$Y_c N$ interaction and $\Lambda_c NN$ charm nuclei

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Introduction

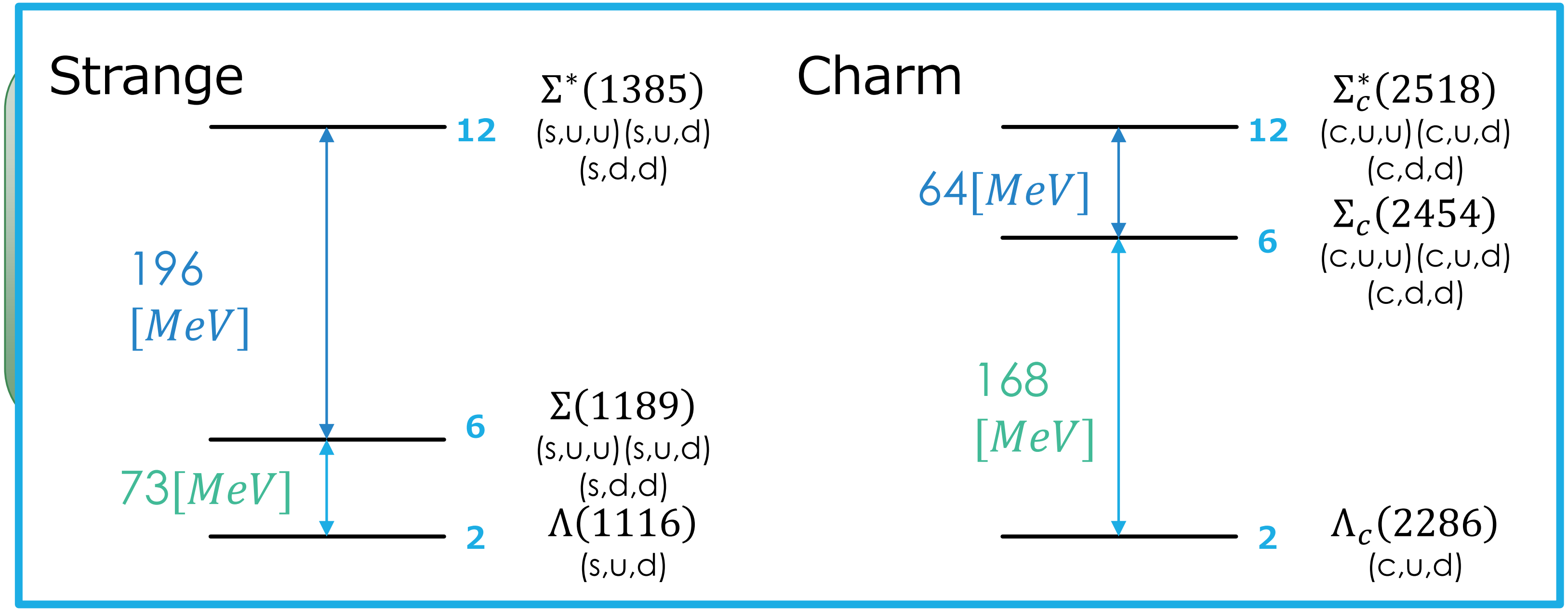
➢ For some 10 years, we have been obtaining many experimental data related to hypernuclei and hyperon-nucleon(YN) and hyperon-hyperon(YY) interactions.

the next stage ⇨ **Approaching to charm nuclei structure with theoretical knowledge**

➢ Interesting character of charm nuclei

- Heavy quark symmetry
- Channel coupling including higher state than strange sector.

Introduction



- Heavy quark symmetry
- Channel coupling including higher state than strange sector.

$Y_c N$ interaction

- $Y_c N$ potential ($Y_c = \Lambda_c, \Sigma_c, {\Sigma_c}^*$)

In this study, we construct hybrid potential models constructed with a hadron model and a quark model, in particular as follows,

