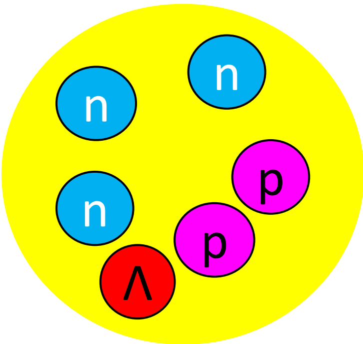
P-shell to heavier Λ hypernuclei

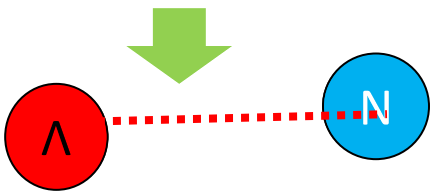
Emiko Hiyama (Tohoku/RIKEN)

Since 1998

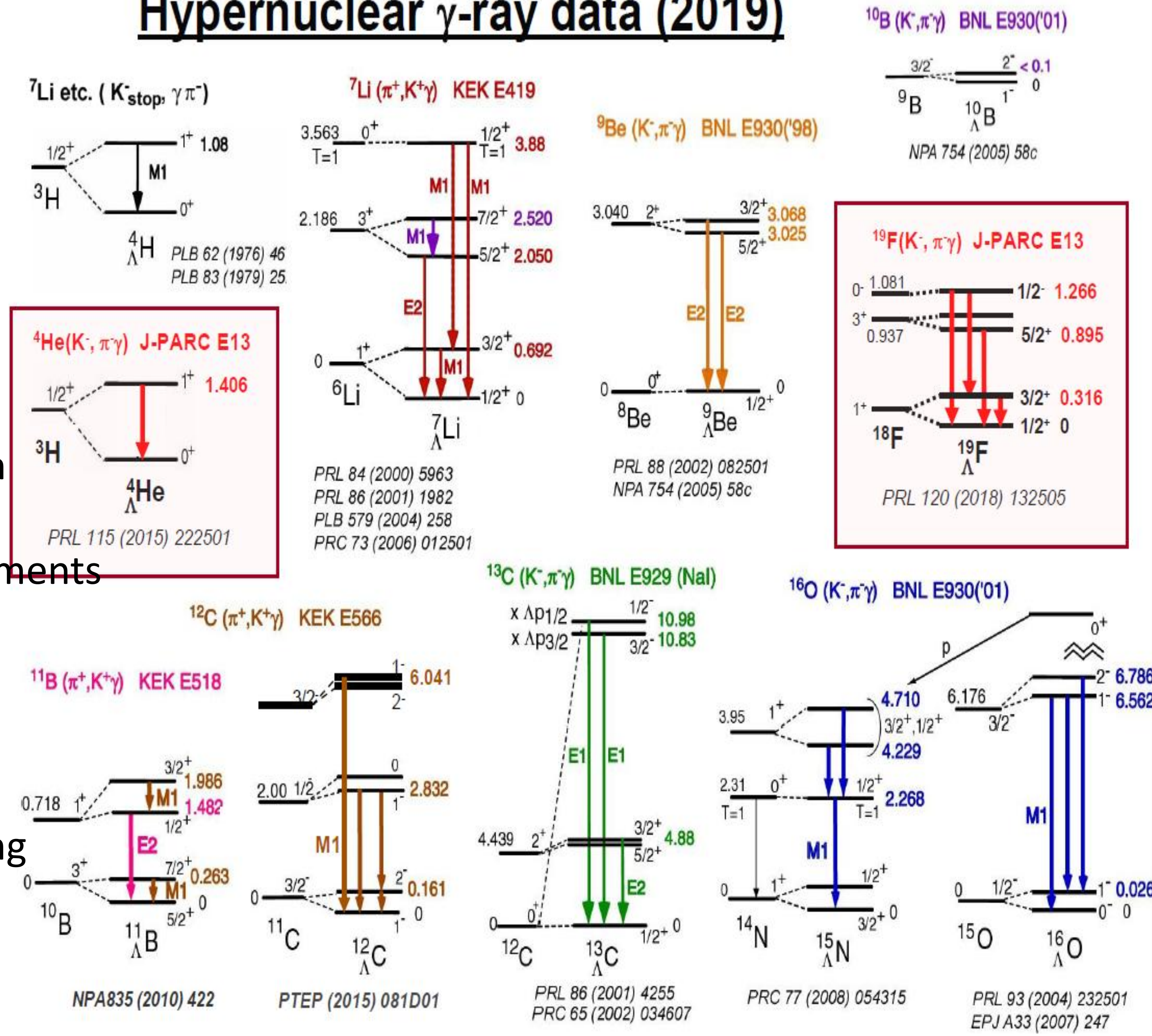
Hypernuclear γ-ray data (2019)



Few-body calculation
Shell model calculation
+
High-resolution experiments



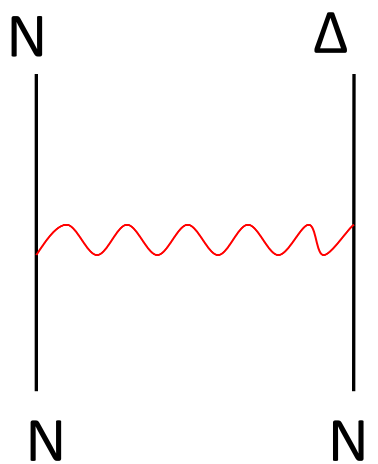
We have been obtaining information on ΛN two-body interaction.

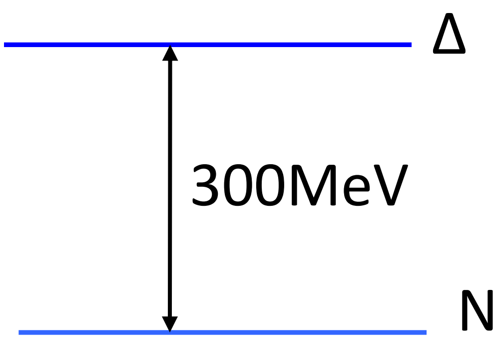


$$V_{\Lambda N} = V_0 + \boldsymbol{\sigma}_\Lambda \cdot \boldsymbol{\sigma}_N V_{\sigma\cdot\sigma} + \mathbf{L}\cdot(\mathbf{s}_\Lambda + \mathbf{s}_N) V_{\mathrm{SLS}} + \mathbf{L}\cdot(\mathbf{s}_\Lambda - \mathbf{s}_N) V_{\mathrm{ALS}} + S_{12} V_{\mathrm{tensor}} + \cdots\cdots$$

ΛN — ΣN coupling

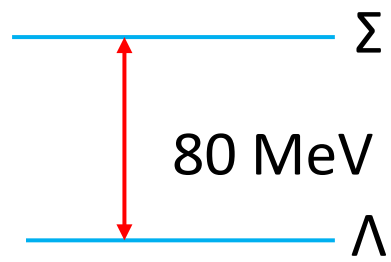
Non-strangeness sector





Probability of Δ in nuclei is not large.

S=-1



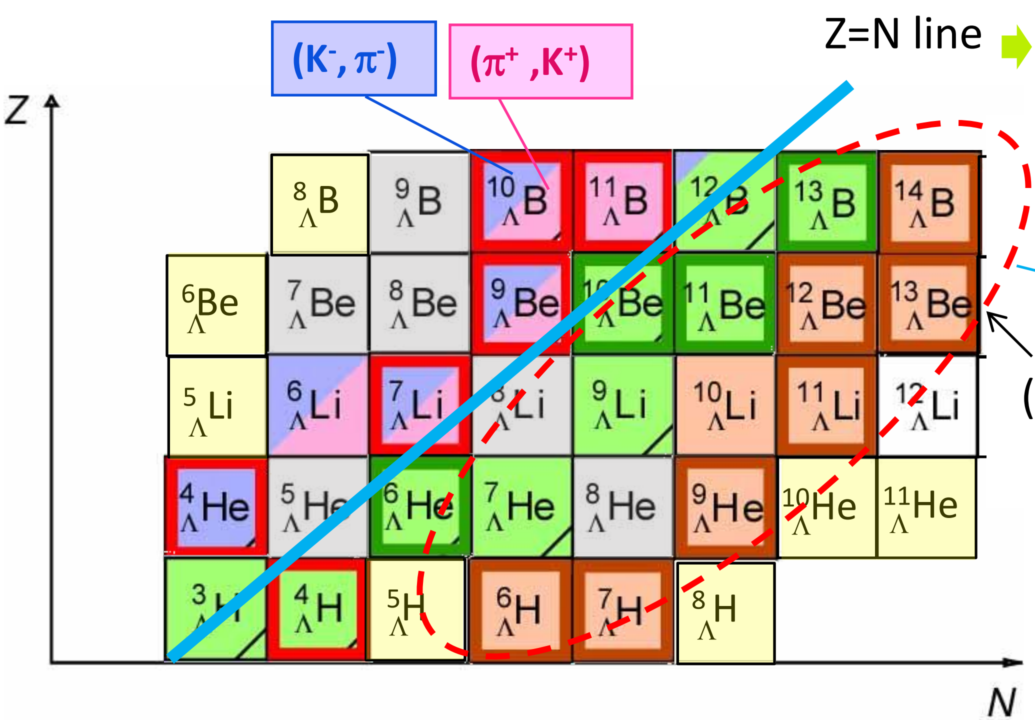
Mass is smaller.
It is expected that Λ-Σ conversion might affect in structure of Λ hypernuclei.

ΛN-ΣN coupling =>three-body force and CSB interaction

How do we obtain information on ΛN-ΣN coupling?

(1)YN scattering experiment at J-PARC, Femtoscopic experiment

(2) To study neutron-rich Λ hypernuclei at J-PARC



difficult to obtain information on ΛN-ΣN coupling
Total isosopin of core nuclei is small.

(π⁻,K⁺)

Total isospin is larger.
ΛN-ΣN coupling give a great contribution to binding energy of neutron-rich Λ hypernuclei.

