THE CHARM BARYON-NUCLEON INTERACTION AND $\Lambda_c NN$ NUCLEI

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  - potential
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- $\Lambda_c NN$ charm nuclei
  - Effective potential
  - Binding energy and structure
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INTRODUCTION

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

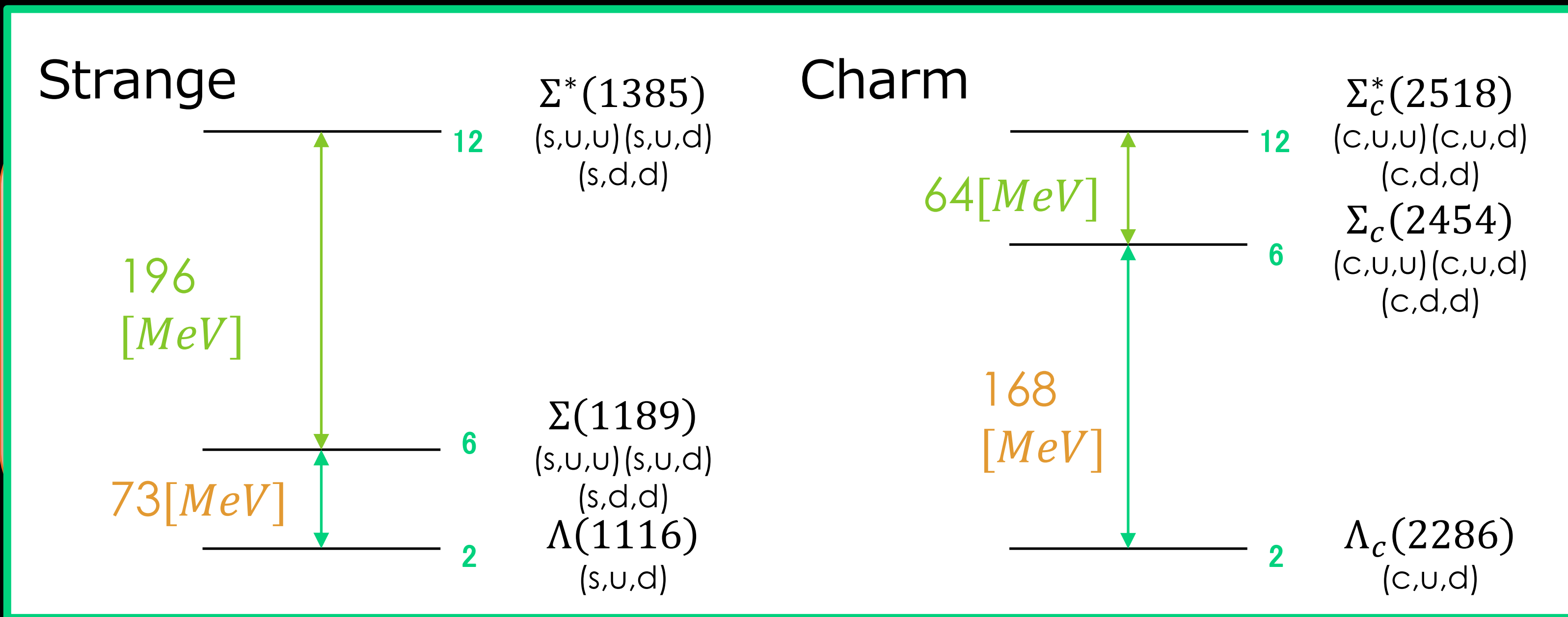
the next stage ⇨ **Approaching to charm nuclei structure with theoretical knowledge**

- Interesting properties of charm nuclei

▪Heavy quark symmetry

▪Channel coupling including higher state than strange sector.

