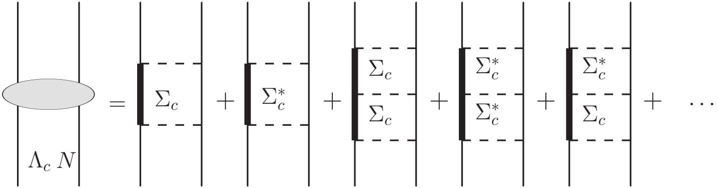
Channels	1	2	3	4	5
$J^P = 0^+$	$\Lambda_c\Lambda_c(^1S_0)$	$\Sigma_c\Sigma_c(^1S_0)$	$\Sigma_c^*\Sigma_c^*(^1S_0)$	$\Sigma_c^*\Sigma_c^*(^5D_0)$	$\Sigma_c\Sigma_c^*(^5D_0)$

TABLE II: The S-wave $\Lambda_c\Lambda_c$ states and the channels which couple to them.

For loosely bound molecule, short-range D meson exchange small, $\Xi_{cc}N$ neglected.

The systems: thresholds & coupled channel effects

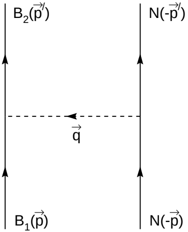




The model

Framework

- Heavy quark limit
- One-meson-exchange potential model (OMEP): π, σ, ρ, ω



B_1, B_2: Λ_c^+, Σ_c, Σ_c^*
(For $\Lambda_c\Lambda_c$, $N \to B_1, B_2$)

-

Baryon:	heavy quark symmetry
π:	chiral symmetry
ρ, ω:	hidden local symmetry

Heavy quark symmetry for (qqQ) baryon

- q: triplet of $SU(3)_F$, Q: singlet of $SU(3)_F$
- Flavor: $3 \times 3 = \bar{3}(antisymmetric) + 6(symmetric)$
- Spin: $\begin{pmatrix} 0 \\ 1 \end{pmatrix}_{\text{diquark}} + (\frac{1}{2})_Q = \begin{pmatrix} \frac{1}{2} \\ \frac{1}{2}, \frac{3}{2} \end{pmatrix}_{\text{total}}$

$$B_{\bar{3}} = \begin{pmatrix} 0 & \Lambda_c^+ & \Xi_c^+ \\ -\Lambda_c^+ & 0 & \Xi_c^0 \\ -\Xi_c^+ & -\Xi_c^0 & 0 \end{pmatrix}, \quad B_6 = \begin{pmatrix} \Sigma_c^{++} & \frac{1}{\sqrt{2}}\Sigma_c^+ & \frac{1}{\sqrt{2}}\Xi_c'^+ \\ \frac{1}{\sqrt{2}}\Sigma_c^+ & \Sigma_c^0 & \frac{1}{\sqrt{2}}\Xi_c'^0 \\ \frac{1}{\sqrt{2}}\Xi_c'^+ & \frac{1}{\sqrt{2}}\Xi_c'^0 & \Omega_c^0 \end{pmatrix}$$

$$B_6^* = \begin{pmatrix} \Sigma_c^{*++} & \frac{1}{\sqrt{2}}\Sigma_c^{*+} & \frac{1}{\sqrt{2}}\Xi_c^{*\prime+} \\ \frac{1}{\sqrt{2}}\Sigma_c^{*+} & \Sigma_c^{*0} & \frac{1}{\sqrt{2}}\Xi_c^{*\prime0} \\ \frac{1}{\sqrt{2}}\Xi_c^{*\prime+} & \frac{1}{\sqrt{2}}\Xi_c^{*\prime0} & \Omega_c^{*0} \end{pmatrix}$$

Heavy quark spin symmetry $\Rightarrow$ B_6 and B_6^* degenerate

- Superfield: $S_\mu = B_\mu^* + \delta\frac{1}{\sqrt{3}}(\gamma_\mu + v_\mu)\gamma^5 B_6$ $[\sigma_h^z S_\mu = S_\mu \Rightarrow \delta = -1]$