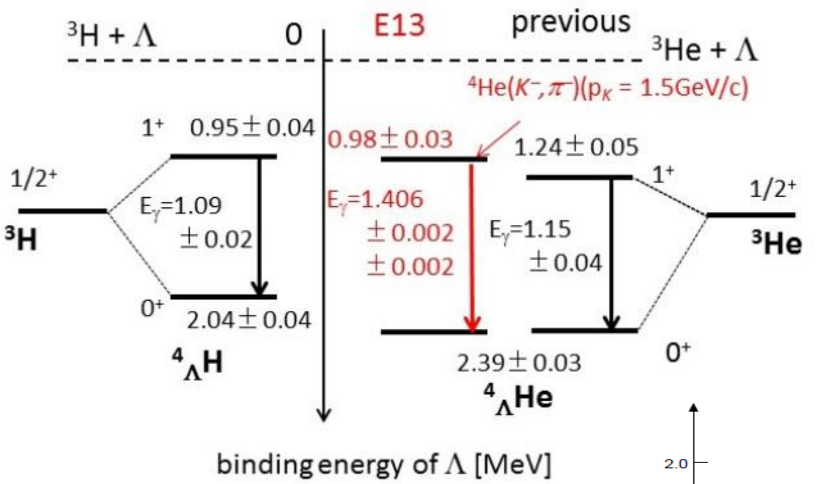
These neutron-rich Λ hypernuclei are important.

By neutron-rich Λ hypernuclei, we could obtain information on

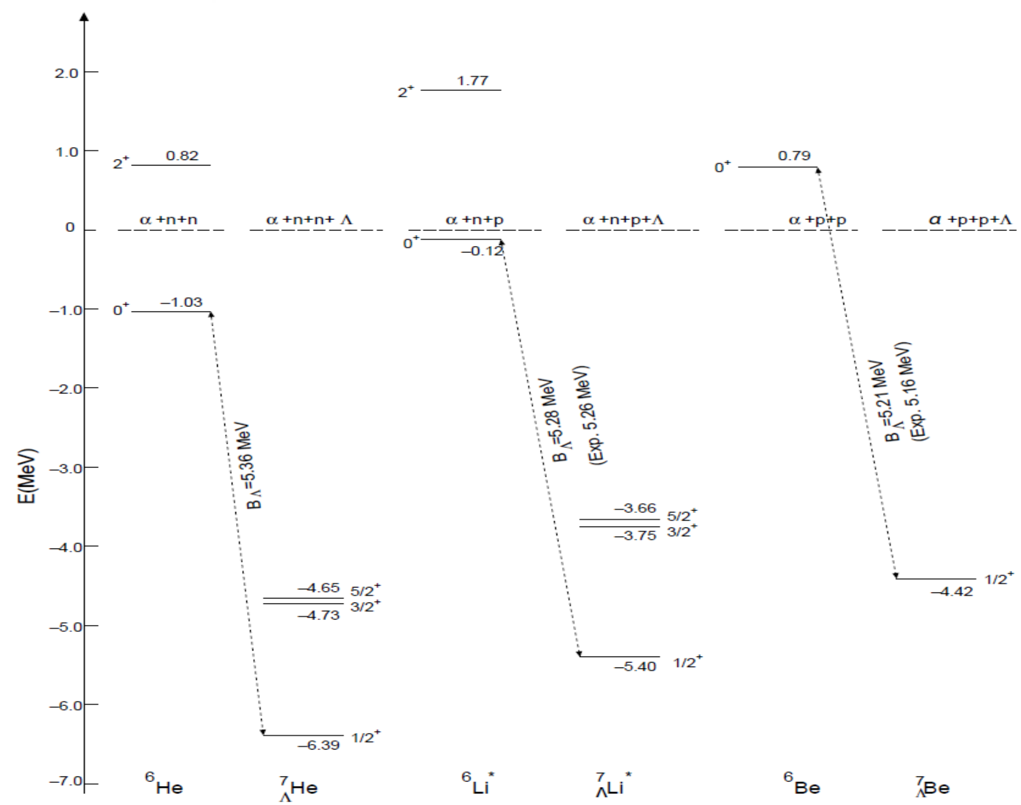
long-range part of ΛN-ΣN coupling. ➡ Long-range part of ΛNN three-body force

Furthermore, we need short-range part of ΛNN three-body force.: important for the study of neutron star

CSB interaction



How do we understand this difference?
Odd state of CSB?



Now, it is interesting to see as follows:

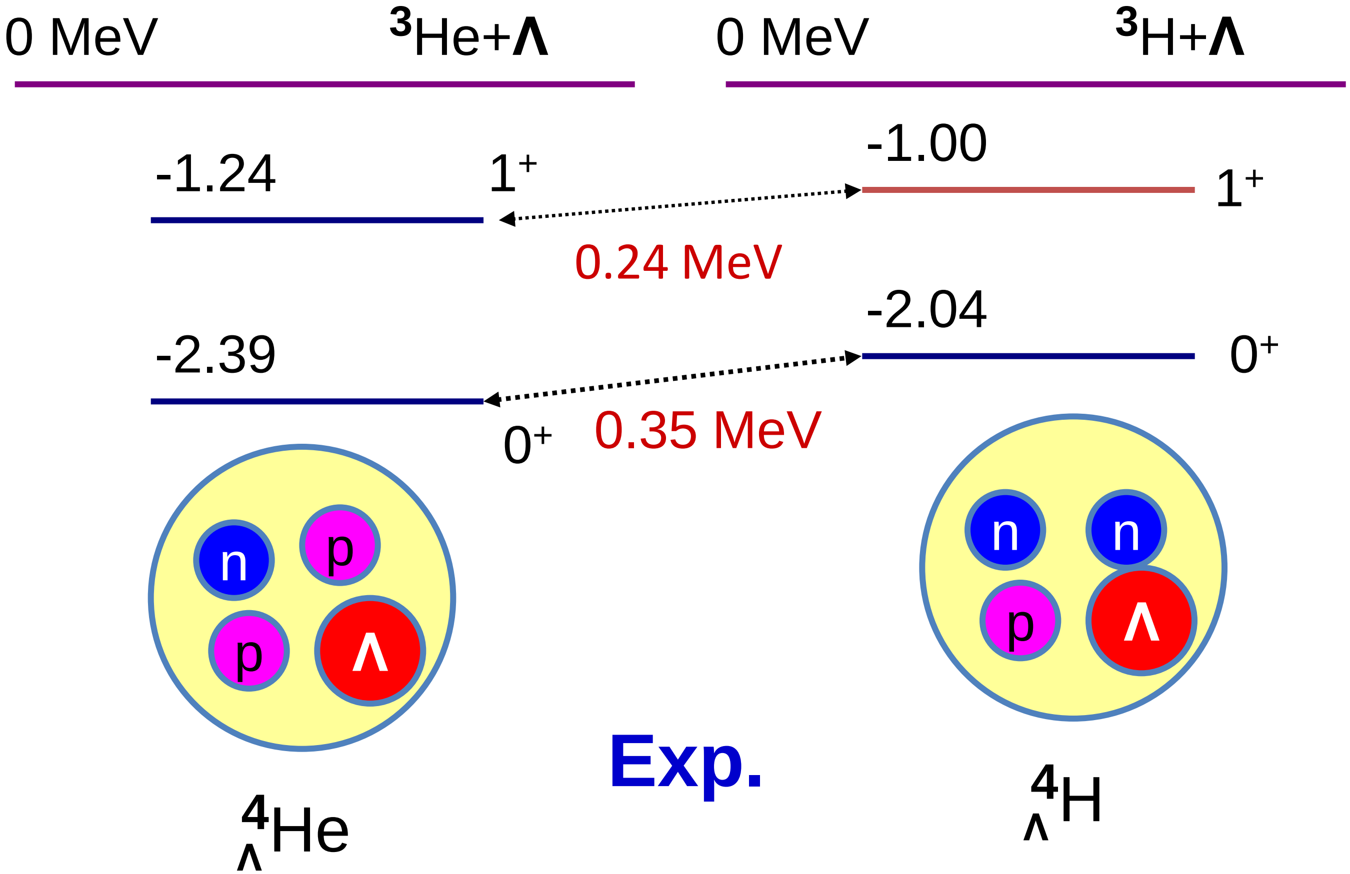
(1)What is the level structure of A=7 hypernuclei without CSB interaction?

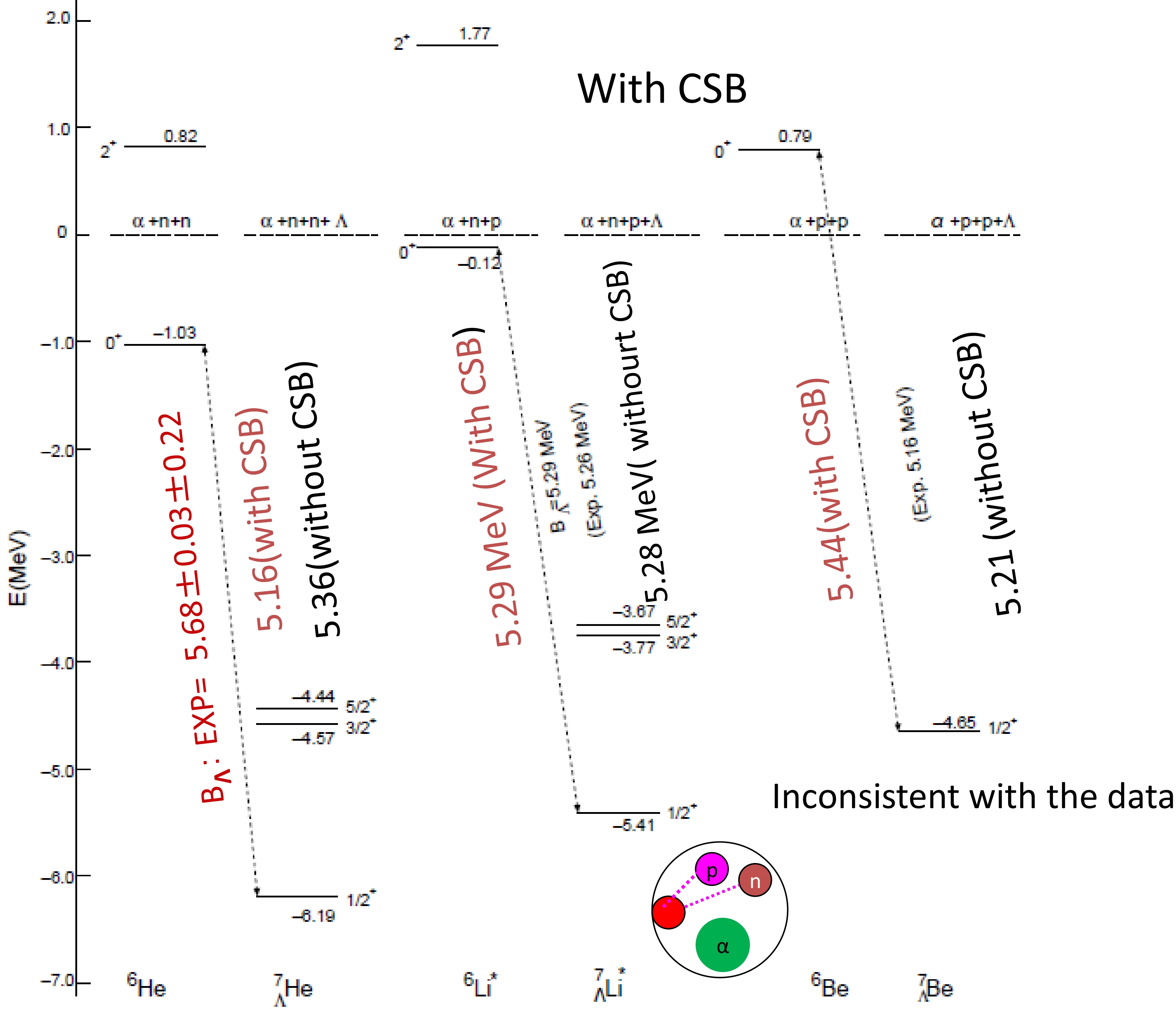
(2) What is the level structure of A=7 hypernuclei with CSB interaction?