- One Boson Exchange potential [Y.R.Liu, M.Oka, Phys. Rev. D 85, 014015 (2012)]
- Quark Cluster Model [M.Oka, Nuclear Physics A 881 (2012) 6–13]

$$V_{(Y_c N)} = V_{OBEP} + V_{QCM}$$

- Channel coupling

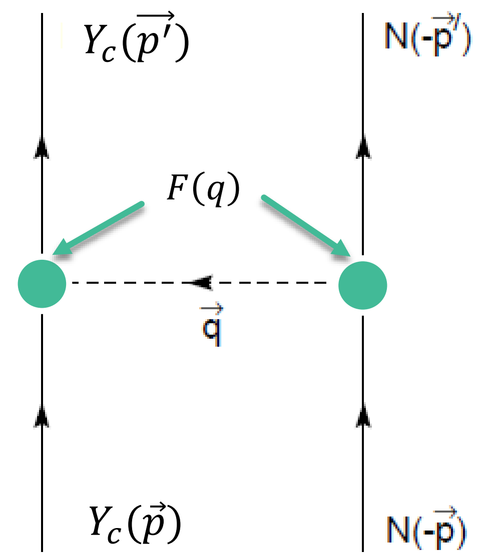
Channels	1	2	3	4	5	6	7
$J^\pi = 0^+$	$\Lambda_c N(^1S_0)$	$\Sigma_c N(^1S_0)$	$\Sigma_c^* N(^5D_0)$				
$J^\pi = 1^+$	$\Lambda_c N(^3S_1)$	$\Sigma_c N(^3S_1)$	$\Sigma_c^* N(^3S_1)$	$\Lambda_c N(^3D_1)$	$\Sigma_c N(^3D_1)$	$\Sigma_c^* N(^3D_1)$	$\Sigma_c^* N(^5D_1)$

$Y_c N$ interaction

- One Boson Exchange potential

We assume that pion and sigma meson exchange between the charm baryon and the nucleon.
At the vertices of exchange, we introduce the form factor as follows

$$F(q) = \frac{\Lambda^2 - m^2}{\Lambda^2 - q^2}$$



$Y_c N$ interaction

- One Boson Exchange potential

The meson exchange parts contain the spin-independent central, spin-spin, tensor and the spin-orbit potentials,

$$V_\pi(i,j) = C_\pi(i,j)\frac{m_\pi^3}{24\pi f_\pi^2}\left\{\langle\mathcal{O}_{spin}\rangle_{ij} Y_1(m_\pi,\Lambda_\pi,r) + \langle\mathcal{O}_{ten}\rangle_{ij} H_3(m_\pi,\Lambda_\pi,r)\right\}$$

$$V_\sigma(i,j) = C_\sigma(i,j)\frac{m_\sigma}{16\pi}\left\{\langle\mathbf{1}\rangle_{ij}\, 4Y_1(m_\sigma,\Lambda_\sigma,r) + \langle\mathcal{O}_{LS}\rangle_{ij}\left(\frac{m_\sigma}{M_N}\right)^2 Z_3(m_\sigma,\Lambda_\sigma,r)\right\}$$

The coupling strength and the cutoff parameters are determined later.

$Y_c N$ interaction

- Quark Cluster Model (QCM)

In a previous approach, we considered exchanges of the vector mesons for short range part of the $Y_c N$ interaction.

However, they do not provide enough repulsion at short distances and result in very deep bound states with compact wave functions.

As the wave function of the baryons overlap significantly at short distances, we consider quark exchange interactions of the quark cluster model(QCM).

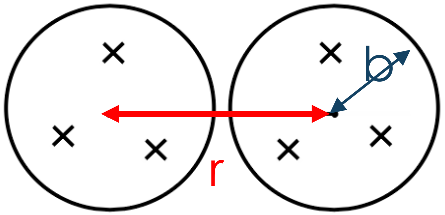
$Y_c N$ interaction

- Quark Cluster Model (QCM)

The QCM consider **clusters** each made of **three quarks as baryons**.

When two baryons overlap completely, r=0, all the six quarks occupy the lowest energy orbit with a single center.

The strengths of the repulsive potential at r=0 are thus given by the difference of the expectation values of the quark model Hamiltonian for the single-centered six-quark states and for the individual baryons.



$Y_c N$ interaction

- Quark Cluster Model (QCM)

Color-magnetic interaction

$$V_{CM} = -\beta \sum_{i<j} (\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j)(\boldsymbol{\lambda}_i \cdot \boldsymbol{\lambda}_j)$$

Expectation value

$$\langle V_{CM} \rangle = \beta \left[8N + \frac{4}{3} S(S+1) + 2C_2 \left[SU(3)_c \right] - 4C_2 \left[SU(6)_{cs} \right] \right]$$

Potential equation

$$V_{QCM} = V_0 e^{-\frac{r^2}{b^2}}$$

$Y_c N$ interaction

- Quark Cluster Model (QCM)

Color-r

$$C_2\left[SU(g)\right] = \frac{1}{2}\left[\sum_i f_i(f_i - 2i + g + 1) - \frac{N^2}{g}\right]$$