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

$$V^\mu = i\frac{g_V}{\sqrt{2}}\begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}^\mu,$$

$$A_\mu = \frac{i}{2}[\xi^\dagger(\partial_\mu\xi) + (\partial_\mu\xi)\xi^\dagger], \quad \Gamma_\mu = \frac{1}{2}[\xi^\dagger(\partial_\mu\xi) - (\partial_\mu\xi)\xi^\dagger],$$

$$\xi = \exp[\tfrac{i\Pi}{2f}], \quad F_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu + [V_\mu, V_\nu],$$

$$D_\mu B_{\bar{3}} = \partial_\mu B_{\bar{3}} + \Gamma_\mu B_{\bar{3}} + B_{\bar{3}}\Gamma_\mu^T,$$

$$D_\mu S_\nu = \partial_\mu S_\nu + \Gamma_\mu S_\nu + S_\nu\Gamma_\mu^T.$$

Effective Lagrangian

$$\mathcal{L}_{\mathcal{B}} = \mathcal{L}_{B_{\bar{3}}} + \mathcal{L}_S + \mathcal{L}_{int}, \tag{1}$$

$$\mathcal{L}_{B_{\bar{3}}} = \frac{1}{2}\mathrm{tr}[\bar{B}_{\bar{3}}(iv\cdot D)B_{\bar{3}}] + i\beta_B \mathrm{tr}[\bar{B}_{\bar{3}} v^\mu(\Gamma_\mu - V_\mu)B_{\bar{3}}] + \ell_B \mathrm{tr}[\bar{B}_{\bar{3}}\sigma B_{\bar{3}}] \tag{2}$$

$$\mathcal{L}_S = -\mathrm{tr}[\bar{S}^\alpha(iv\cdot D - \Delta_B)S_\alpha] + \frac{3}{2}g_1(iv_\kappa)\epsilon^{\mu\nu\lambda\kappa}\mathrm{tr}[\bar{S}_\mu A_\nu S_\lambda] + i\beta_S \mathrm{tr}[\bar{S}_\mu v_\alpha(\Gamma^\alpha - V^\alpha)S^\mu] + \lambda_S \mathrm{tr}[\bar{S}_\mu F^{\mu\nu}S_\nu] + \ell_S \mathrm{tr}[\bar{S}_\mu \sigma S^\mu] \tag{3}$$

$$\mathcal{L}_{int} = g_4 \mathrm{tr}[\bar{S}^\mu A_\mu B_{\bar{3}}] + i\lambda_I \epsilon^{\mu\nu\lambda\kappa} v_\mu \mathrm{tr}[\bar{S}_\nu F_{\lambda\kappa} B_{\bar{3}}] + h.c., \tag{4}$$

$$\mathcal{L}_N = -\frac{g_A}{2f}\bar{N}\gamma^\mu\gamma^5\partial_\mu(\pi^i\tau^i)N - h_\sigma \bar{N}\sigma N - h_V \bar{N}\gamma^\mu(\tau^i\rho^i_\mu + \omega_\mu)N - h_T\bar{N}\sigma^{\mu\nu}\partial_\mu(\tau^i\rho^i_\nu + \omega_\nu)N.$$

Coupling constants

- π: g_1, g_4
  σ: ℓ_B, ℓ_S
  ρ,ω: β_B, β_S, λ_S, λ_I

Couping	Quark Model	Chiral Multiplet	VMD	QSR	Decay
g_1	1.00				
g_4	1.06			0.94	0.999
ℓ_B	-3.65	$-\frac{\Delta M}{2f_\pi} \approx -3.1$			
ℓ_S	7.30	$\frac{\Delta M}{f_\pi} \approx 6.2$			
$(\beta_B g_V)$	-6.0		≈ -5.04		
$(\beta_S g_V)$	12.0		≈ 10.08		
$(\lambda_S g_V)$	19.2 GeV^{-1}			$21.0, 13.5$ GeV^{-1}	
$(\lambda_I g_V)$	-6.8 GeV^{-1}				
g_A	1.25				
h_σ	10.95			14.6	
h_V	3.0				
h_T	6.4 GeV^{-1}				

Table: The coupling constants in different methods. For the quark model estimation, we use $g_A^q = 0.75$, $g_\sigma^q = 3.65$, $g_\rho^q = 3.0$, and $f_\rho^q = 0.0$.

Potentials

- Approximations in deriving non-relativistic potentials:
  (1). For $\Lambda_c N$, $q^0 = 0$, do not consider term like $\frac{q^0}{M_N} \times$ ...
  (2). Neglect $\mathcal{O}(\frac{1}{M_{\Lambda_c}})$ correction. For $\Lambda_c N$, keep $\mathcal{O}(\frac{1}{M_N^2})$ term.
  (3). Neglect δ-functional terms.