Next we introduce a phenomenological CSB potential with the central force component only.

$$V_{\Lambda N}^{\mathrm{CSB}}(r) = \qquad (3.3)$$
$$-\frac{\tau_z}{2}\Big[\frac{1+P_r}{2}\big(v_0^{\mathrm{even,CSB}} + \boldsymbol{\sigma}_\Lambda\cdot\boldsymbol{\sigma}_N v_{\sigma_\Lambda\cdot\sigma_N}^{\mathrm{even,CSB}}\big)\, e^{-\beta_{\mathrm{even}} r^2}$$
$$+\frac{1-P_r}{2}\big(v_0^{\mathrm{odd,CSB}} + \boldsymbol{\sigma}_\Lambda\cdot\boldsymbol{\sigma}_N v_{\sigma_\Lambda\cdot\sigma_N}^{\mathrm{odd,CSB}}\big)\, e^{-\beta_{\mathrm{odd}} r^2}\Big],$$

Strength, range are determined so as to reproduce the data.





With CSB
E(MeV)
2.0
1.0
0
−1.0
−2.0
−3.0
−4.0
−5.0
−6.0
−7.0
2+ 0.82
α +n+n
0+ −1.03
α +n+n+ Λ
5/2+ −4.44
3/2+ −4.57
1/2+ −6.19
2+ 1.77
α +n+p
0+ −0.12
α +n+p+Λ
5/2+ −3.67
3/2+ −3.77
1/2+ −5.41
0+ 0.79
α +p+p
α +p+p+Λ
1/2+ −4.65
BΛ : EXP= 5.68±0.03±0.22
5.16(with CSB)
5.36(without CSB)
5.29 MeV (With CSB)
BΛ=5.29 MeV
(Exp. 5.26 MeV)
5.28 MeV(withourt CSB)
5.44(with CSB)
(Exp. 5.16 MeV)
5.21 (without CSB)
Inconsistent with the data
p
n
α
6He
7ΛHe
6Li*
7ΛLi*
6Be
7ΛBe

We include odd-state of CSB to reproduce the data of A=7 Λ hypernuclei. =>apply to A=10 Λ hypernuclei

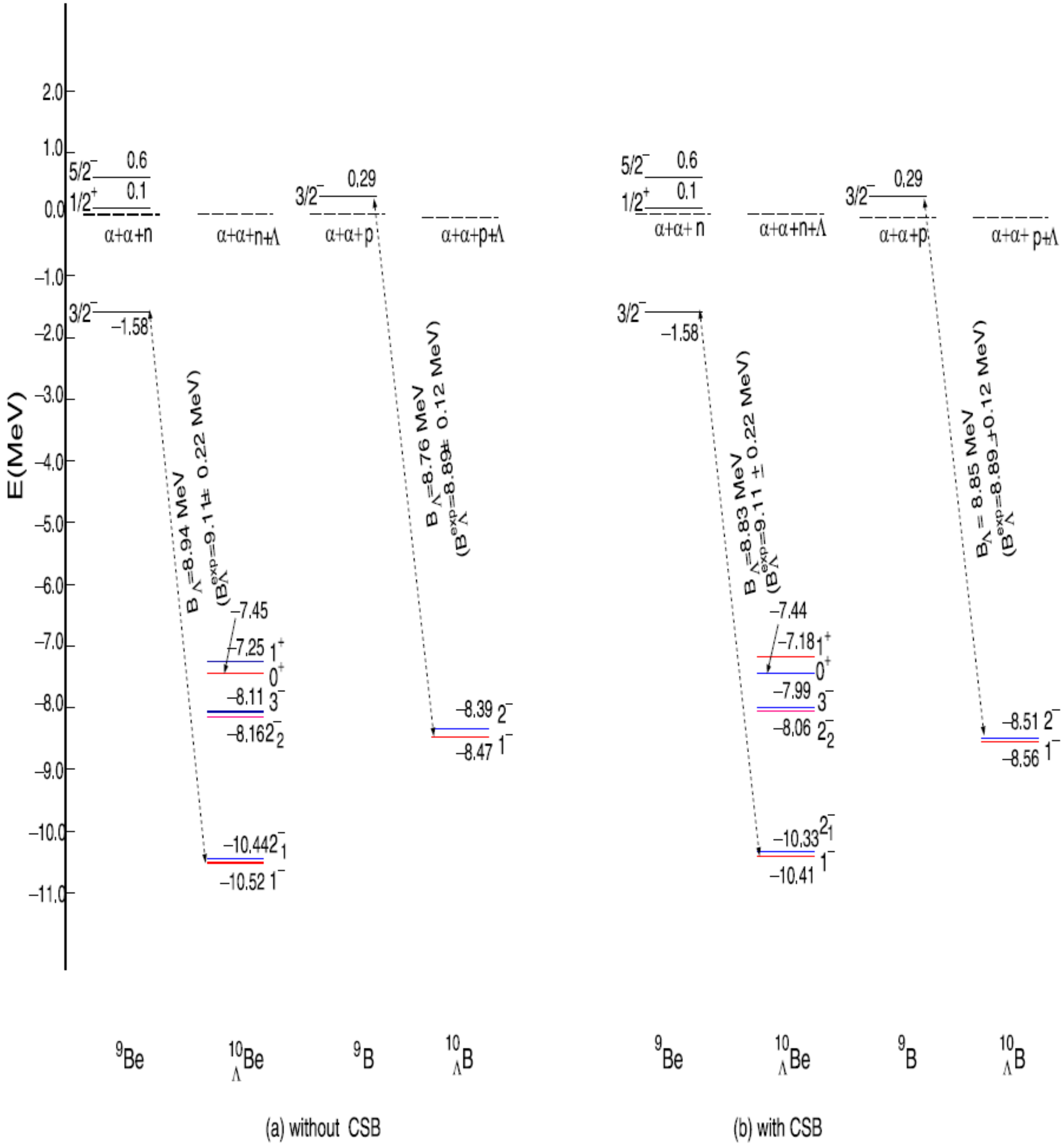
Progress of Theoretical Physics, Vol. 128, No. 1, July 2012

Structure of ${}^{10}_{\Lambda}$Be and ${}^{10}_{\Lambda}$B Hypernuclei Studied with the Four-Body Cluster Model

Emiko HIYAMA and Yasuo YAMAMOTO

$$V_{\Lambda N}^{\rm CSB}(r) = -\frac{\tau_z}{2}\Big[\frac{1+P_r}{2}(v_0^{\rm even,CSB} + \boldsymbol{\sigma}_\Lambda \cdot \boldsymbol{\sigma}_N v_{\sigma_\Lambda\cdot\sigma_N}^{\rm even,CSB})\, e^{-\beta_{\rm even}\, r^2}$$

$$+ \frac{1-P_r}{2}(v_0^{\rm odd,CSB} + \boldsymbol{\sigma}_\Lambda \cdot \boldsymbol{\sigma}_N v_{\sigma_\Lambda\cdot\sigma_N}^{\rm odd,CSB})\, e^{-\beta_{\rm odd}\, r^2}\Big],$$



What about Experimental data?

Even CSB)

