$Y_c N$ and $\Lambda_c NN$ bound states in the potential model

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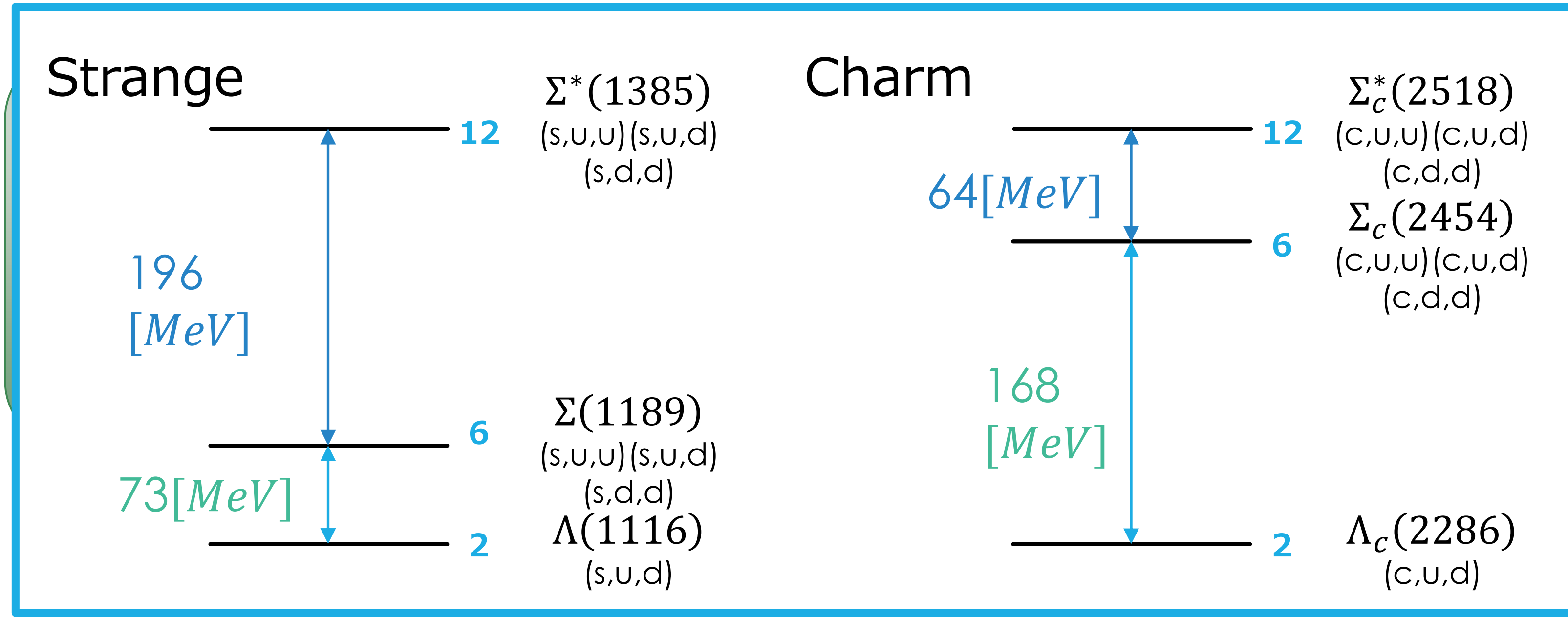
Introduction

➢ We have been obtaining many experimental data related to hypernuclei and hyperon-nucleon(YN) interactions.

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

- Interesting properties 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 a hybrid potential using a hadron model and a quark model

- 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
$J^\pi = 0^+$	$\Lambda_c N(^1S_0)$	$\Sigma_c N(^1S_0)$	$\Sigma_c^* N(^5D_0)$				
$J^\pi = 1^+$	$\Lambda_c N(^3S_1)$	$\Sigma_c N(^3S_1)$	$\Sigma_c^* N(^3S_1)$	$\Lambda_c N(^3D_1)$	$\Sigma_c N(^3D_1)$	$\Sigma_c^* N(^3D_1)$	$\Sigma_c^* N(^5D_1)$