$$
\begin{aligned}
V_\pi &= C_\pi(i,j)\frac{m_\pi^3}{24\pi f_\pi^2}\Big\{\vec{\mathcal{O}}_1\cdot\vec{\mathcal{O}}_2 Y_1(m_\pi,\Lambda,r) + \mathcal{O}_{ten} H_3(m_\pi,\Lambda,r)\Big\},\\
V_\sigma &= C_\sigma(i)\frac{m_\sigma}{16\pi}\Big\{4Y_1(m_\sigma,\Lambda,r) + \vec{L}\cdot\vec{\sigma}_2\left(\frac{m_\sigma}{M_N}\right)^2 Z_3(m_\sigma,\Lambda,r)\Big\},\\
V_\rho &= C_{\rho 1}(i,j)\frac{m_\rho}{32\pi}\Big\{8Y_1(m_\rho,r) + (1+\frac{4M_N h_T}{h_V})\frac{m_\rho^2}{M_N^2}\Big[Y_1(m_\rho,r) - 2\vec{L}\cdot\vec{\sigma}_2 Z_3(m_\rho,r)\Big]\\
&+ C_{\rho 2}(i,j)\frac{m_\rho^3}{36\pi M_N}\Big\{(1+\frac{2M_N h_T}{h_V})\Big[2\vec{\mathcal{O}}_1\cdot\vec{\mathcal{O}}_2 Y_1(m_\rho,r) - \mathcal{O}_{ten} H_3(m_\rho,\Lambda,r)\Big]\\
&-6\vec{L}\cdot\vec{\mathcal{O}}_1 Z_3(m_\rho,r)\Big\},
\end{aligned}
$$

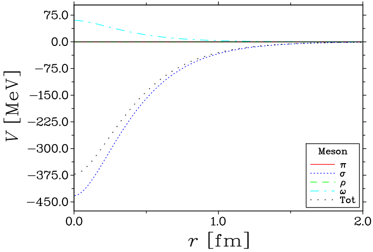
Potentials

$$
\begin{aligned}
Y(x) &= \frac{e^{-x}}{x}, \quad Z(x) = (\frac{1}{x} + \frac{1}{x^2})Y(x), \quad H(x) = (1 + \frac{3}{x} + \frac{3}{x^2})Y(x), \\
Y_1(m, \Lambda, r) &= Y(mr) - \left(\frac{\Lambda}{m}\right) Y(\Lambda r) - \frac{\Lambda^2 - m^2}{2m\Lambda} e^{-\Lambda r}, \\
Y_3(m, \Lambda, r) &= Y(mr) - \left(\frac{\Lambda}{m}\right) Y(\Lambda r) - \frac{(\Lambda^2 - m^2)\Lambda}{2m^3} e^{-\Lambda r}, \\
Z_3(m, \Lambda, r) &= Z(mr) - \left(\frac{\Lambda}{m}\right)^3 Z(\Lambda r) - \frac{(\Lambda^2 - m^2)\Lambda}{2m^3} Y(\Lambda r), \\
H_3(m, \Lambda, r) &= H(mr) - \left(\frac{\Lambda}{m}\right)^3 H(\Lambda r) - \frac{(\Lambda^2 - m^2)\Lambda}{2m^3} Y(\Lambda r) - \frac{(\Lambda^2 - m^2)\Lambda}{2m^3} e^{-\Lambda r}.
\end{aligned}
$$

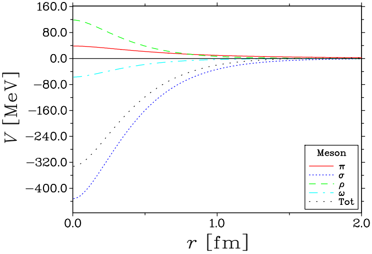
Cutoff Λ: $F(q) = \frac{\Lambda^2 - m^2}{\Lambda^2 - q^2}$, [Free parameters: Λ_π, Λ_σ, Λ_ρ, Λ_ω]

$\Lambda_c N$: 0^+

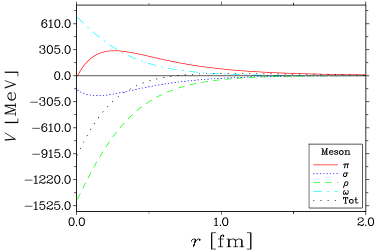
Diagonal potentials with $\Lambda_\pi = \Lambda_\sigma = \Lambda_{\text{vec}} = 1$ GeV



(11): $\Lambda_c N(^1S_0) \leftrightarrow \Lambda_c N(^1S_0)$



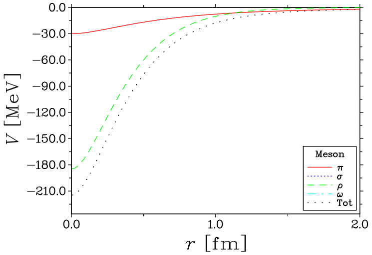
(22): $\Sigma_c N(^1S_0) \leftrightarrow \Sigma_c N(^1S_0)$



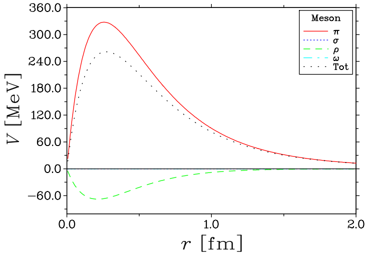
$\Leftarrow$ (33): $\Sigma_c^* N(^5D_0) \leftrightarrow \Sigma_c^* N(^5D_0)$