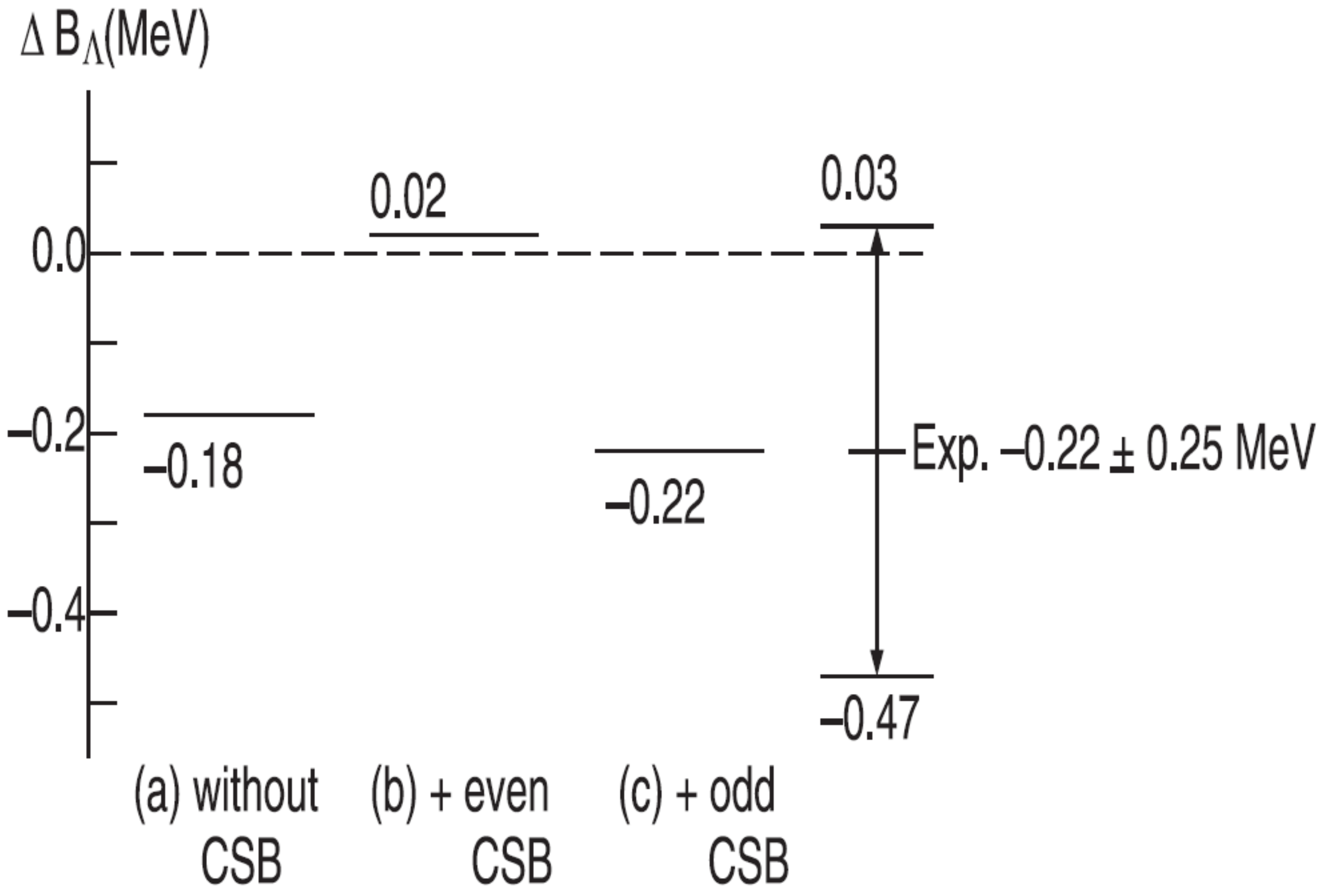
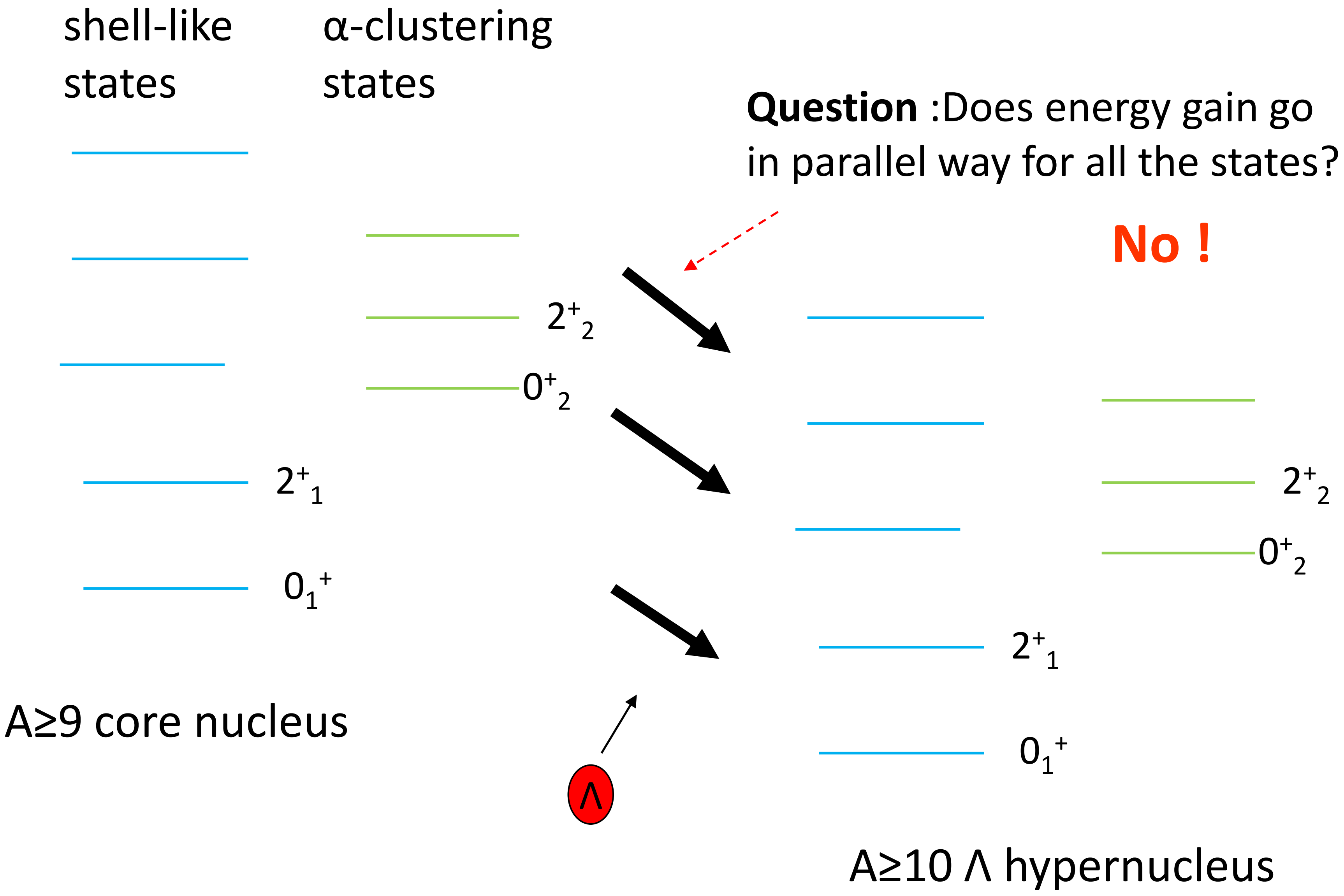


Fig. 7. Calculated energy difference of ${}^{10}_{\Lambda}$Be and ${}^{10}_{\Lambda}$B, $\Delta B_\Lambda(B_\Lambda({}^{10}_{\Lambda}\mathrm{B}) - B_\Lambda({}^{10}_{\Lambda}\mathrm{Be})$, (a) without CSB, (b) with even-state CSB, and (c) with both even- and odd-state CSB interactions.

What about data by Gogami san?

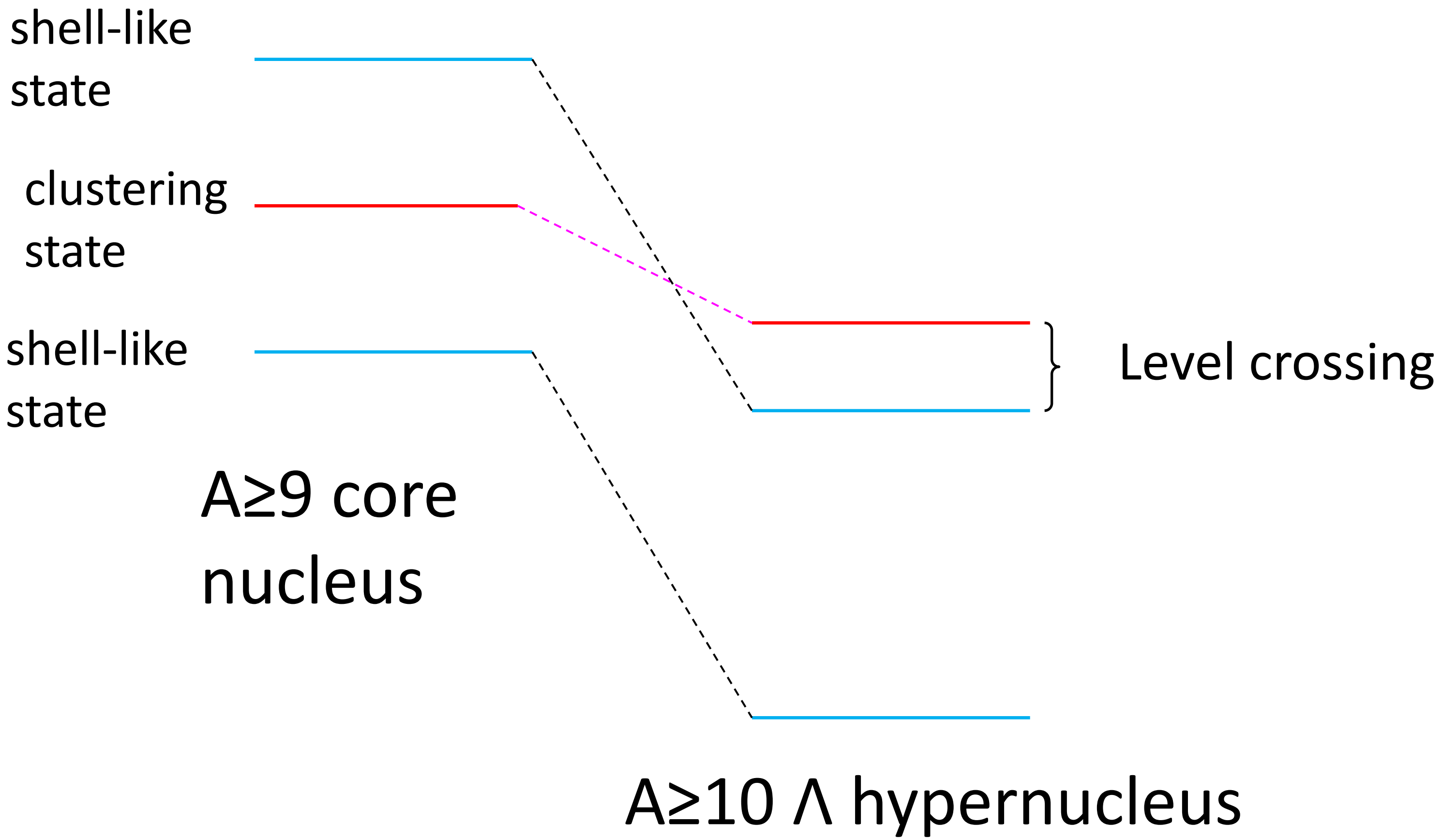
$^{10}{}_{\Lambda}Be$ is interesting to investigate structure modified by addition of Λ particle.