Expectation value

$$\langle V_{CM}\rangle = \beta\left[8N + \frac{4}{3}S(S+1) + 2C_2\left[SU(3)_c\right] - 4C_2\left[SU(6)_{cs}\right]\right]$$

Potential equation

$$V_{QCM} = V_0 e^{-\frac{r^2}{b^2}}$$

$Y_c N$ interaction

System	V_0 [MeV]
$(NN)^{S=0}_{I=1}$	450
$(NN)^{S=1}_{I=0}$	350
$(\Lambda_c N)^{S=0}_{I=1/2}$	300
$(\Lambda_c N)^{S=1}_{I=1/2}$	300

$$\begin{pmatrix} \Sigma_c N \\ \Sigma_c^* N \end{pmatrix}^{S=0}_{I=1/2} = \begin{pmatrix} 100 & 0 \\ 0 & 0 \end{pmatrix} \quad \begin{pmatrix} \Sigma_c N \\ \Sigma_c^* N \end{pmatrix}^{S=1}_{I=1/2} = \begin{pmatrix} 166.7 & -24.0 \\ -24.0 & 108.3 \end{pmatrix}$$

Potential equation

$$V_{QCM} = V_0 e^{-\frac{r^2}{b^2}}$$

$Y_c N$ interaction

- Parameter fix

we determine the parameters of the potential so as to reproduce the NN interaction data using the same model.

・Fixed parameter

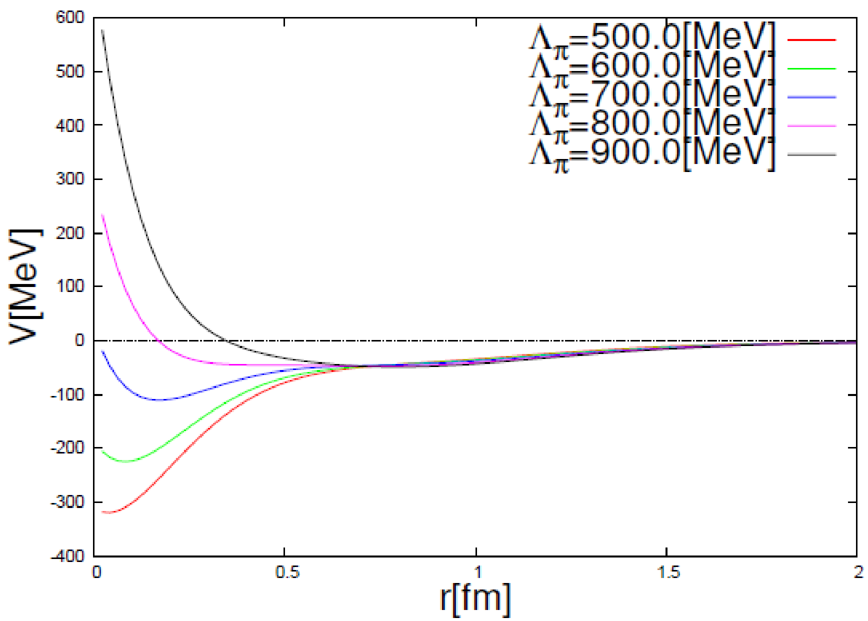
Pi-baryon coupling constants, Range parameter of QCM