$\Lambda_c N$: 0^+

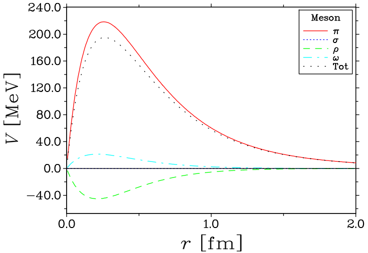
Transition potentials with $\Lambda_\pi = \Lambda_\sigma = \Lambda_{\text{vec}} = 1$ GeV



(12): $\Lambda_c N(^1S_0) \leftrightarrow \Sigma_c N(^1S_0)$



(13): $\Lambda_c N(^1S_0) \leftrightarrow \Sigma_c^* N(^5D_0)$



$\Leftarrow$ (23): $\Sigma_c N(^1S_0) \leftrightarrow \Sigma_c^* N(^5D_0)$

- Variational method

$$\begin{cases} OPEP \begin{cases} \text{w/o} \\ \text{w/} \end{cases} \\ OMEP \begin{cases} \Lambda_\pi = \Lambda_\sigma = \Lambda_{\text{vec}} = \Lambda_{\text{com}} \begin{cases} \text{w/o} \\ \text{w/} \end{cases} \Leftarrow \text{common cutoff} \\ \alpha_\pi = \alpha_\sigma = \alpha_\rho = \alpha_\omega = \alpha \begin{cases} \text{w/o} \\ \text{w/} \end{cases} \Leftarrow \text{scaled cutoff} \end{cases} \end{cases}$$

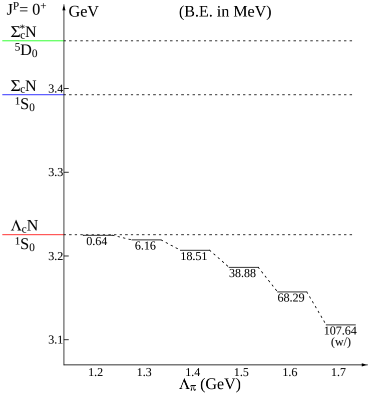
OPEP: one-pion-exchange potential
OMEP: one-meson-exchange potential
w/o: without channel coupling
w/: with channel coupling
$\Lambda_{\text{exch}} = m_{\text{exch}} + \alpha\Lambda_{QCD}$

- Only present OPEP results

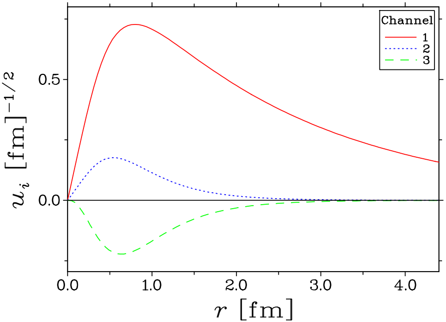
$\Lambda_c N$: 0^+

OPEP model:

Λ_π (GeV)	1.2	1.3	1.4	1.5
$B.E.(J=0)$ (MeV)	0.64	6.16	18.51	38.88
$\sqrt{\langle r^2 \rangle}$ (fm)	5.2	1.9	1.2	0.9
Prob. (%)	(98.2/0.6/1.2)	(94.0/2.3/3.7)	(89.3/4.6/6.1)	(84.5/7.2/8.3)



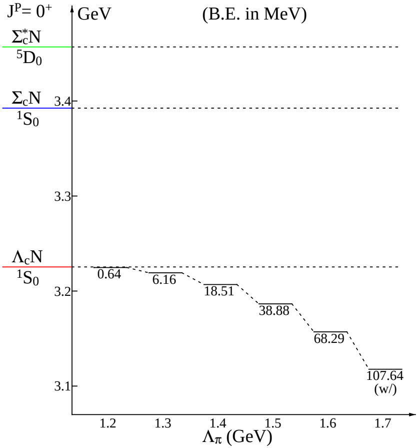
Binding energies (B.E.)