Schematic illustration



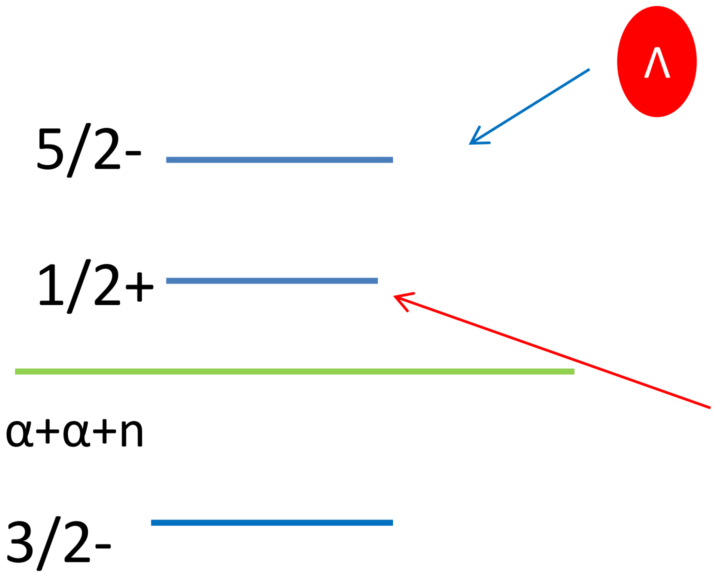
Energy gain by Λ-particle addition

ΔE(shell-like) > ΔE(clustering)

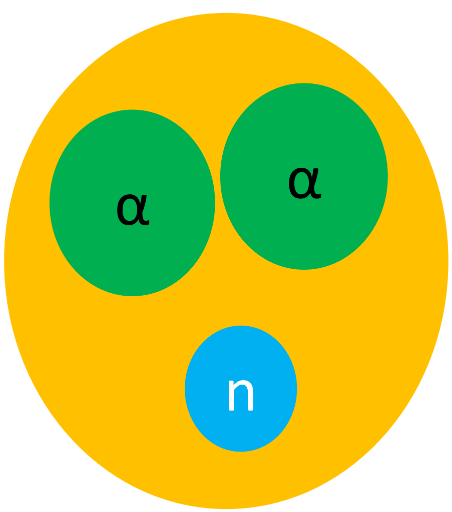


Interesting phenomena such as level crossing is seen in ^{9}Be and $^{10}_{\Lambda}$Be combination.

When a Λ particle is injected into each state, is there change of energy spectra?

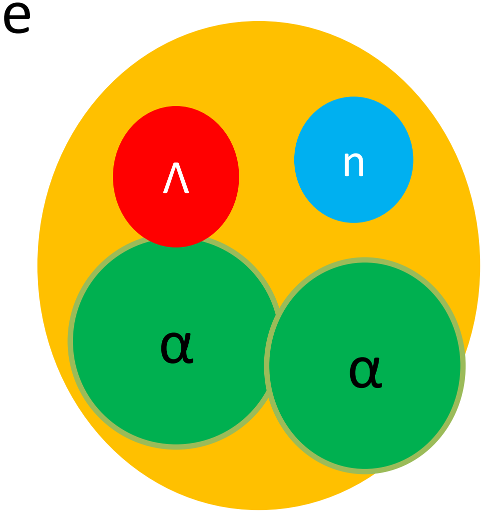


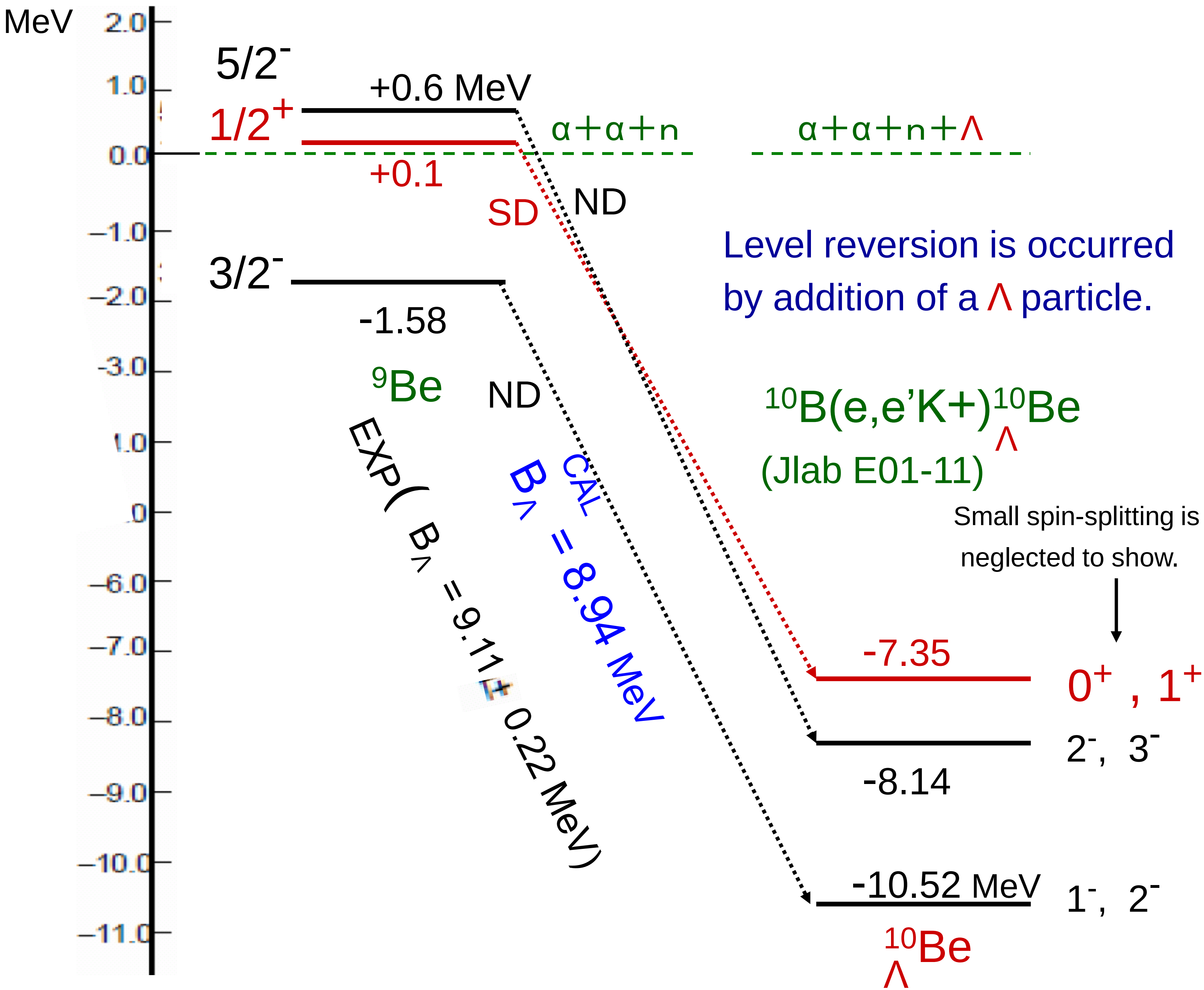
It is well known that a valence neutron is occupied in $1S_{1/2}$ orbit in the simple shell model configuration.



^{9}Be

$^{10}_{\Lambda}$Be





MeV
5/2-
+0.6 MeV
1/2+
+0.1
α+α+n
α+α+n+Λ
SD
ND
-1.58
3/2-
9Be
ND
EXP(BΛ = 9.11 ± 0.22 MeV)
CAL BΛ = 8.94 MeV
Level reversion is occurred by addition of a Λ particle.
10B(e,e'K+)10ΛBe
(Jlab E01-11)
Small spin-splitting is neglected to show.
-7.35
0+ , 1+
2-, 3-
-8.14
-10.52 MeV
1-, 2-
10ΛBe

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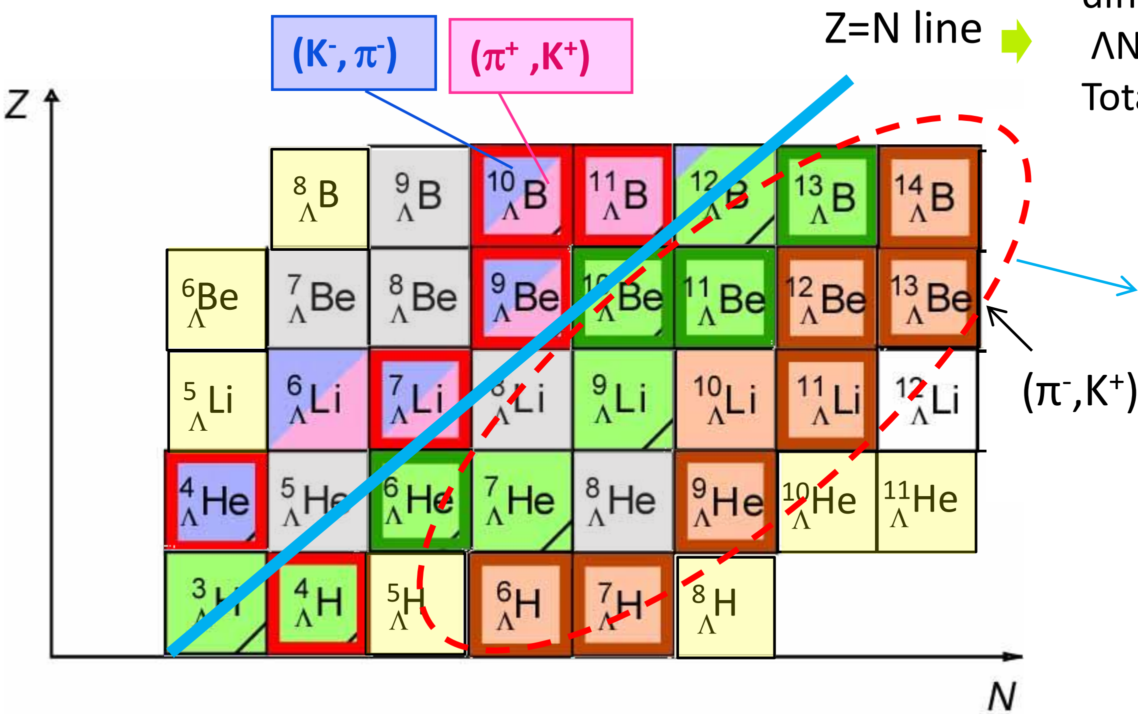

difficult to obtain information on ΛN-ΣN coupling
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ΛN-ΣN coupling give a great contribution to binding energy of neutron-rich Λ hypernuclei.