INTRODUCTION



- Interesting properties of charm nuclei

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

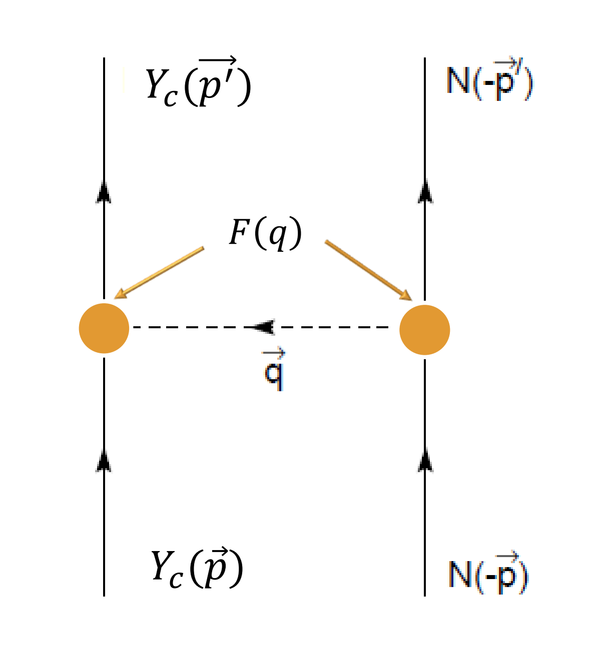
$Y_c N$ INTERACTION

- 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

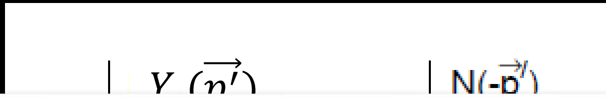
$$F(q) = \frac{\Lambda^2 - m^2}{\Lambda^2 - q^2}$$



$Y_c N$ INTERACTION

- One Boson Exchange potential

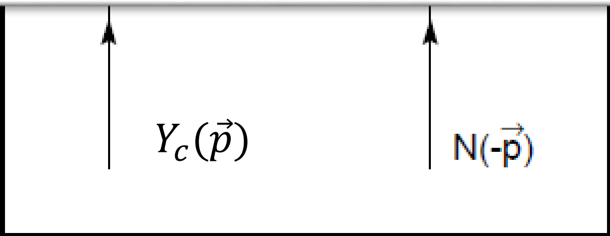
We assume that the pion and



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

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

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



$Y_c N$ INTERACTION

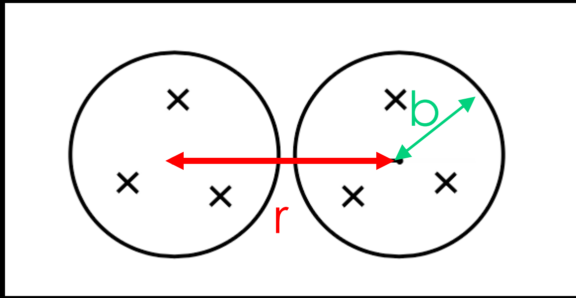
- Quark Cluster Model (QCM)

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

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



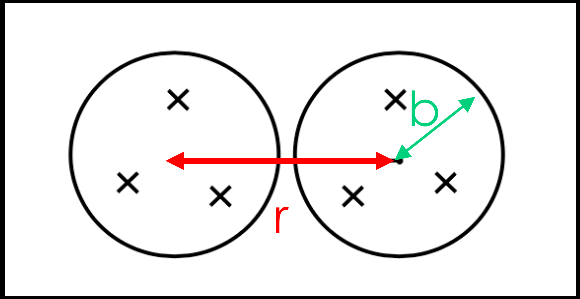
$Y_c N$ INTERACTION

- 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 quark ... gle 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

$Y_c N$-Corresponding To NN

we determine the parameters of the potential so as to reproduce th ame model.

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 paran

Pi-baryon co er of 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]	-	2.62×10^{-4}	1.97×10^{-2}	1.57
(+ 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$(\Sigma_c N)[\%]$	-	-	$7.0\ \times 10^{-3}$	0.20
probability$(\Sigma_c^* N)[\%]$	-	-	$2.1\ \times 10^{-2}$	0.51

$J^\pi = 1^+$	CTNN-a	CTNN-b	CTNN-c	CTNN-d
probability$(\Lambda_c N)[\%]$	-	99.99	99.90	99.23
probability$(\Sigma_c N)[\%]$	-	$6.1\ \times 10^{-3}$	$5.0\ \times 10^{-2}$	0.39
(D-wave $(^3D_1)$)	-	$5.6\ \times 10^{-3}$	$4.6\ \times 10^{-2}$	0.35
probability$(\Sigma_c^* N)[\%]$	-	$5.8\ \times 10^{-3}$	$4.7\ \times 10^{-2}$	0.38
(D-wave $(^5D_1)$)	-	$3.9\ \times 10^{-3}$	$3.3\ \times 10^{-2}$	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_c^*[illegible]	[illegible]	[illegible]	[illegible] 10^{-2}	0.51