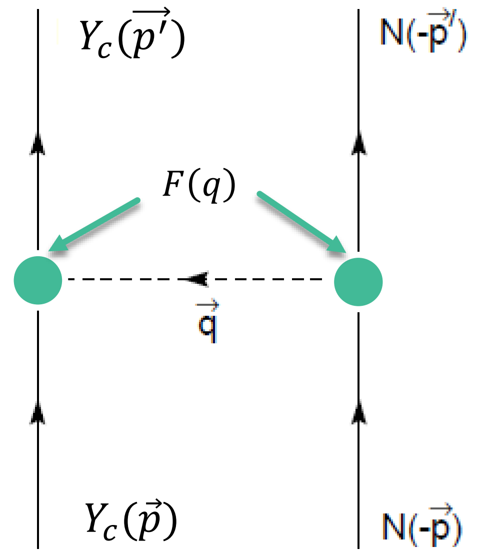
$Y_c N$ interaction

- One Boson Exchange potential

We assume that the pion and the sigma meson exchange between the charm baryon and the nucleon.

At the vertices, we introduce the form factor $F(q)$ as follows

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



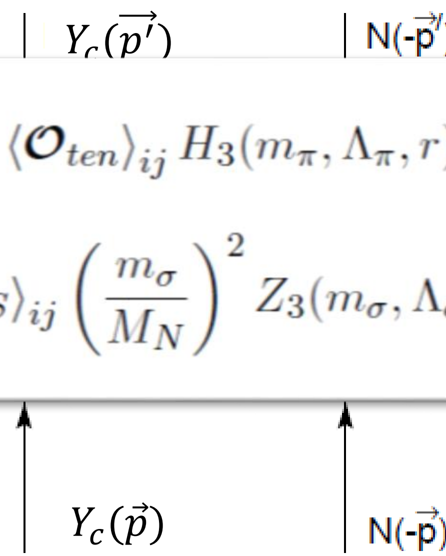
$Y_c N$ interaction

- One Boson Exchange potential

We assume that the pion and the sigma

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

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



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

$Y_c N$ interaction

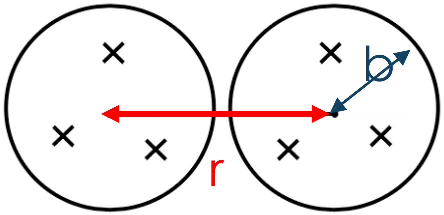
- Quark Cluster Model (QCM)

The QCM considers **two baryon clusters** each made of **three quarks**.

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

Potential equation

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



$Y_c N$ interaction

- Quark Cluster Model (QCM)

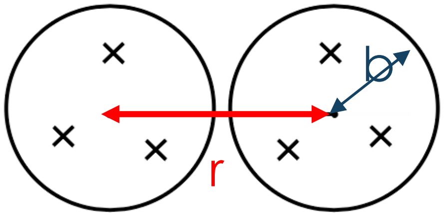
The QCM considers **two baryon clusters** each made of **three quarks**.

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

$$V(r=0) \approx < 6q|H|6q > -2 < 3q|H|3q >$$

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

we determine the parameters of the potential so as to reproduce the NN interac

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

- Fixed param

Pi-baryon cou QCM

- Determined parameter

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

$Y_c N$ interaction

- Result of binding energy and scattering length

$J^\pi = 0^+$	CTNN-a	CTNN-b	CTNN-c	CTNN-d
B.E. [MeV]	-	-	1.72×10^{-3}	1.37
(+ Coulomb)				(0.56)
scattering length [fm]	-3.64	-65.15	130.93	5.31

$J^\pi = 1^+$	CTNN-a	CTNN-b	CTNN-c	CTNN-d
B.E. [MeV]	-	1.67×10^{-4}	1.91×10^{-2}	1.56
(+ Coulomb)				(0.72)
scattering length [fm]	-4.11	337.53	39.27	5.01

$Y_c N$ interaction

- Effects of channel coupling

$J^\pi = 0^+$	CTNN-a	CTNN-b	CTNN-c	CTNN-d
probability($\Lambda_c N$)[%]	-	-	99.97	99.29
probability($\Sigma_c N$)[%]	-	-	7.0×10^{-3}	0.20
probability($\Sigma_c^* N$)[%]	-	-	2.1×10^{-2}	0.51