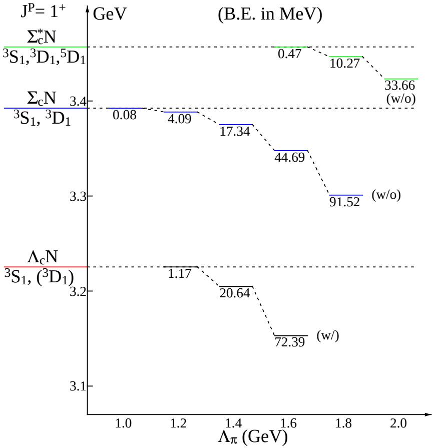
Wave functions with $\Lambda_\pi = 1.3$ GeV

$\Lambda_c N$: 1^+

OPEP model (compare with 0^+)



$J^P = 0^+$



$J^P = 1^+$

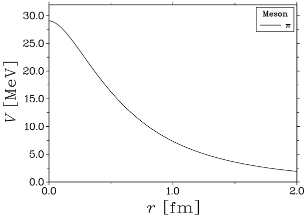
J^P		$\Lambda_c N$ (S-wave)	$\Lambda_c N - \Sigma_c N - \Sigma_c^* N$
0^+	OPEP (Λ)	$\times$	[1.367: 13.60, 1.38]
	OMEP (Λ)	[0.900: 1.24, 3.86]	[0.900: 13.60, 1.46]
	OMEP (α)	[1.533: 0.25, 8.13]	[1.533: 13.57, 1.37]
1^+	OPEP (Λ)	$\times$	[1.353: 13.54, 1.40]
	OMEP (Λ)	[0.900: 1.24, 3.86]	[0.900: 13.49, 1.47]
	OMEP (α)	[1.618: 0.80, 4.72]	[1.618: 13.47, 1.39]

Table: Comparison among different cases. The meaning of the numbers are [cutoff $\Lambda_{\rm com}$ in GeV or dimensionless α: B.E. in MeV, RMS radius in fm].
$(\Lambda = m_{meson} + \alpha\Lambda_{QCD})$

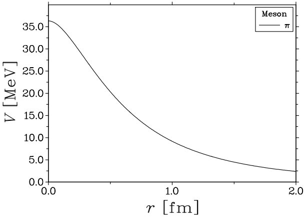
For the coupled channel calculation, one may get similar binding energies (and the corresponding RMS radiuses) in the OMEP model and in the OPEP model.

$\Lambda_c\Lambda_c$ ($J^P = 0^+$): Diagonal potentials with $\Lambda_\pi = 1$ GeV

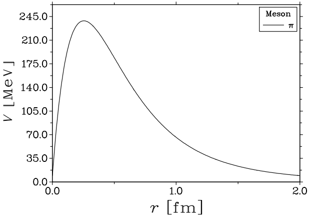
OPEP model



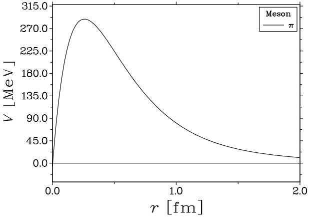
(22): $\Sigma_c\Sigma_c({}^1S_0) \to \Sigma_c\Sigma_c({}^1S_0)$



(33): $\Sigma_c^*\Sigma_c^*({}^1S_0) \to \Sigma_c^*\Sigma_c^*({}^1S_0)$

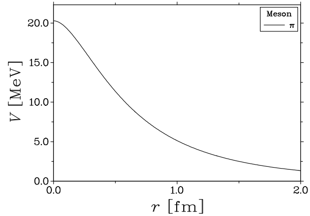


(44): $\Sigma_c^*\Sigma_c^*({}^5D_0) \to \Sigma_c^*\Sigma_c^*({}^5D_0)$

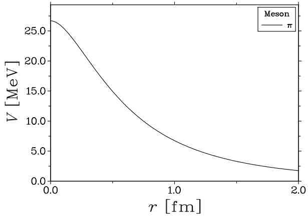


(55): $\Sigma_c\Sigma_c^*({}^5D_0) \to \Sigma_c\Sigma_c^*({}^5D_0)$

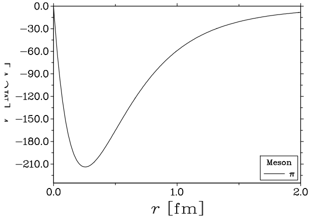
$\Lambda_c\Lambda_c$ ($J^P = 0^+$): Transition potentials with $\Lambda_\pi = 1$ GeV
OPEP model



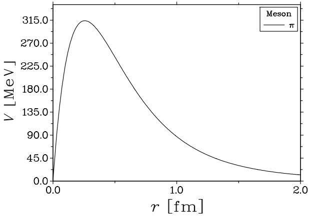
(12): $\Lambda_c\Lambda_c(^1S_0) \to \Sigma_c\Sigma_c(^1S_0)$



(13): $\Lambda_c\Lambda_c(^1S_0) \to \Sigma_c^*\Sigma_c^*(^1S_0)$



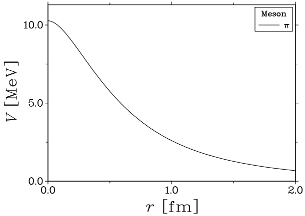
(14): $\Lambda_c\Lambda_c(^1S_0) \to \Sigma_c^*\Sigma_c^*(^5D_0)$