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

J^π [illegible]	[illegible]	[illegible]	[illegible]NN-c	CTNN-d
probability($\Lambda_c N$)[%]	-	99.99	99.90	99.23
probability($\Sigma_c N$)[%]	-	6.1×10^{-3}	5.0×10^{-2}	0.39
(D-wave ($^3D_1$))	-	5.6×10^{-3}	4.6×10^{-2}	0.35
probability($\Sigma_c^* N$)[%]	-	5.8×10^{-3}	4.7×10^{-2}	0.38
(D-wave ($^5D_1$))	-	3.9×10^{-3}	3.3×10^{-2}	0.25

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

$Y_c N$ INTERACTION

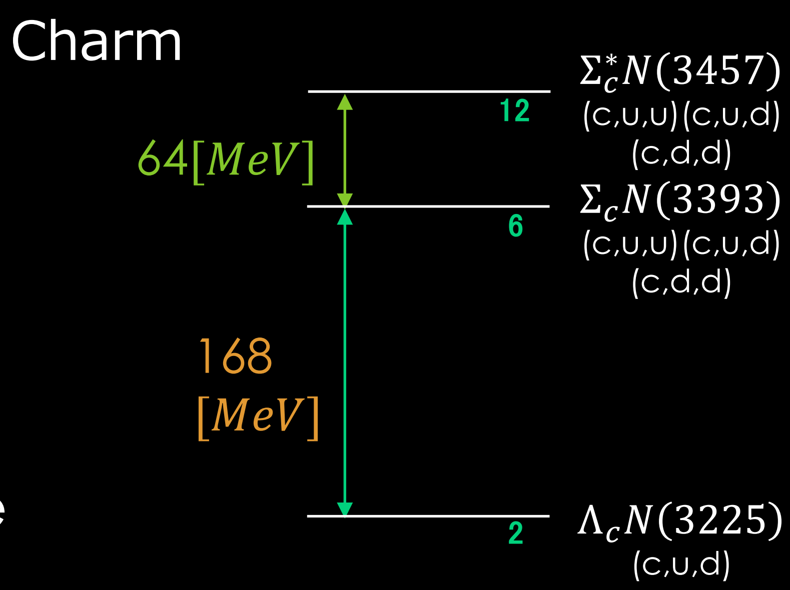
- Resonance

In the previous calculation, we consider only the state under the $\Lambda_c N$ threshold.

So, we calculate with the Complex scaling method

[J. Aguilar, J.M. Combes, Commun. Math. Phys. 22 (1971) 269.]

to search the state above the $\Lambda_c N$ threshold with $Y_c N$-CTNN d-potential.



$Y_c N$ INTERACTION

- Resonance

▪$J^P = 2^+$

$\Lambda_c N$ and $\Sigma_c N$ channel have no S-wave because of the rule of total angular momentum.

The S-wave and G-wave are the characteristic behavior of Σ_c^* having the spin = $\frac{3}{2}$

Channels	1	2	3	4	5	6	7	8
$J^\pi = 2^+$	$\Lambda_c N(^1D_2)$	$\Sigma_c N(^1D_2)$	$\Lambda_c N(^3D_2)$	$\Sigma_c N(^3D_2)$	$\Sigma_c^* N(^3D_2)$	$\Sigma_c^* N(^5S_2)$	$\Sigma_c^* N(^5D_2)$	$\Sigma_c^* N(^5G_2)$