$J^\pi = 1^+$	CTNN-a	CTNN-b	CTNN-c	CTNN-d
probability($\Lambda_c N$)[%]	-	99.99	99.90	99.23
probability($\Sigma_c N$)[%]	-	4.9×10^{-3}	4.9×10^{-2}	0.39
(D-wave ($^3D_1$))	-	4.5×10^{-3}	4.6×10^{-2}	0.35
probability($\Sigma_c^* N$)[%]	-	4.6×10^{-3}	4.6×10^{-2}	0.38
(D-wave ($^5D_1$))	-	3.1×10^{-3}	3.2×10^{-2}	0.25

$Y_c N$ interaction

- Effects of channel coupling

$J^\pi = 0^+$	CTNN-a	CTNN-b	CTNN-c	CTNN-d
probability($\Lambda_c N$)[%]	-	-	99.97	99.29
probability($\Sigma_c N$)[%]	-	-	7.0×10^{-3}	0.20
probability(Σ[illegible]	[illegible]	[illegible]	[illegible] 10^{-2}	0.51

Is channel coupling negligible for $Y_c N$ 2-body system ?

[illegible]	[illegible]	[illegible]	[illegible]N-c	CTNN-d
probability($\Lambda_c N$)[%]	-	99.99	99.90	99.23
probability($\Sigma_c N$)[%]	-	4.9×10^{-3}	4.9×10^{-2}	0.39
(D-wave ($^3D_1$))	-	4.5×10^{-3}	4.6×10^{-2}	0.35
probability($\Sigma_c^* N$)[%]	-	4.6×10^{-3}	4.6×10^{-2}	0.38
(D-wave ($^5D_1$))	-	3.1×10^{-3}	3.2×10^{-2}	0.25

Y_cN interaction

- Effects of channel coupling
  - Scattering length

	$\Lambda_cN-\Sigma_cN-\Sigma_c^*N$		Λ_cN		$\Lambda_cN-\Sigma_cN$		$\Lambda_cN-\Sigma_c^*N$	
J^π	0^+	1^+	0^+	1^+	0^+	1^+	0^+	1^+
CTNN-a	-3.63	-4.10	-1.11	-1.11	-1.16	-2.07	-3.13	-2.09
CTNN-b	-63.25	398.67	-2.62	-2.62	-2.78	−6.74	-20.84	-7.00
CTNN-c	139.07	39.96	-3.01	-3.01	-3.19	-8.61	-48.56	-9.00
CTNN-d	5.32	5.02	-28.59	-28.59	-44.65	9.79	6.01	9.36
B.E.	1.37	1.56	-	-	-	0.36	1.09	0.39

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

$Y_c N$ interaction

- Effects of channel coupling
  - Scattering length

	$\Lambda_c N - \Sigma_c N - \Sigma_c^* N$		$\Lambda_c N$		$\Lambda_c N - \Sigma_c N$		$\Lambda_c N - \Sigma_c^* N$	
J^π	0^+	1^+	0^+	1^+	0^+	1^+	0^+	1^+
CTNN-a	-3.63	-4.10	-1.11	-1.11	-1.16	-2.07	-3.13	-2.09
CTNN-b	-63.25	398.67	-2.62	-2.62	-2.78	−6.74	-20.84	-7.00
CTNN-c	139.07	39.96	-3.01	-3.01	-3.19	-8.61	-48.56	-9.00
CTNN-d	5.32	5.02	-28.59	-28.59	-44.65	9.79	6.01	9.36
B.E.	1.37	1.56	-	-	-	0.36	1.09	0.39

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

$\Lambda_c NN$ charm nuclei

- Effective potential

We replace the $Y_c N$-CTNN potential by a 2-range Gaussian potential to renormalize the effect of channel coupling to $\Lambda_c N$ S-wave.