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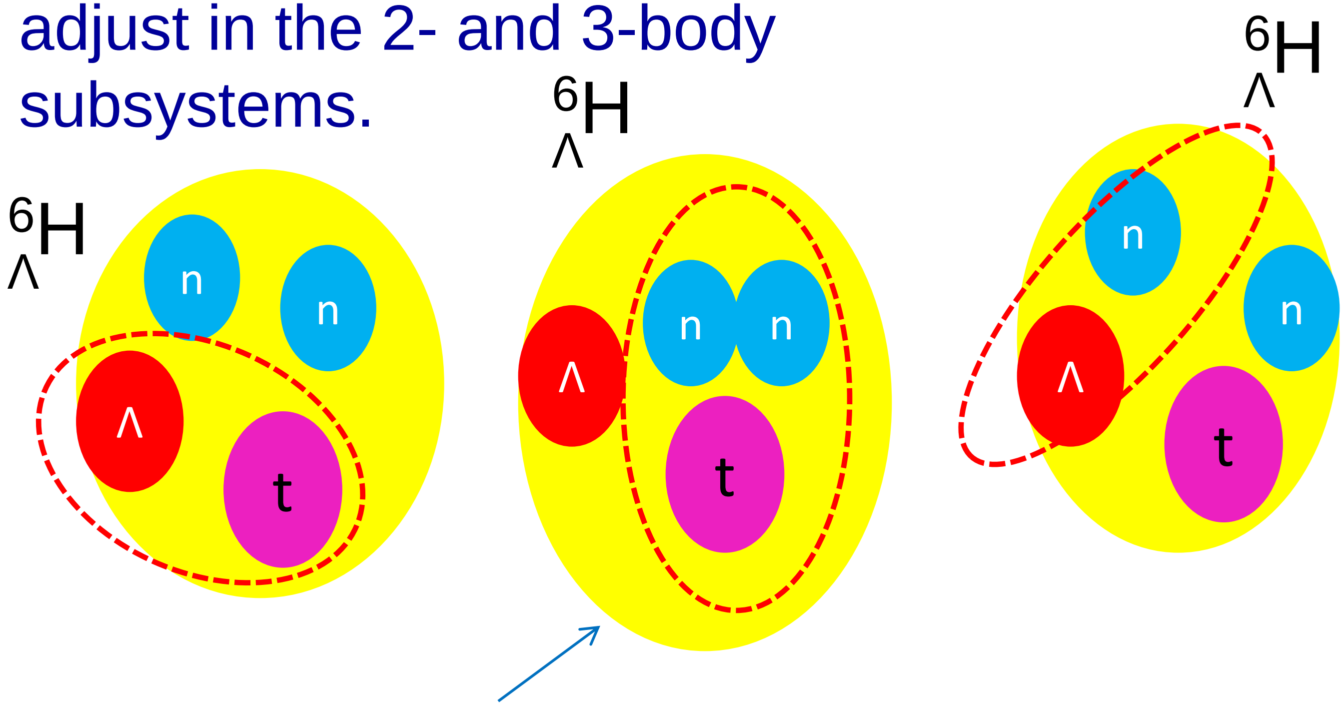
Furthermore, we need short-range part of ΛNN three-body force.: important for the study of neutron star

So far, search ${}^{6}_{\Lambda}H$ experiment has been done.

Conflict between FINUDA exp. and J-PARC exp.

Before doing full 4-body calculation,
it is important and necessary to reproduce
the observed binding energies of all the sets
of subsystems in $^{6}_{\Lambda}H$.

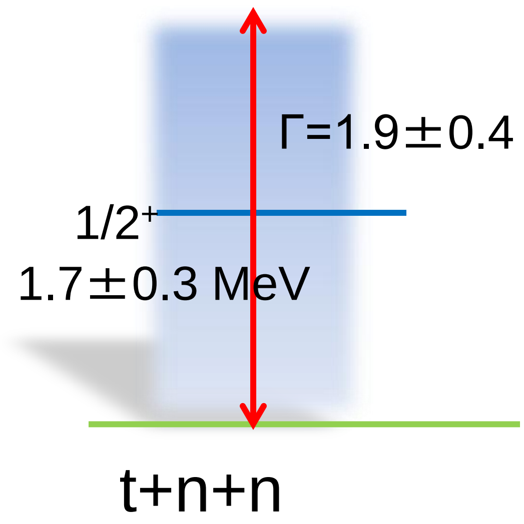
Namely, All the potential parameters are needed to adjust in the 2- and 3-body subsystems.



Among the subsystems, it is extremely important to adjust the energy and decay width of ^{5}H core nucleus.

Framework:

To calculate the binding energy of ${}_{\Lambda}^{6}H$, it is very important to reproduce the binding energy of the core nucleus ^{5}H.



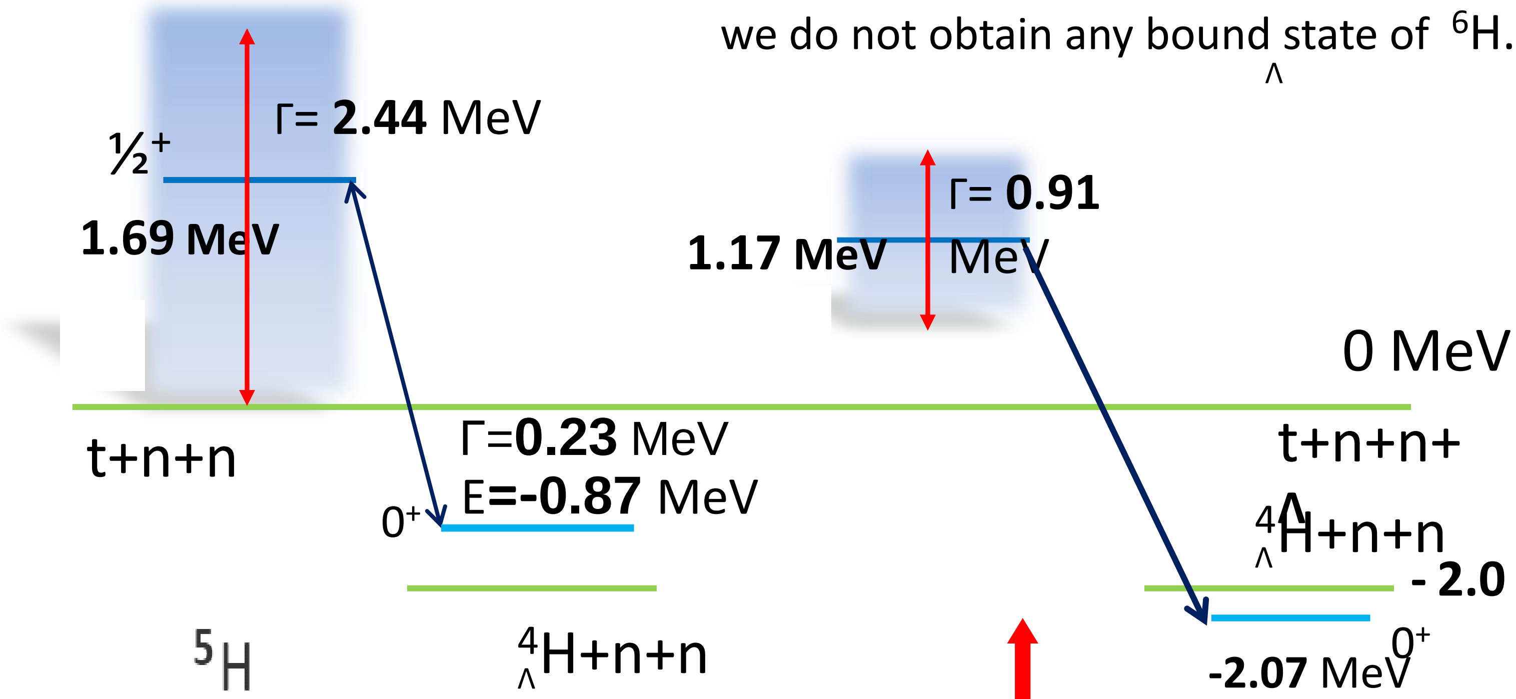
transfer reaction p(^{6}He, ^{2}He)^{5}H

A. A. Korcheninnikov, et al. Phys. Rev. Lett. 87 (2001) 092501.

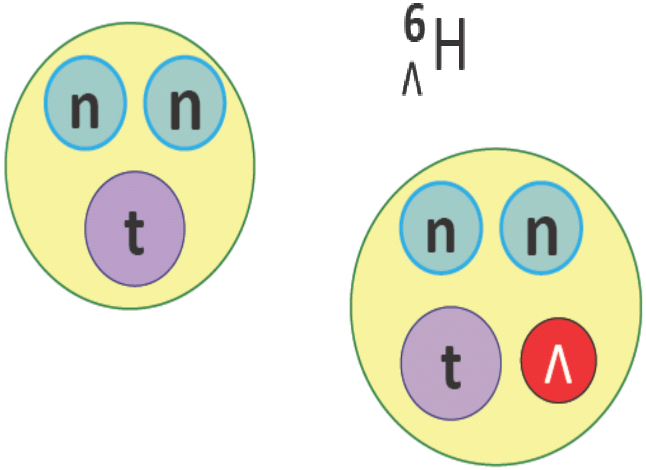
To reproduce the data, for example,
R. De Diego et al, Nucl. Phys. A786 (2007), 71.
calculated the energy and width of ^{5}H with t+n+n three-body model using complex scaling method.
The calculated binding energy for the ground state of ^{5}H is 1.6 MeV with respect to t+n+n threshold an width has 1.5 MeV.

Exp: 1.7 ±0.3 MeV
Γ=1.9 ±0.4 MeV

Even if the potential parameters were tuned so as to reproduce the lowest value of the Exp. , E=1.4 MeV, Γ=1.5 MeV, we do not obtain any bound state of $^{6}_{\Lambda}H$.