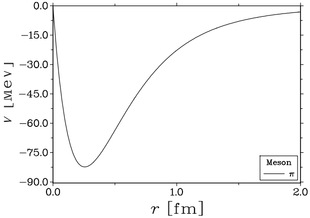
(15): $\Lambda_c\Lambda_c(^1S_0) \to \Sigma_c\Sigma_c^*(^5D_0)$

$\Lambda_c\Lambda_c$ ($J^P = 0^+$): Transition potentials with $\Lambda_\pi = 1$ GeV (con't)

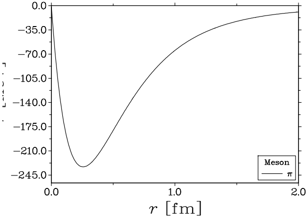
OPEP model



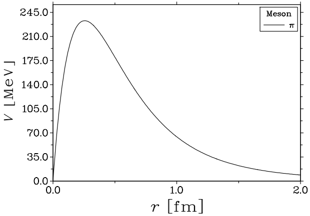
(23): $\Sigma_c\Sigma_c(^1S_0) \to \Sigma_c^*\Sigma_c^*(^1S_0)$



(24): $\Sigma_c\Sigma_c(^1S_0) \to \Sigma_c^*\Sigma_c^*(^5D_0)$

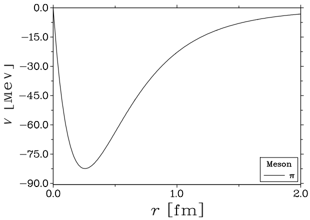


(25): $\Sigma_c\Sigma_c(^1S_0) \to \Sigma_c\Sigma_c^*(^5D_0)$

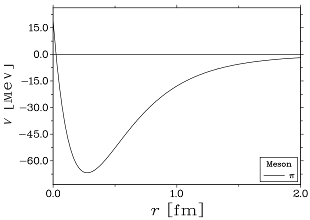


(34): $\Sigma_c^*\Sigma_c^*(^1S_0) \to \Sigma_c^*\Sigma_c^*(^5D_0)$

$\Lambda_c\Lambda_c$ ($J^P = 0^+$): Transition potentials with $\Lambda_\pi = 1$ GeV (con't)
OPEP model



(35): $\Sigma_c^*\Sigma_c^*(^1S_0) \to \Sigma_c\Sigma_c^*(^5D_0)$



(45): $\Sigma_c^*\Sigma_c^*(^5D_0) \to \Sigma_c\Sigma_c^*(^5D_0)$

- Tensor force is important.

$\Lambda_c\Lambda_c$ ($J^P = 0^+$)

- Without channel coupling: No S-wave $\Lambda_c\Lambda_c$ and $\Sigma_c\Sigma_c$ binding solutions

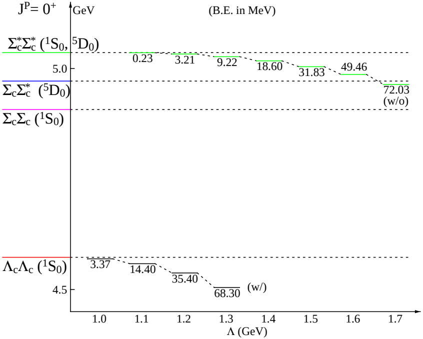
	Λ (GeV)	1.1	1.3	1.5	1.7
	B.E. (MeV)	0.23	9.22	31.83	72.03
$\Sigma_c^*\Sigma_c^*$	$\sqrt{\langle r^2 \rangle}$ (fm)	5.9	1.3	0.9	0.7
	Prob. (%)	(94.8, 5.2)	(88.1, 11.9)	(86.3, 13.7)	(85.2, 14.8)

- With channel coupling

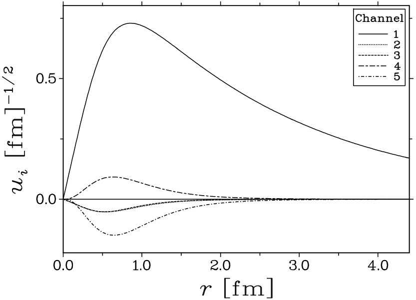
Λ (GeV)	1.0	1.1	1.2	1.3
B.E. (MeV)	3.39	14.45	35.44	68.37
$\sqrt{\langle r^2 \rangle}$ (fm)	2.0	1.2	0.9	0.7
Prob. (%)	(97.4/0.2/0.2 /0.6/1.6)	(94.3/0.5/0.5 /1.3/3.4)	(90.7/1.1/1.0 /2.0/5.2)	(86.8/1.8/1.8 /2.6/7.0)
D-wave prob.	2.2%	4.7%	7.2%	9.6%

$\Lambda = 1.0 \sim 1.2$ GeV are molecule-like but $\Lambda = 1.3 \sim 1.5$ GeV may be beyond our model.