$Y_c N$ INTERACTION

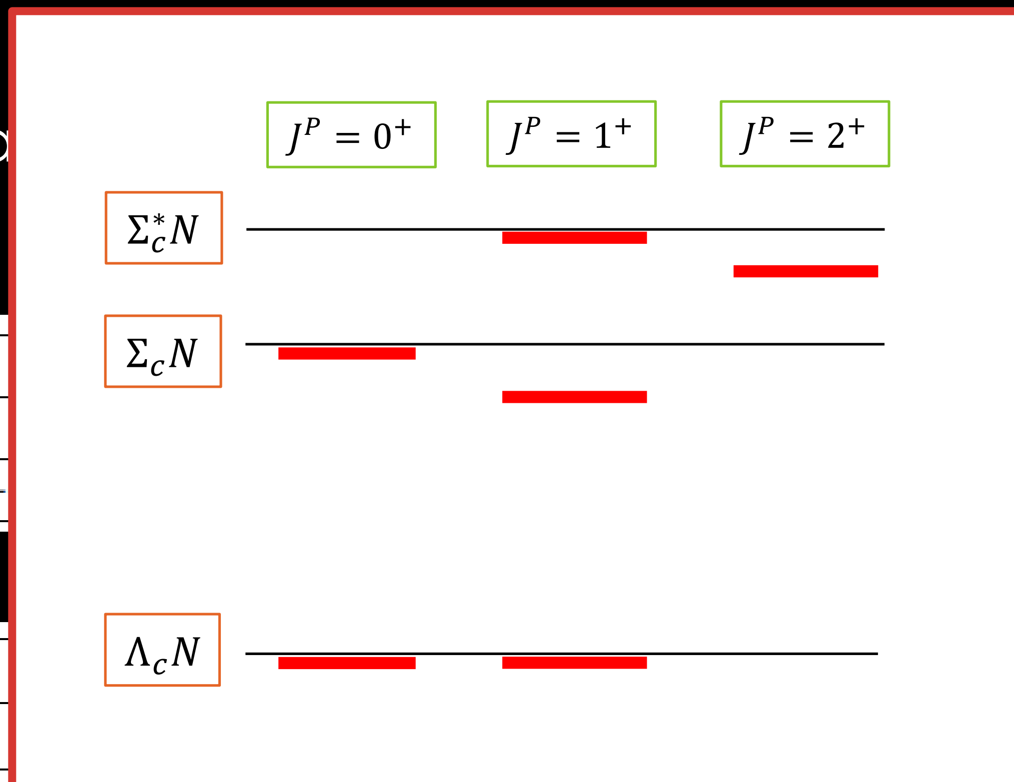
- Resonance
  - Result

	$J^\pi = 0^+$ near $\Sigma_c N$		$J^\pi = 1^+$ near $\Sigma_c^* N$	
	resonance	width	resonance	width
CTNN-d	163.09 (-4.01)	1.09	225.00 (-6.51)	1.54

	$J^\pi = 1^+$ near $\Sigma_c N$		$J^\pi = 2^+$ near $\Sigma_c^* N$	
	resonance	width	resonance	width
CTNN-d	144.28 (-22.82)	11.92	206.34 (-25.17)	14.01

$Y_c N$ INTERACTION

- Resona
  - Result



		ar $\Sigma_c^* N$
		width
CTNN-	)	1.54

						ear $\Sigma_c^* N$
						width
CTNN-d	144.28	(-22.82)	11.92	206.34	(-25.17)	14.01

$Y_c N$ INTERACTION

- Resonance

▪Heavy quark limit

We assume $\Sigma_c N$ and $\Sigma_c^* N$ are doublet, so we set the $Y_c N$ threshold in substitute for $\Sigma_c N$ and $\Sigma_c^* N$ threshold.

$\Sigma_c^* N(3457)$
(c,u,u)(c,u,d)
(c,d,d)

$\Sigma_c N(3393)$
(c,u,u)(c,u,d)
(c,d,d)

$\Lambda_c N(3225)$
(c,u,d)

$Y_c N(3414)$
(c,u,u)(c,u,d)
(c,d,d)

$\Lambda_c N(3225)$
(c,u,d)

$Y_c N$ INTERACTION

- Resonance
  - Result

	$J^\pi = 0^+$ near $\Sigma_c N$		$J^\pi = 1^+$ near $\Sigma_c^* N$	
	resonance	width	resonance	width
CTNN-d	183.79 (-4.78)	0.91	183.72 (-4.85)	0.89