6ΛH



On the contrary, if we tune the potentials to have a bound state in $^{6}_{\Lambda}H$, then what is the energy and width of ^{5}H?

(E_R, Γ_R) (MeV)	
J^π	$1/2^+$
^{5}H (full)	(1.57, 1.53)
^{5}H ($d = 0$)	(1.55, 1.35)
Theor. [16]	(2.26, 2.93)
Theor. [12]	(2.5–3.0, 3–4)
Theor. [13]	(3.0–3.2, 1–4)
Theor. [15]	(1.59, 2.48)
Exp. [3]	$(1.7 \pm 0.3, 1.9 \pm 0.4)$ ←
Exp. [8]	$(1.8 \pm 0.1, < 0.5)$
Exp. [4]	(1.8, 1.3)
Exp. [5]	(2, 2.5)
Exp. [6]	(3, 6)
Exp. [9]	$(5.5 \pm 0.2, 5.4 \pm 0.6)$

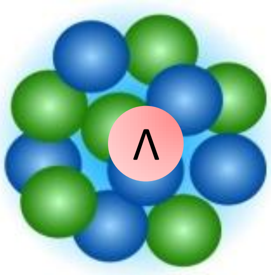
We cited this experiment.
However, you have many different decay widths.
width is strongly related to the size of wavefunction.
Then, I hope that
The decay width will be determined at RCNP this year.

[3] A.A. Korosheninnikov et al., PRL87 (2001) 092501
[8] S.I. Sidorchuk et al., NPA719 (2003) 13
[4] M.S. Golovkov et al. PRC 72 (2005) 064612
[5] G. M. Ter-Akopian et al., Eur. Phys. J A25 (2005) 315.

For the study of neutron-rich Λ hypernuclei,
We should exclude ambiguity of the energy and decay width of core nuclei.
For this purpose, ^{8}He and $^{9}_{\Lambda}He$ is the best candidate to perform search experiment.

heavier Λ hypernuclei

For example: Pb, Sn, Zr, La, Y etc. Istopes



Density of heavier nuclei is high and then, Λ particle is acting in such high dense matter.=> We could obtain information on the short-range part of ΛNN interaction.

In heavier nuclei, density becomes high.

$^{208}_{\Lambda}$Pb, $^{139}_{\Lambda}$La, $^{89}_{\Lambda}$Y: plan in the project at HIHR

I request the experimentalists to produce $^{112\text{-}124}$Sn, $^{90\text{-}96}$ Zr Λ hypernuclei.

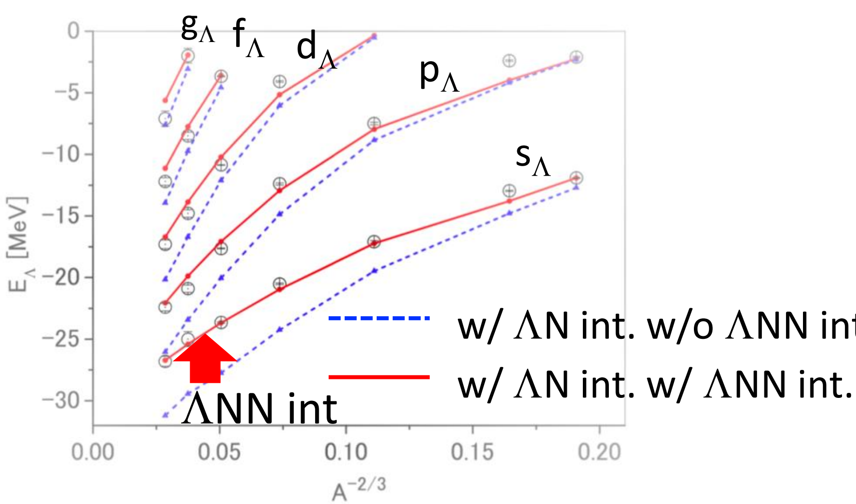
Heavy Λ hypernuclei exp. + theoretical cal.

Isotope dependence of ΛNN three-body force

Determine ΛNN interaction

Reliable EOS

Calc. by Nijmegen ESC16 model



Effects of Many-body Interactions in the Hyperon with Skyrme and KIDS Functionals for Finite Nuclei and Nuclear Matter

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[2]*Center for Exotic Nuclear Studies,*

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[3]*Department of Physics, Tohoku University, Sendai 980-8578, Japan*

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Submitted to EPJA

$$H_{\Lambda\rho} = \frac{3}{8}\rho_\Lambda \sum_{i=1}^{N_f} u_{3i}\left(1+\frac{1}{2}y_{3i}\right)\rho_N^{1+i/3}.$$

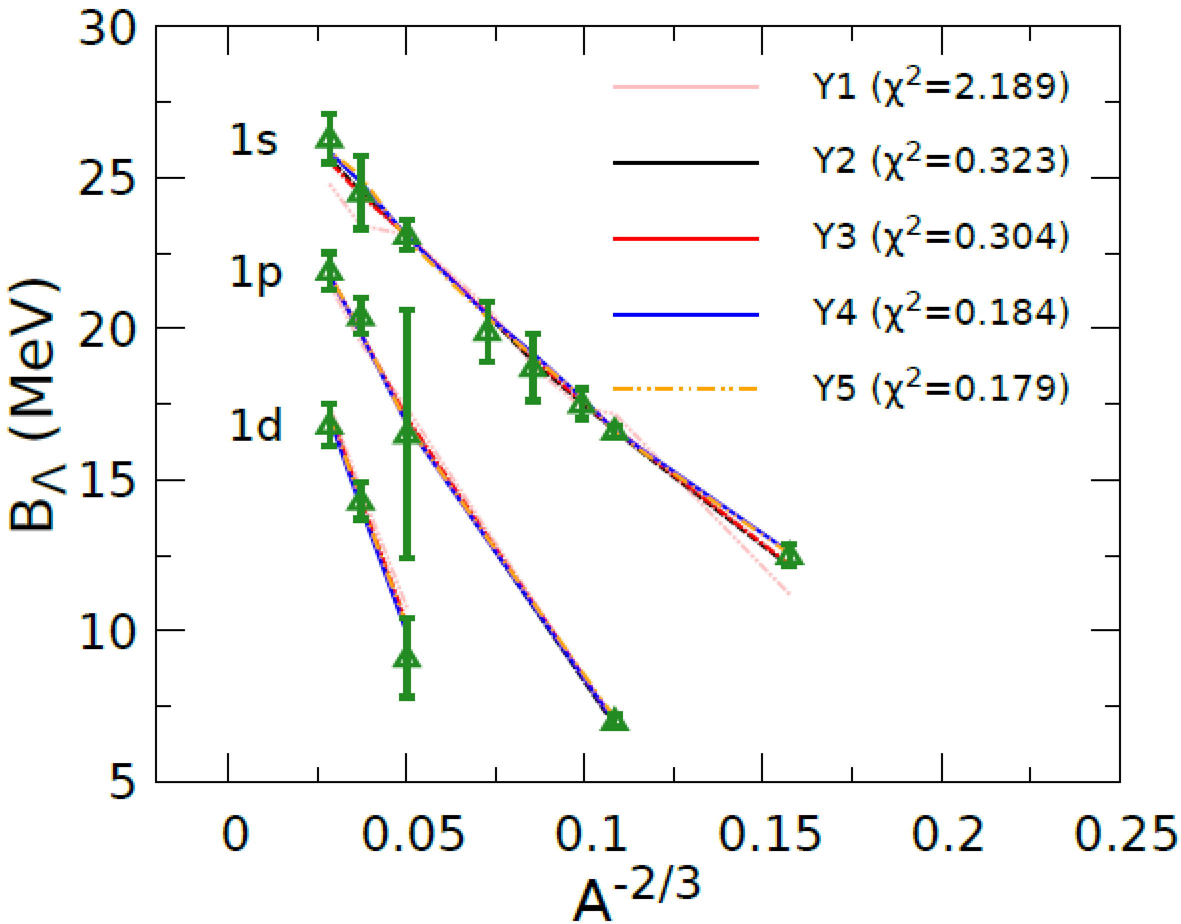
This new type of functional is added to the two-body interaction terms given as

$$\begin{aligned} H_{\Lambda N} &= \frac{\hbar^2}{2m_\Lambda}\tau_\Lambda + u_0\left(1+\frac{1}{2}y_0\right)\rho_N\rho_\Lambda \\ &+\frac{1}{4}(u_1+u_2)(\tau_\Lambda\rho_N+\tau_N\rho_\Lambda)+\frac{1}{8}(3u_1-u_2)(\nabla\rho_N\cdot\nabla\rho_\Lambda) \\ &+\frac{1}{2}W_\Lambda(\nabla\rho_N\cdot\vec{J}_\Lambda+\nabla\rho_N\cdot\vec{J}_\Lambda). \end{aligned}$$