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

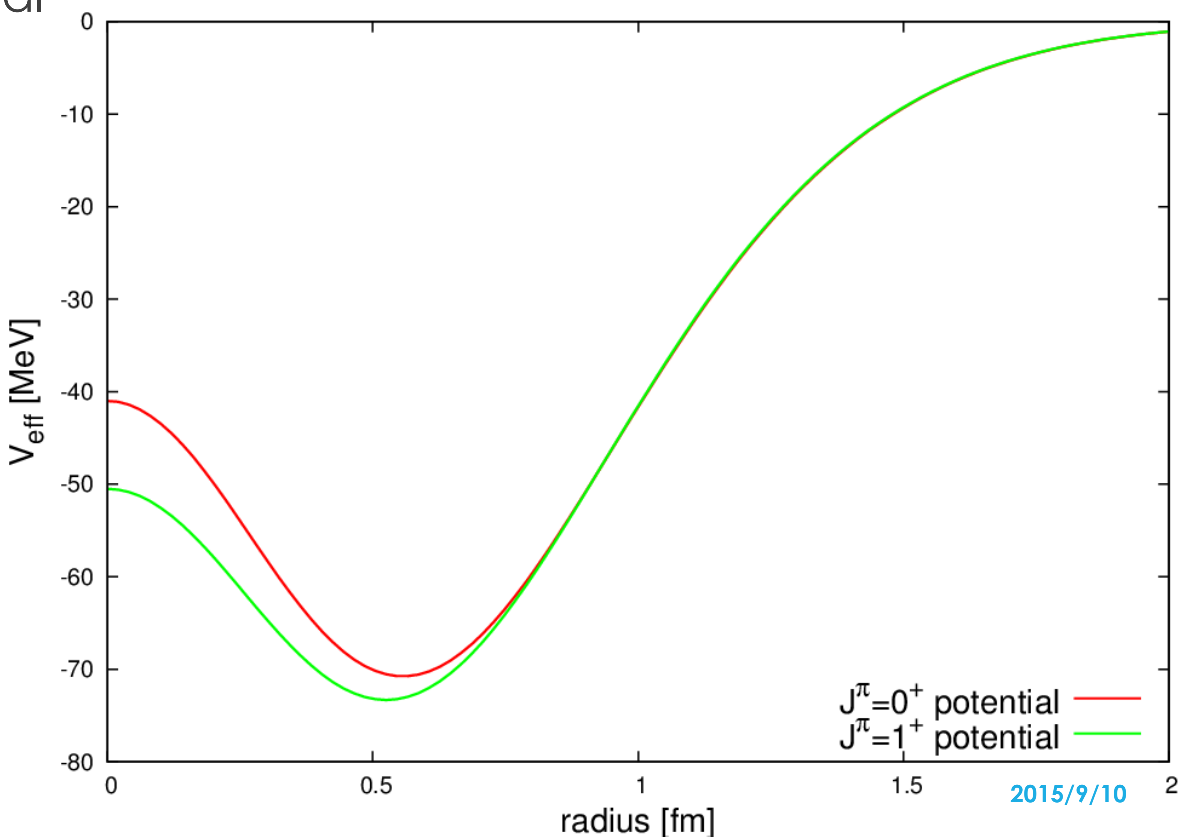
OBEP like QCM like

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

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

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

V

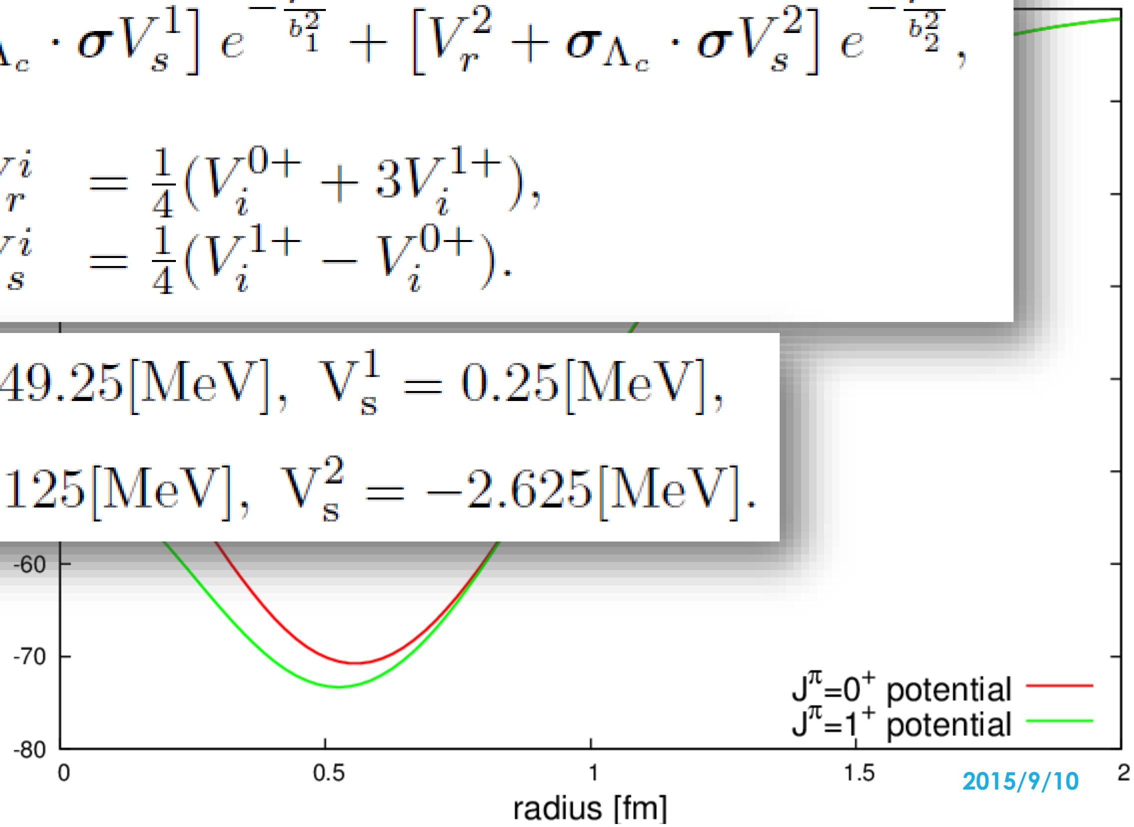
$\mathrm{V}_2^{0+} = 109.0$

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

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