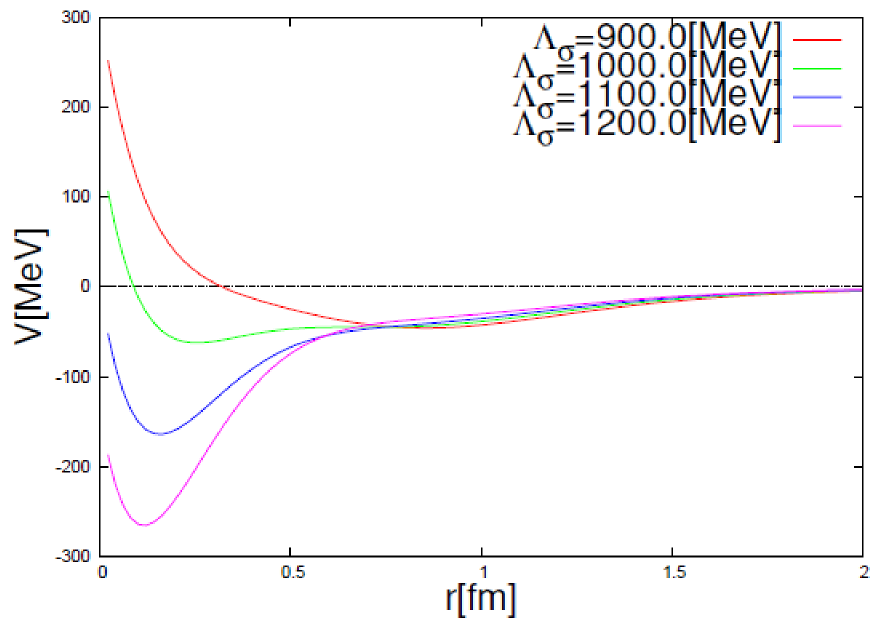
・Determined parameter

Cutoff parameter (Λ_π, Λ_σ), sigma-baryon coupling constants

$Y_c N$ interaction

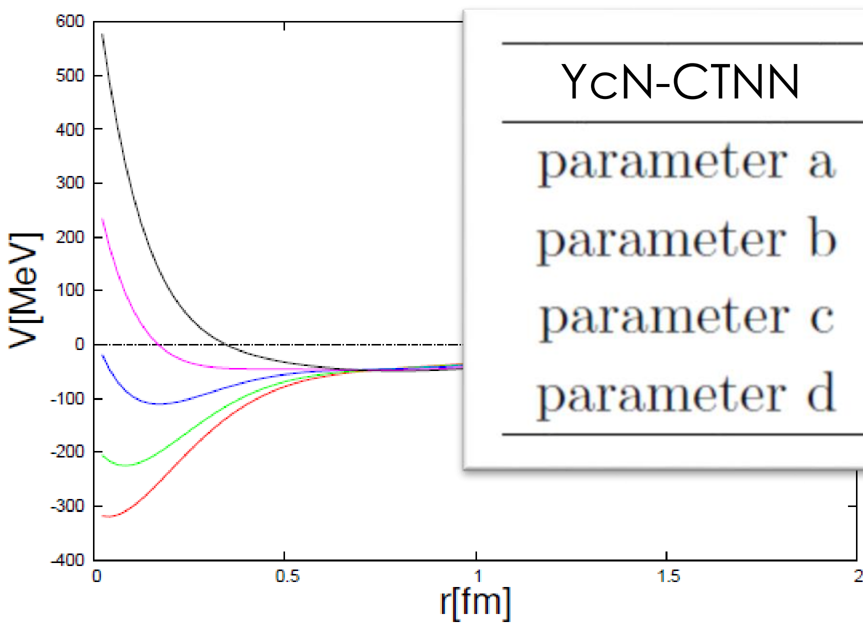
- Parameter fix



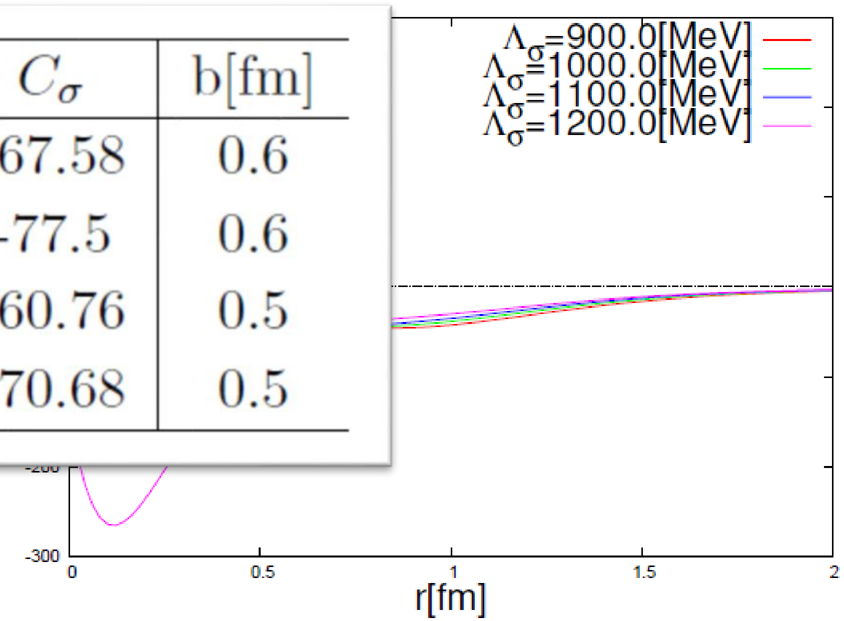


$Y_c N$ interaction

- Parameter fix



YcN-CTNN	C_σ	b[fm]
parameter a	-67.58	0.6
parameter b	-77.5	0.6
parameter c	-60.76	0.5
parameter d	-70.68	0.5