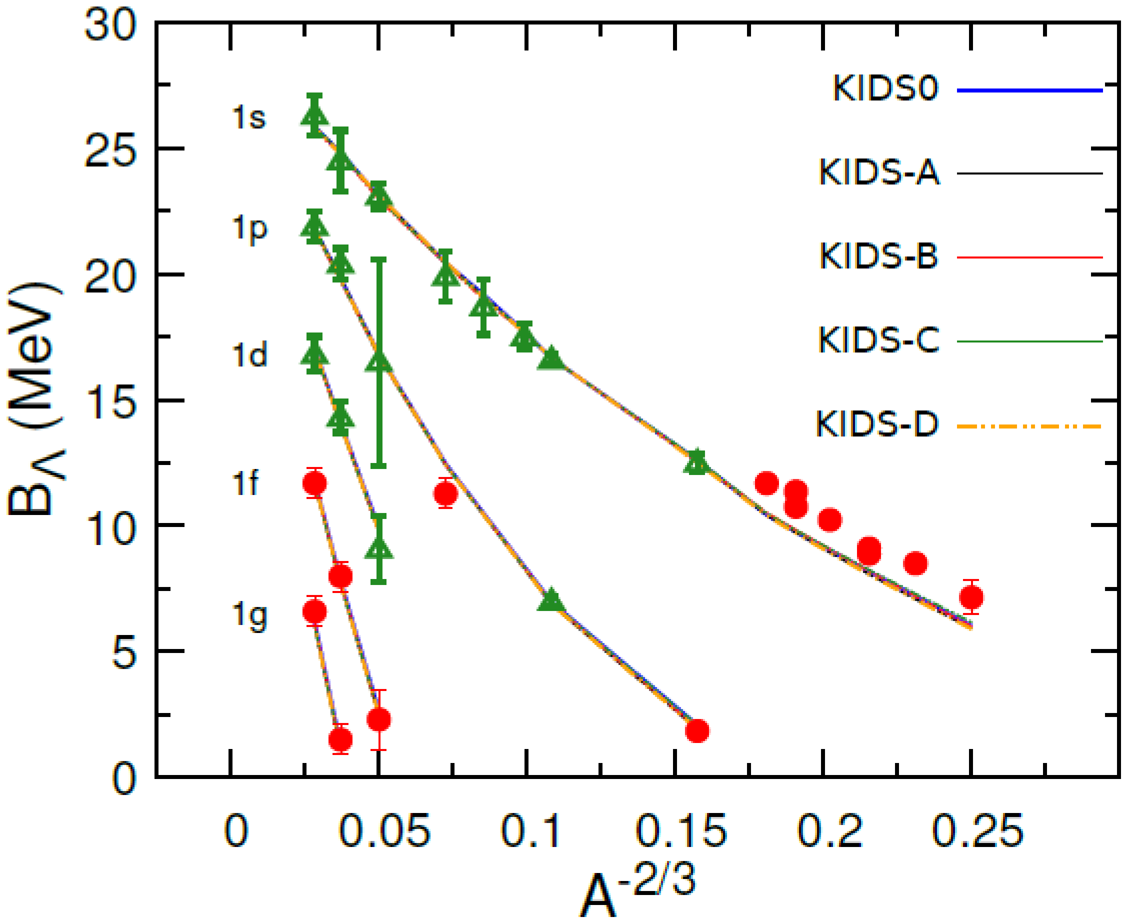
Nuclear density functional theory: two-body interaction + many body force

Model parameters u_0, y_0, u_1, u_2, W_Λ, u_{3i} and y_{3i} :fitted so as to reproduce the data

Nuclei	$1s$ (MeV)	$1p$ (MeV)	$1d$ (MeV)
$^{16}_{\Lambda}$O [13, 14]	12.50 ± 0.35		
$^{28}_{\Lambda}$Si [2, 15]	16.60 ± 0.20	7.0 ± 0.2	
$^{32}_{\Lambda}$S [16]	17.50 ± 0.50		
$^{40}_{\Lambda}$Ca [17, 18]	18.70 ± 1.1		
$^{51}_{\Lambda}$V [19, 20]	19.9 ± 1.0		
$^{89}_{\Lambda}$Y [2, 20]	23.10 ± 0.50	16.50 ± 4.1	9.1 ± 1.3
$^{139}_{\Lambda}$La [2]	24.50 ± 1.20	20.40 ± 0.6	14.3 ± 0.6
$^{208}_{\Lambda}$Pb [2]	26.30 ± 0.80	21.90 ± 0.6	16.8 ± 0.7

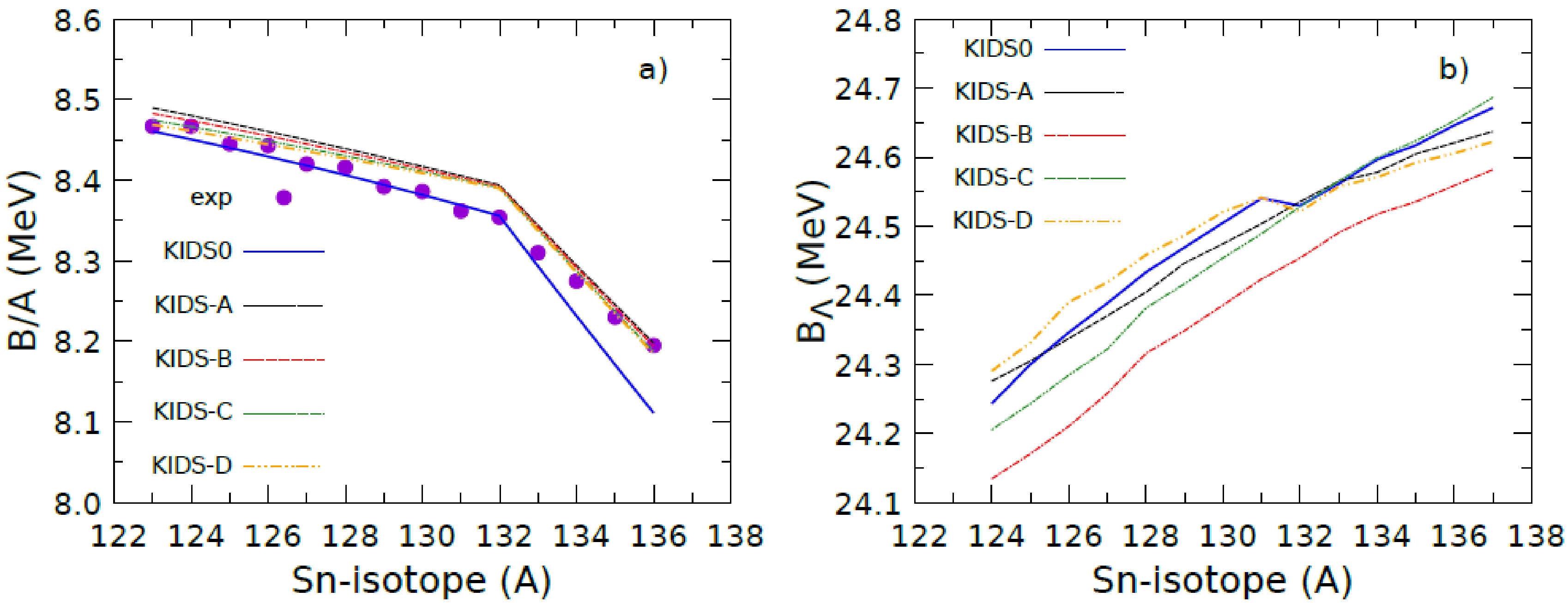


We construct 5 types interaction.

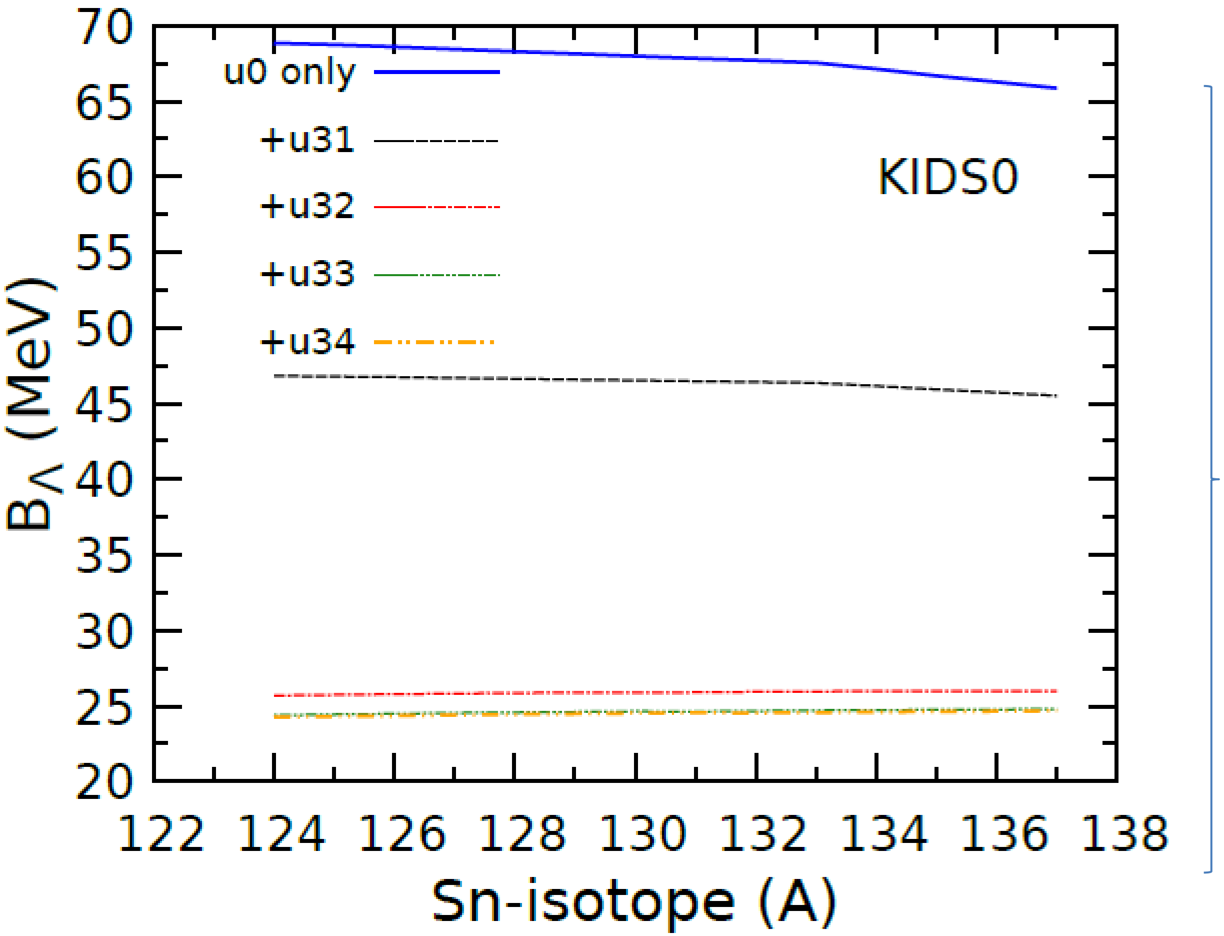


30
25
20
15
10
5
0
1s
1p
1d
1f
1g
KIDS0
KIDS-A
KIDS-B
KIDS-C
KIDS-D
B_Λ (MeV)
0
0.05
0.1
0.15
0.2
0.25
$A^{-2/3}$

Apply to Sn



The energies of core nuclei, Sn isotope are reproduced.



Three-body
Effect is repulsive.

Summary

ΛN-ΣN coupling: neutron-rich Λ hypernuclei

It would be better to have deeper binding.

Heavier neutron-rich Λ hypernuclei

Sn Isotope?