$$V_r^1 = -149.25[\mathrm{MeV}],\ \mathrm{V}_s^1 = 0.25[\mathrm{MeV}],$$

$$\mathrm{V}_r^2 = 101.125[\mathrm{MeV}],\ \mathrm{V}_s^2 = -2.625[\mathrm{MeV}].$$



$\Lambda_c NN$ charm nuclei

- Charm 3-body calculation

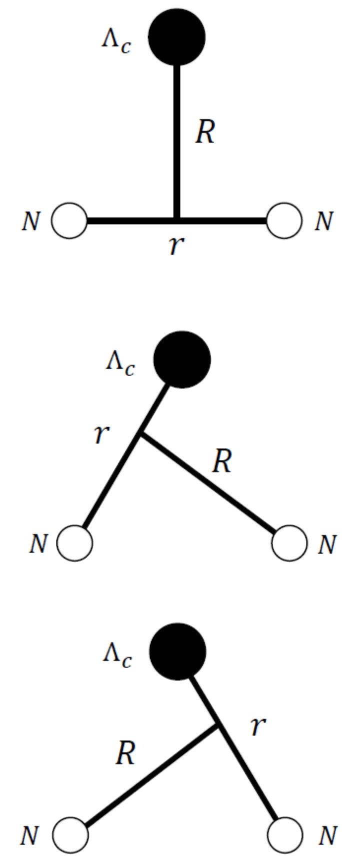
$$I = 0 \quad \cdots \quad S_{NN} = 1, \text{and } \mathrm{J}^{\pi} = \tfrac{1}{2} \text{ and } \tfrac{3}{2},$$
$$I = 1 \quad \cdots \quad S_{NN} = 0, \text{and } \mathrm{J}^{\pi} = \tfrac{1}{2}.$$