$Y_c N$ interaction

- $Y_c N$ 2-body system

$Y_c n$: YcN-CTNN potential

$Y_c p$: YcN-CTNN potential + Coulomb potential

・Coulomb potential

For $\Sigma_c p, \Sigma_c{}^* p$

$$\left| |(\Sigma_c N)_{I=\frac{1}{2}, I_3=+\frac{1}{2}} \right\rangle = -\sqrt{\frac{1}{3}} \left| \Sigma_c^+ p \right\rangle + \sqrt{\frac{2}{3}} \left| \Sigma_c^{++} n \right\rangle$$

$$V_{coulomb}^{\Lambda_c N}(r) = \frac{\alpha\hbar}{r}, \quad V_{coulomb}^{\Sigma_c N}(r) = \frac{1}{3}\frac{\alpha\hbar c}{r}, \quad V_{coulomb}^{\Sigma_c^* N}(r) = \frac{1}{3}\frac{\alpha\hbar c}{r}$$

$Y_c N$ interaction

- Result of binding energy and scattering length

$J^\pi = 0^+$	CTNN-a	CTNN-b	CTNN-c	CTNN-d
B.E. [MeV]($J^\pi = 0^+$)	-	-	1.7×10^{-3}	1.37
(+ Coulomb)				(0.56)
scattering length [fm]	-3.63	-63.25	139.07	5.32

$J^\pi = 1^+$	CTNN-a	CTNN-b	CTNN-c	CTNN-d
B.E. [MeV]($J^\pi = 0^+$)	-	1.67×10^{-4}	1.9×10^{-3}	1.56
(+ Coulomb)				(0.72)
scattering length [fm]	-4.10	398.67	39.96	5.02

$\Lambda_c NN$ charm nuclei

- Effective potential

We replace $Y_c N$-CTNN potential with 2-range Gaussian potential to renormalize effects of excited states to $\Lambda_c N$ S-wave.

$$V_{\Lambda_c N} = \underline{V_1 e^{-\frac{r^2}{{b_1}^2}}} + \underline{V_2 e^{-\frac{r^2}{{b_2}^2}}}$$