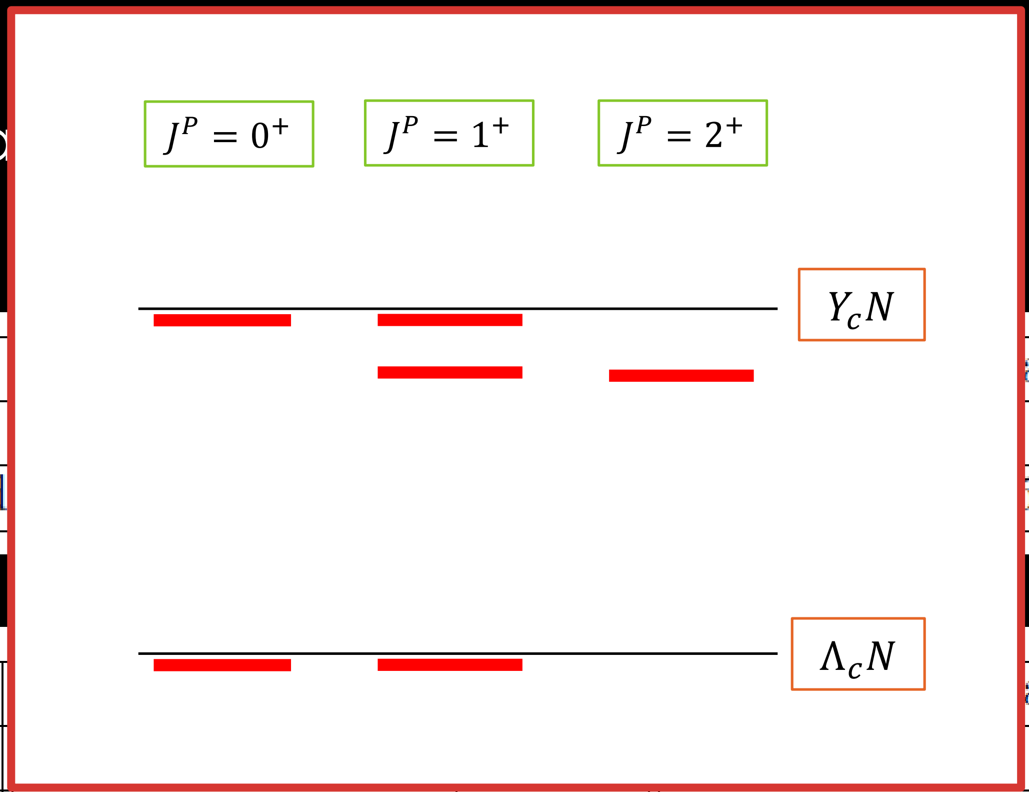
	$J^\pi = 1^+$ near $\Sigma_c N$		$J^\pi = 2^+$ near $\Sigma_c^* N$	
	resonance	width	resonance	width
CTNN-d	163.88 (-24.69)	13.16	163.84 (-24.73)	12.46

Y_cN INTERACTION

- Resona
- Result

		ar $\Sigma_c^* N$
		width
CTNN-d	5)	0.89

					ar $\Sigma_c^* N$
					width
CTNN-d	163.88	(-24.69)	13.16	163.84 (-24.73)	12.46



$\Lambda_c NN$ 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.