$\Lambda_c\Lambda_c$ ($J^P = 0^+$)



Binding energies (B.E.)



Wave functions with $\Lambda_\pi = 1.0$ GeV

Discussion

- Channel coupling is important in binding charmed baryons
- For $\Lambda_c N$, solutions almost spin-independent. How about $\Lambda_c \Sigma_c$, $\Lambda_c \Lambda$, $\Lambda_c \Sigma$, $\Lambda_c \Delta$, or ... ?
- Cutoff dependence including δ-functional terms in OPEP model

	Λ (GeV)	0.75	0.80	0.85
$\Lambda_c N$	$E_{J=0}$ (MeV)	0.1	14.8	43.9
	$\sqrt{\langle r^2 \rangle}$ (fm)	10.8	1.1	0.7
	Prob. (%)	(93.3/6.6/0.1)	(51.0/49.0/0.0)	(37.9/62.1/0.0)

	Λ (GeV)	0.70	0.75
$\Lambda_c \Lambda_c$	B.E. (MeV)	3.99	32.77
	$\sqrt{\langle r^2 \rangle}$ (fm)	1.7	0.7
	Prob. (%)	(91.4/4.0/4.2 /0.1/0.3)	(71.8/13.3/14.5 /0.1/0.3)
	D-wave prob.	0.4%	0.4%

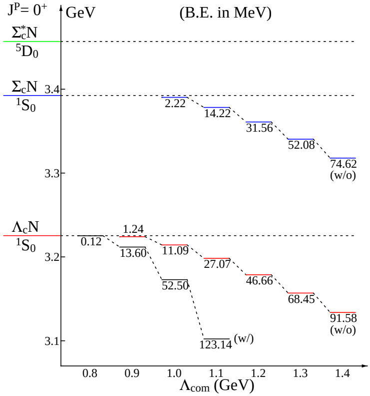
- Possible places to search for $\Lambda_c N$ and $\Lambda_c \Lambda_c$: GSI-Fair, J-PARC, RHIC, BELLE

- Construct Lagrangian reflecting heavy quark, chiral, and hidden local symmetries and determine the coupling constants with various methods
- Channel coupling is important for possible molecule-like bound states $\Lambda_c N$ $(J = 0, 1)$ and $\Lambda_c \Lambda_c$ $(J = 0)$. If they exist, should be stable.
- Preliminary: $\Lambda_c \Sigma_c$ $(I = 1,\ J^P = 0^+, 1^+)$, $\Sigma_c \Sigma_c$ $(I = 2,\ J^P = 0^+)$ may also form molecule-like bound states. But such states decay and need further study.

Thank you !

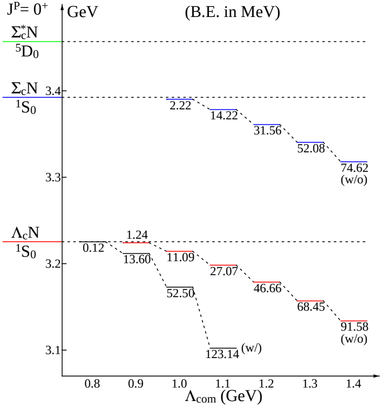
Backup slides

$\Lambda_c N$: 0^+
OMEP model ($\Lambda_{\rm com}$ & α)

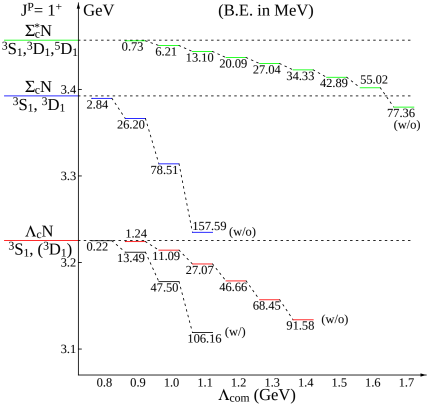


$\Lambda_c N$: 1^+

OMEP model ($\Lambda_{\rm com}$, compare with 0^+)