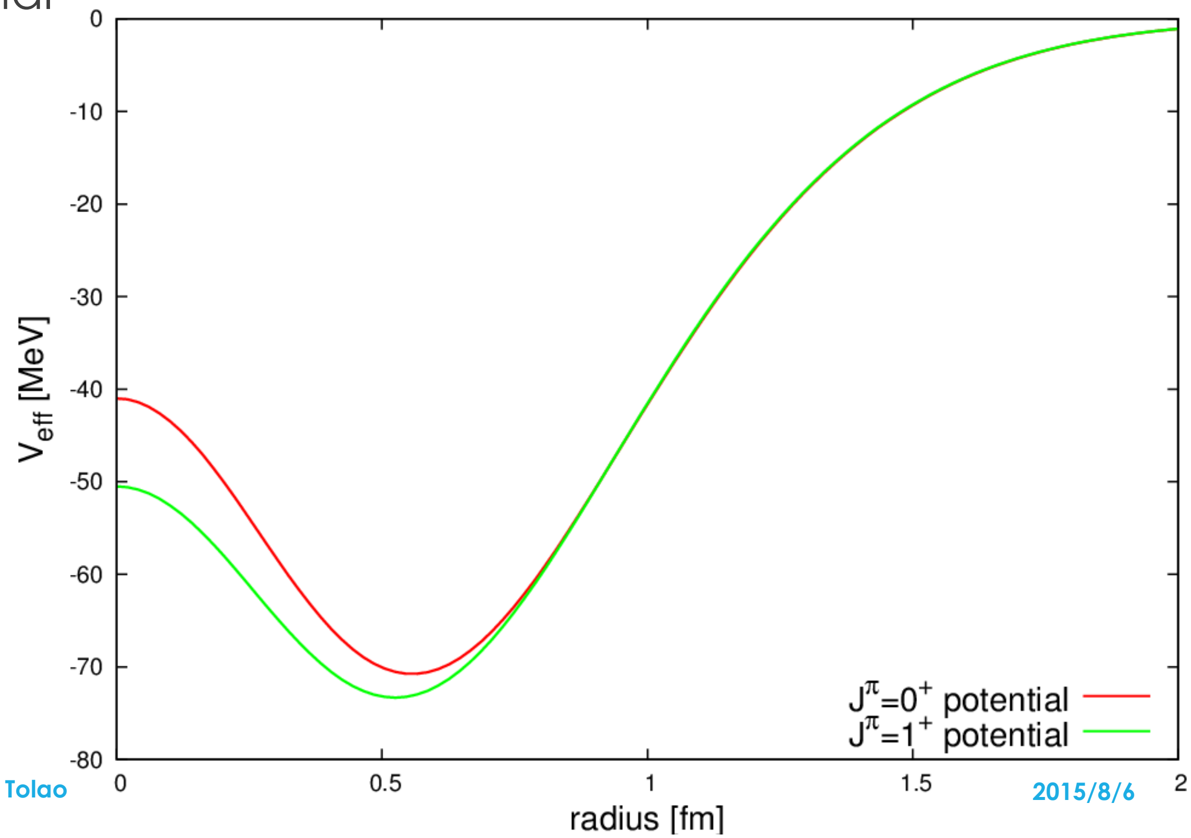
OBEP like QCM like

Parameter fix: $b_1 = 0.9$ fm, $b_2 = 0.5$ fm

$\Lambda_c NN$ charm nuclei

- Effective potential

$$V_1^{0+} = -150.0[\mathrm{MeV}],$$
$$V_2^{0+} = 109.0[\mathrm{MeV}],$$
$$V_1^{1+} = -149.0[\mathrm{MeV}],$$
$$V_2^{1+} = 98.5[\mathrm{MeV}].$$



$\Lambda_c NN$ charm nuclei

$$V_{\mathrm{eff}_{Y_cN}} = \left[V_r^1 + \boldsymbol{\sigma}_{\Lambda_c}\cdot\boldsymbol{\sigma} V_s^1\right] e^{-\frac{r^2}{b_1^2}} + \left[V_r^2 + \boldsymbol{\sigma}_{\Lambda_c}\cdot\boldsymbol{\sigma} V_s^2\right] e^{-\frac{r^2}{b_2^2}},$$

$$V_r^i = \frac{1}{4}(V_i^{0+} + 3V_i^{1+}),$$
$$V_s^i = \frac{1}{4}(V_i^{1+} - V_i^{0+}).$$