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

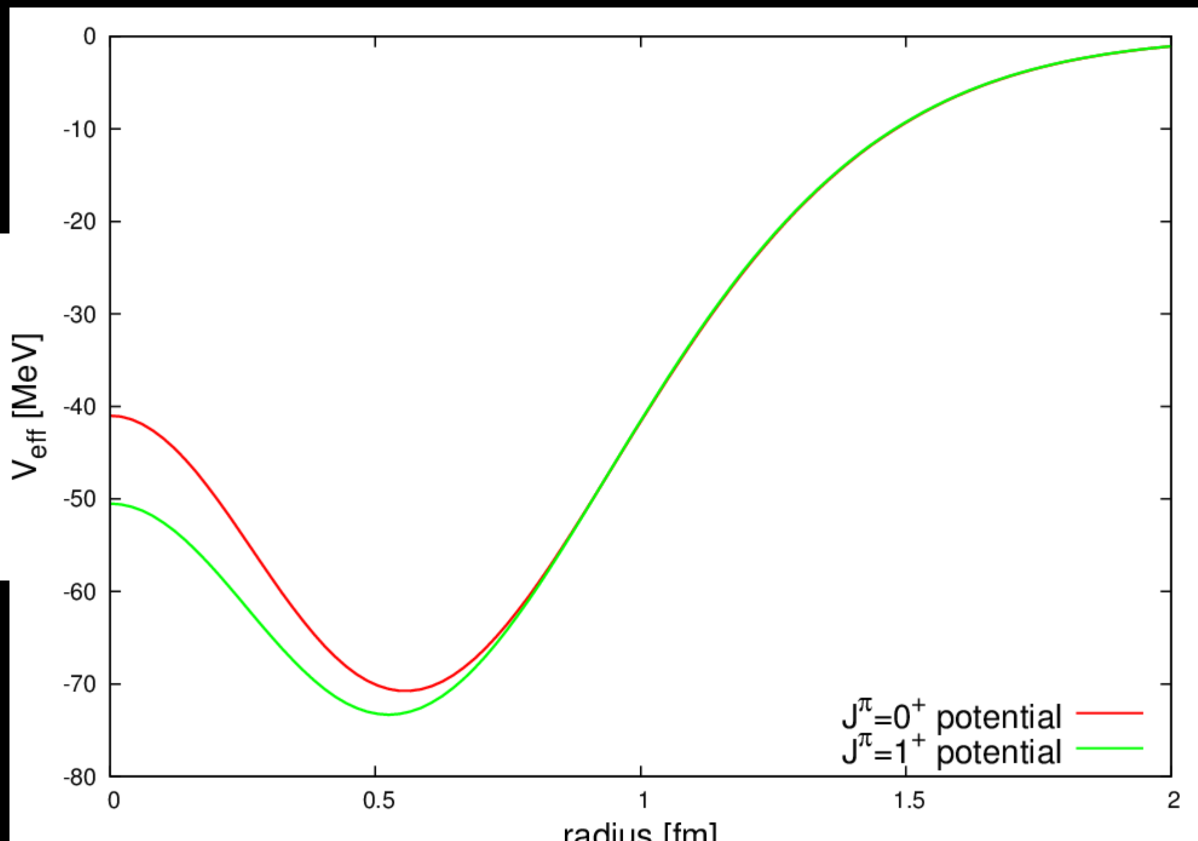
OBEP like QCM like

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

$\Lambda_c NN$ CHARM NUCLEI

- Effective potential

$$V_1^{0+} = -150.0[\mathrm{MeV}],$$
$$\mathrm{V}_2^{0+} = 109.0[\mathrm{MeV}],$$
$$\mathrm{V}_1^{1+} = -149.0[\mathrm{MeV}],$$
$$\mathrm{V}_2^{1+} = 98.5[\mathrm{MeV}].$$



$\Lambda_c NN$ CHARM NUCLEI

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

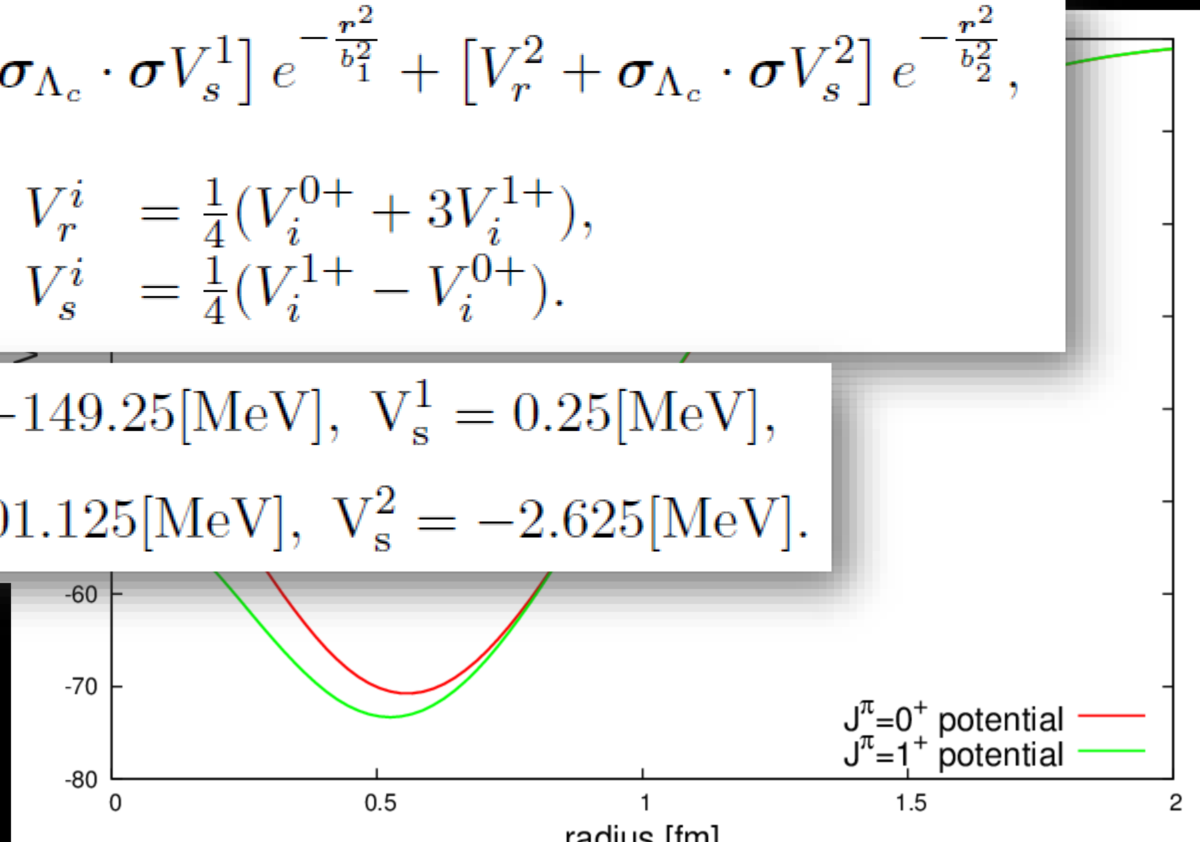
$$V_r^i = \frac{1}{4}(V_i^{0+} + 3V_i^{1+}),$$
$$V_s^i = \frac{1}{4}(V_i^{1+} - V_i^{0+}).$$