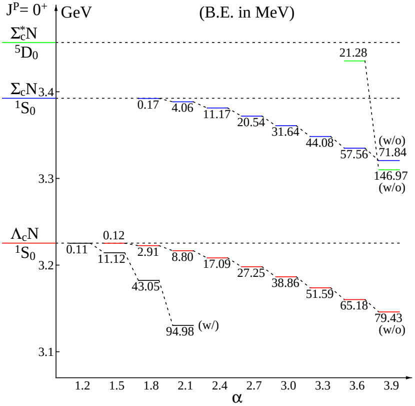
$J^P = 0^+$



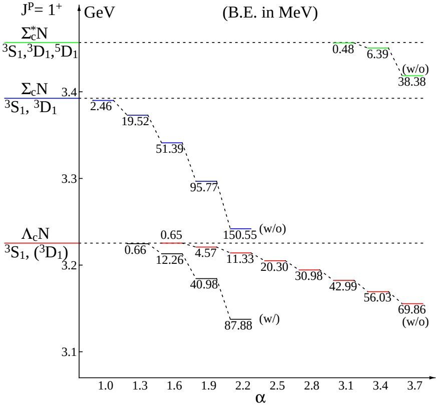
$J^P = 1^+$

$\Lambda_c N$: 1^+

OMEP model (α, compare with 0^+)



$J^P = 0^+$



$J^P = 1^+$

- π: g_1, g_4
  σ: ℓ_B, ℓ_S
  ρ, ω: β_B, β_S, λ_S, λ_I
- Can use strong decay:

$$\Gamma(\Sigma_c^* \to \Lambda\pi) = \frac{g_4^2}{12\pi f_\pi^2}\frac{M_{\Lambda_c}}{M_{\Sigma_c^*}}|\vec{p}_\pi^{\,3}| \Rightarrow g_4 = 0.999$$

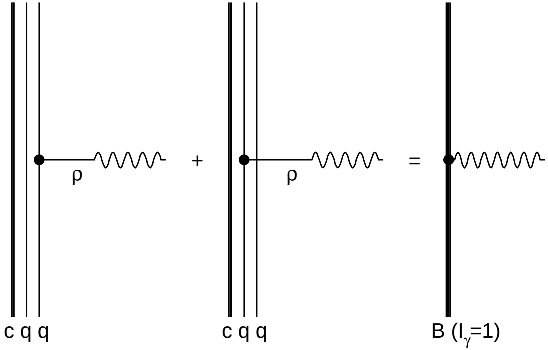
- Can use Quark Model:

$$\begin{aligned}\mathcal{L}_q &= -\frac{g_A^q}{2f}\bar{\psi}\gamma^\mu\gamma^5\partial_\mu(\pi^i\tau^i)\psi - g_\sigma^q\bar{\psi}\sigma\psi - g_\rho^q\bar{\psi}\gamma^\mu(\rho_\mu^i\tau^i + \omega_\mu)\psi \\ &\quad - f_\rho^q\bar{\psi}\sigma^{\mu\nu}\partial_\mu(\rho_\nu^i\tau^i + \omega_\nu)\psi. \qquad (5)\end{aligned}$$

- Can use chiral multiplet assumption:
  $SU(3)_L \times SU(3)_R$ chiral partners: $B_{\bar{3}} \sim \tilde{B}_{\bar{3}}$, $B_6 \sim \tilde{B}_6$
  $\Rightarrow \ell_B = -\frac{M_{\tilde{\Lambda}_c} - M_{\Lambda_c}}{2f_\pi} \sim -3.1, \quad \ell_S = \frac{M_{\tilde{\Sigma}_c} - M_{\Sigma_c}}{f_\pi} \sim 6.2$

Coupling constants

- Can use vector meson dominance (VMD):



$$(\beta_B g_V) = -\frac{\sqrt{2}m_\rho}{f_\rho} = -5.04, \quad (\beta_S g_V) = \frac{2\sqrt{2}m_\rho}{f_\rho} = 10.08$$

- Can use QCD sum rule results (QSR)

Coupling constants

- Phase convention

$$\begin{pmatrix} H_{11} & H_{12} & H_{13} & H_{14} & H_{15} & \cdots \\ & H_{22} & H_{23} & H_{24} & H_{25} & \cdots \\ & & H_{33} & H_{34} & H_{35} & \cdots \\ & & & H_{44} & H_{45} & \cdots \\ & & & & H_{55} & \cdots \\ & & \cdots & & & \end{pmatrix} \tag{6}$$

$$\Rightarrow \begin{pmatrix} H_{11} & \delta_2 H_{12} & \delta_3 H_{13} & \delta_4 H_{14} & \delta_5 H_{15} & \cdots \\ & H_{22} & (\delta_2^* \delta_3) H_{23} & (\delta_2^* \delta_4) H_{24} & (\delta_2^* \delta_5) H_{25} & \cdots \\ & & H_{33} & (\delta_3^* \delta_4) H_{34} & (\delta_3^* \delta_5) H_{35} & \cdots \\ & & & H_{44} & (\delta_4^* \delta_5) H_{45} & \cdots \\ & & & & H_{55} & \cdots \\ & & \cdots & & & \end{pmatrix}, \tag{7}$$

- Phases of g_4 and λ_I do not matter.