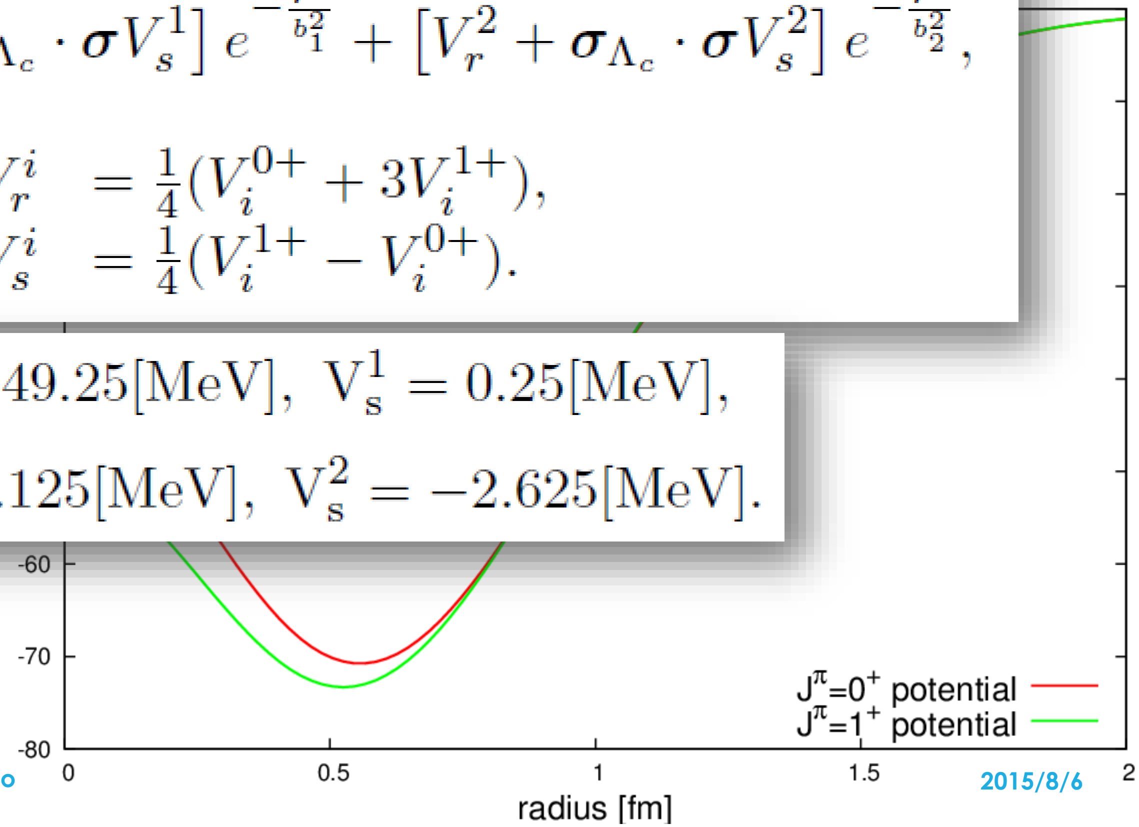
V

$\mathrm{V}_2^{0+} = 109.0$

$\mathrm{V}_1^{1+} = -149$

$\mathrm{V}_2^{1+} = 98.5$

$$V_r^1 = -149.25[\mathrm{MeV}],\ \mathrm{V}_\mathrm{s}^1 = 0.25[\mathrm{MeV}],$$
$$\mathrm{V}_\mathrm{r}^2 = 101.125[\mathrm{MeV}],\ \mathrm{V}_\mathrm{s}^2 = -2.625[\mathrm{MeV}].$$



$\Lambda_c NN$ charm nuclei

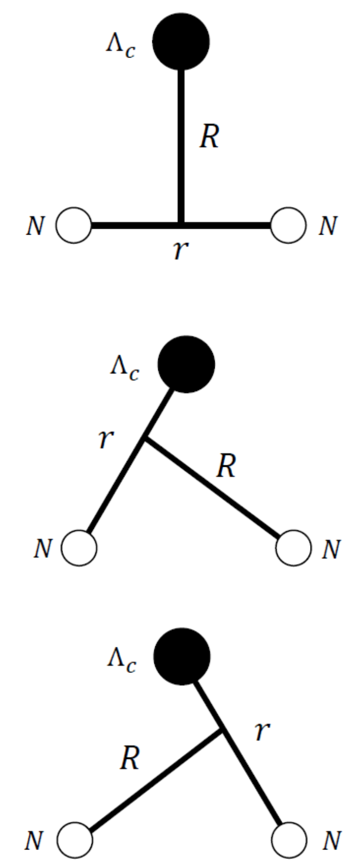
- Charm 3-body calculation

$$I = 0 \quad \cdots \quad S_{NN} = 1, \text{and } J^\pi = \tfrac{1}{2} \text{ and } \tfrac{3}{2},$$
$$I = 1 \quad \cdots \quad S_{NN} = 0, \text{and } J^\pi = \tfrac{1}{2}.$$