- Minnesota potential

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

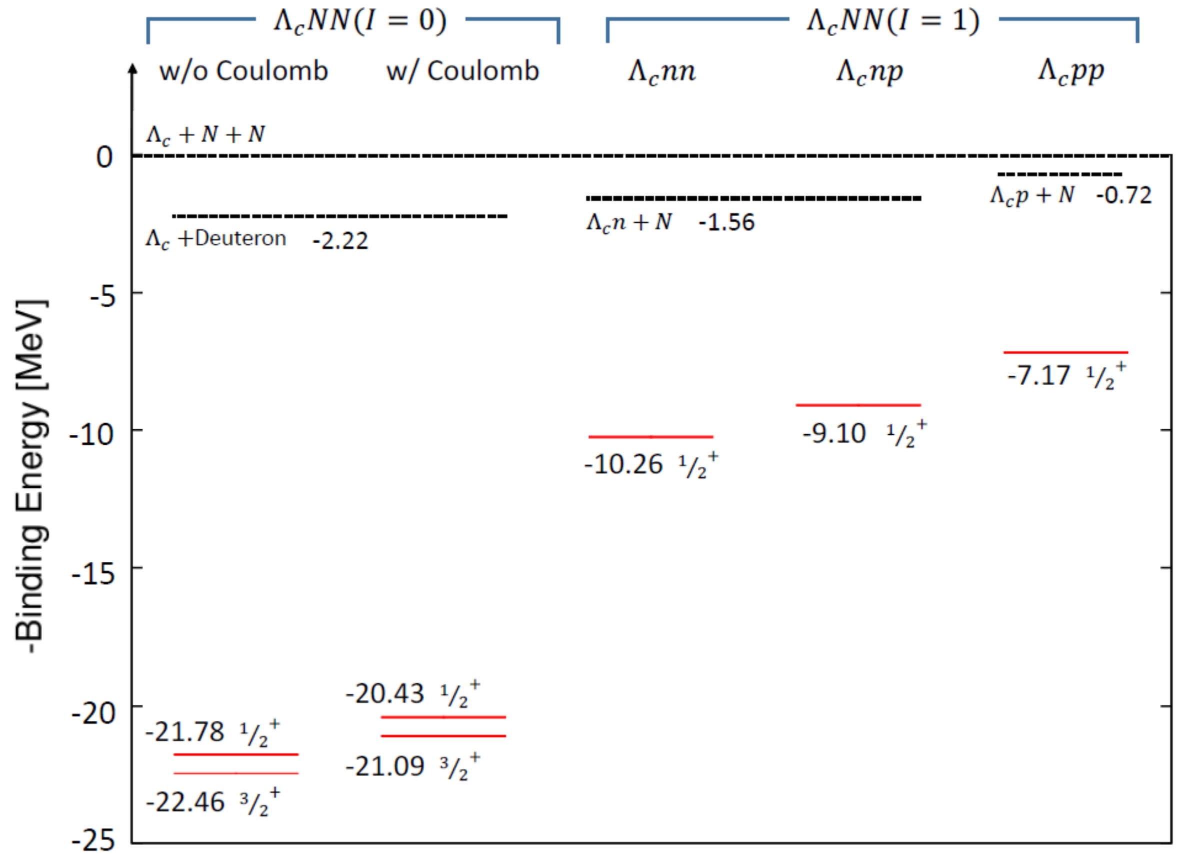
$$P_{ij}^{\sigma} = \frac{1 + (\vec{\sigma_i} \cdot \vec{\sigma_j})}{2}$$

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



$\Lambda_c NN$ charm nuclei

- Binding Energy

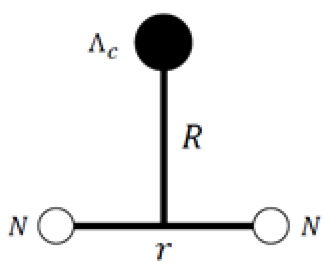


$\Lambda_c NN$ charm nuclei

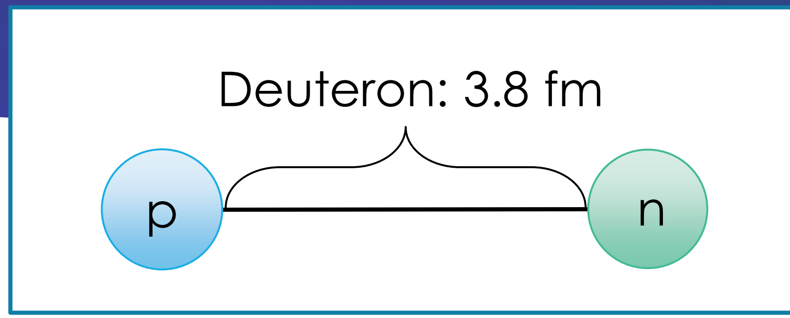
- structure

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



$\Lambda_c NN$ charm nuclei

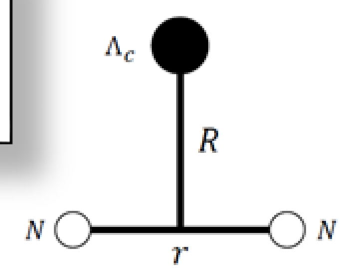


- structure

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]	
$\Lambda_c nn$	2.62	
$\Lambda_c np$	2.67	1.68
$\Lambda_c pp$	2.78	1.75

$$ {}^{3}_{\Lambda}H = d + \Lambda $$
$$ \Lambda_c pn = d + \Lambda_c $$



Summary

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