$V_2^{0+} = 109.0$

$V_1^{1+} = -149$

$V_2^{1+} = 98.5$

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



$\Lambda_c NN$ CHARM NUCLEI

- Charm 3-body calculation

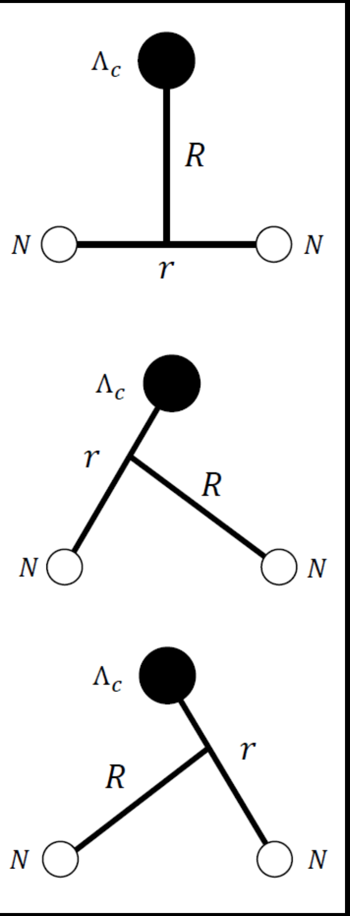
$$I = 0 \quad \cdots \quad S_{NN} = 1, \text{and } \mathrm{J}^\pi = \tfrac{1}{2} \text{ and } \tfrac{3}{2},$$
$$I = 1 \quad \cdots \quad S_{NN} = 0, \text{and } \mathrm{J}^\pi = \tfrac{1}{2}.$$