- Minnesota potential

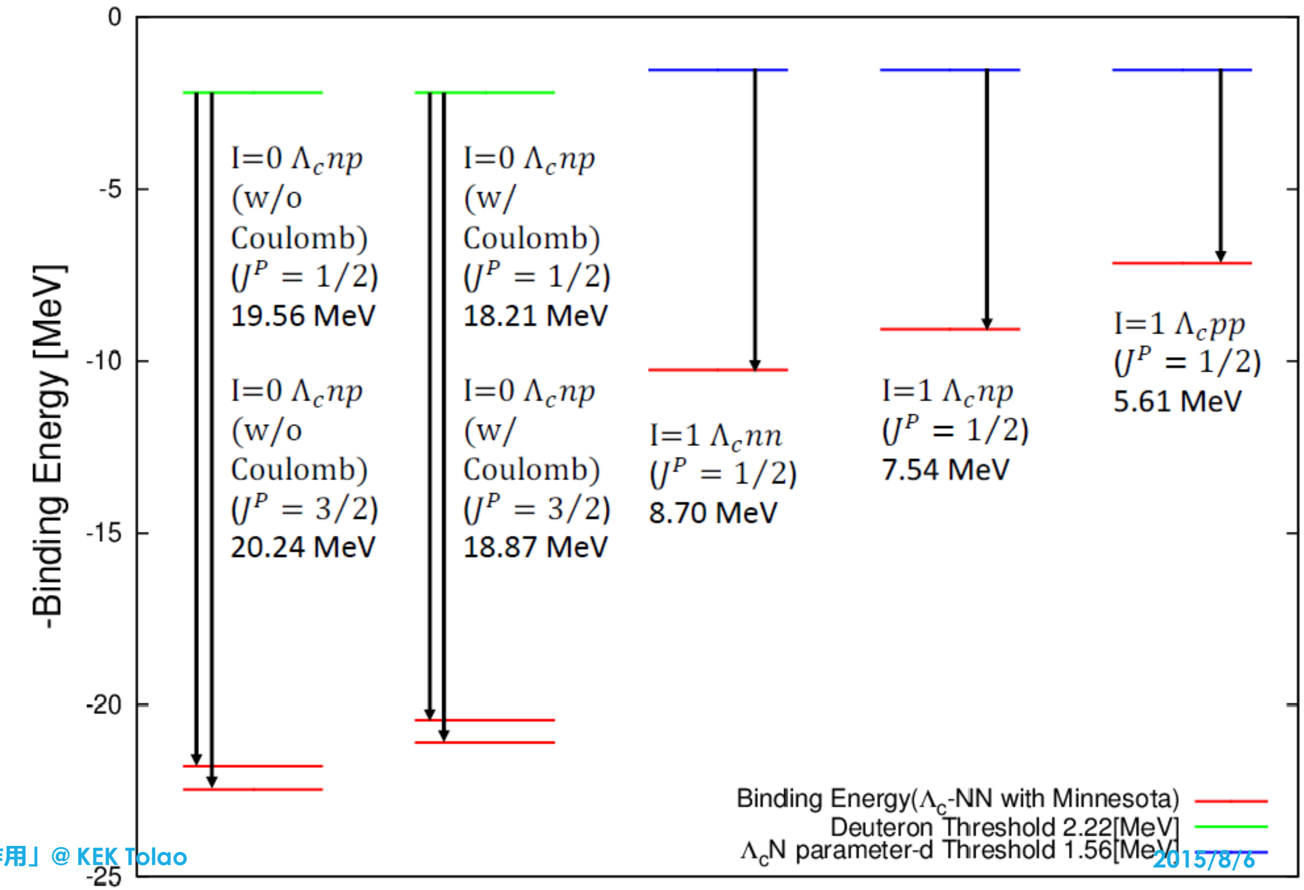
$$V = (V_R + \frac{1}{2}(1 + P_{ij}^{\sigma})V_t + \frac{1}{2}(1 + P_{ij}^{\sigma})V_s)(\frac{1}{2}u + \frac{1}{2}(2-u)P_{ij}^{r})$$
$$P_{ij}^{\sigma} = \frac{1 + (\vec{\sigma_i} \cdot \vec{\sigma_j})}{2}$$

[D. R. Thompson, M. Lemere, and Y. C. Tang, Nuci. Phys. A **286**, 53 (1977)]



$\Lambda_c NN$ charm nuclei

- Binding energy

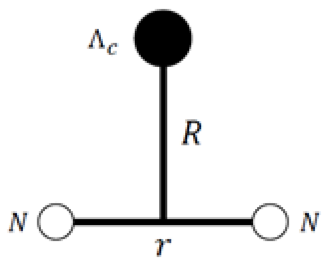


$\Lambda_c NN$ charm nuclei

- construction

parameter set	$\Lambda_c np$			
$I=0$	$J^\pi=\frac{1}{2}^+$ r[fm]	$J^\pi=\frac{1}{2}^+$ R[fm]	$J^\pi=\frac{3}{2}^+$ r[fm]	$J^\pi=\frac{3}{2}^+$ R[fm]
$\Lambda_c np$ w/o Coulomb	1.91	1.34	1.90	1.32
$\Lambda_c np$ w/ Coulomb	1.93	1.36	1.91	1.34

$I=1$	$J^\pi=\frac{1}{2}^+$ r[fm]	$J^\pi=\frac{1}{2}^+$ R[fm]
$\Lambda_c nn$	2.62	1.64
$\Lambda_c np$	2.67	1.68
$\Lambda_c pp$	2.78	1.75



Summary

- We propose the $Y_c N$ potential model based hadron model and quark model, and find four parameter set to reproduce experimental data of NN system.
- Calculating $Y_c N$ 2-body system with Coulomb potential, we get the shallow binding energies for several potential model.
- Using renormalization potential from above potential model, $\Lambda_c NN$ 3-body system has deeply bound states.
- The corresponding wave functions show that the Λ_c baryon makes the size of the NN system significantly smaller by attraction.