- Minnesota potential

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

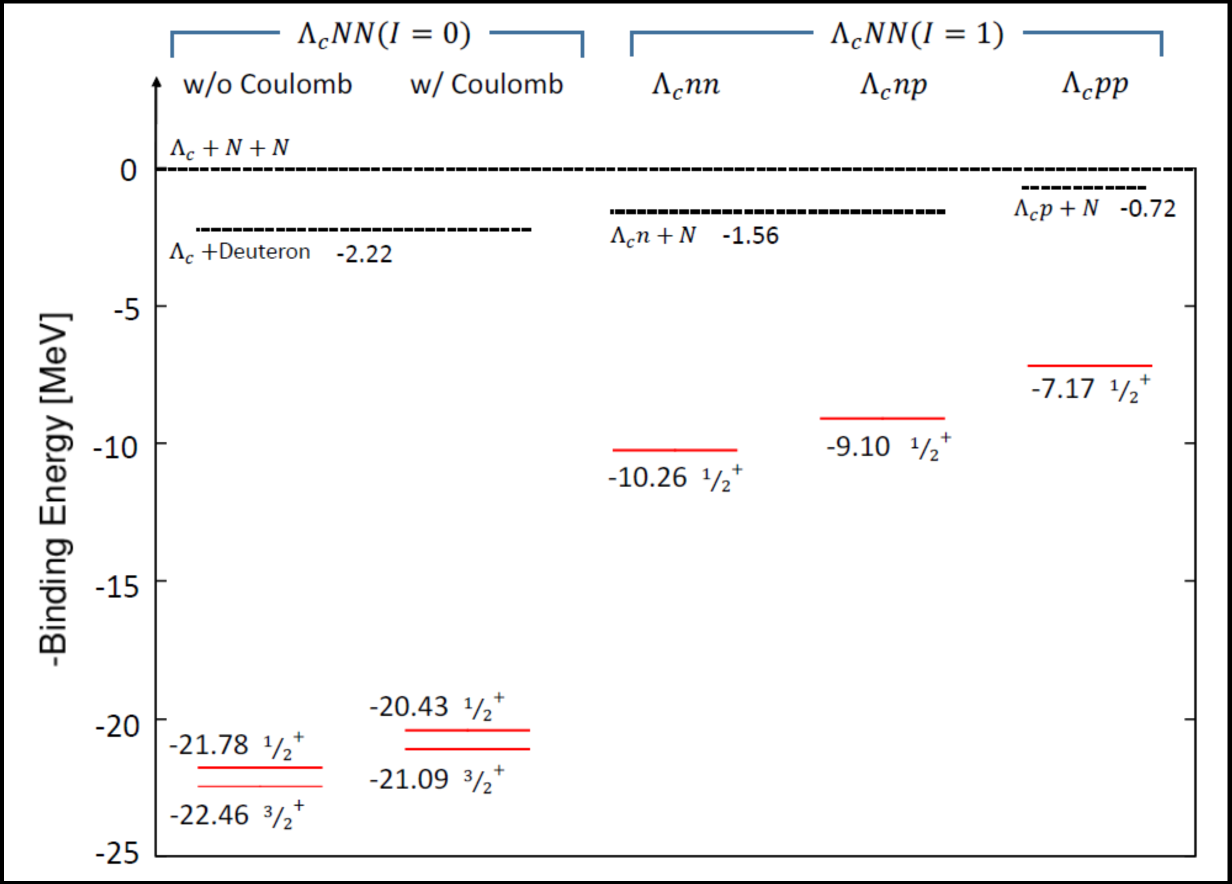
$$P_{ij}^{\sigma} = \frac{1 + (\overrightarrow{\sigma_i} \cdot \overrightarrow{\sigma_j})}{2}$$

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



$\Lambda_c NN$ CHARM NUCLEI

- Binding Energy

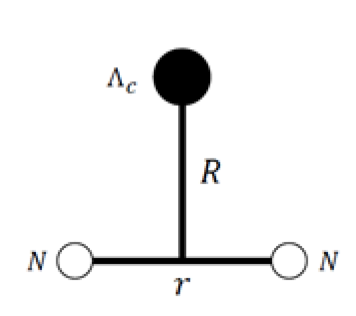


$\Lambda_c NN$ CHARM NUCLEI

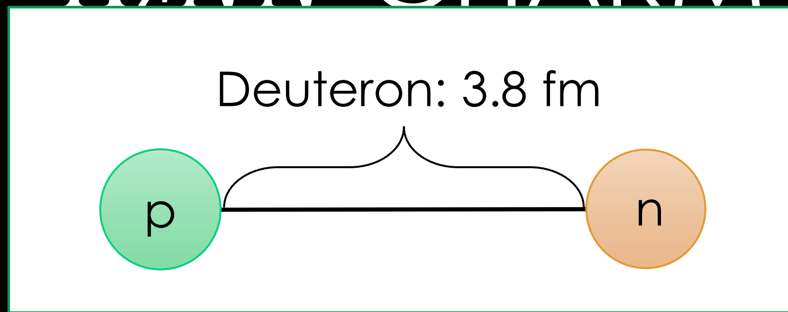
- structure

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

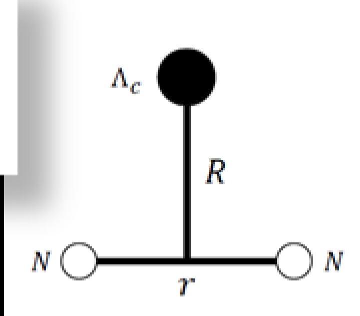


- structure

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

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



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 and resonance states 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.