Recent progress of future aspect of hypernuclear physics --from theory view point---

E. Hiyama (RIKEN)

Hypernuclear physics has recently become very excited owing to new epoch-making experimental data.

Recent progress in hypernuclear physics from a theorist's viewpoint. (of hypernuclear structure.)

The major goal of hypernuclear physics

1) To understand baryon-baryon interactions

Fundamental and important for the study of nuclear physics

To understand the baryon-baryon interaction, two-body scattering experiment is most useful.

Total number of
Nucleon (N) -Nucleon (N) data: 4, 000

・Total number of differential cross section
Hyperon (Y) -Nucleon (N) data: **40**

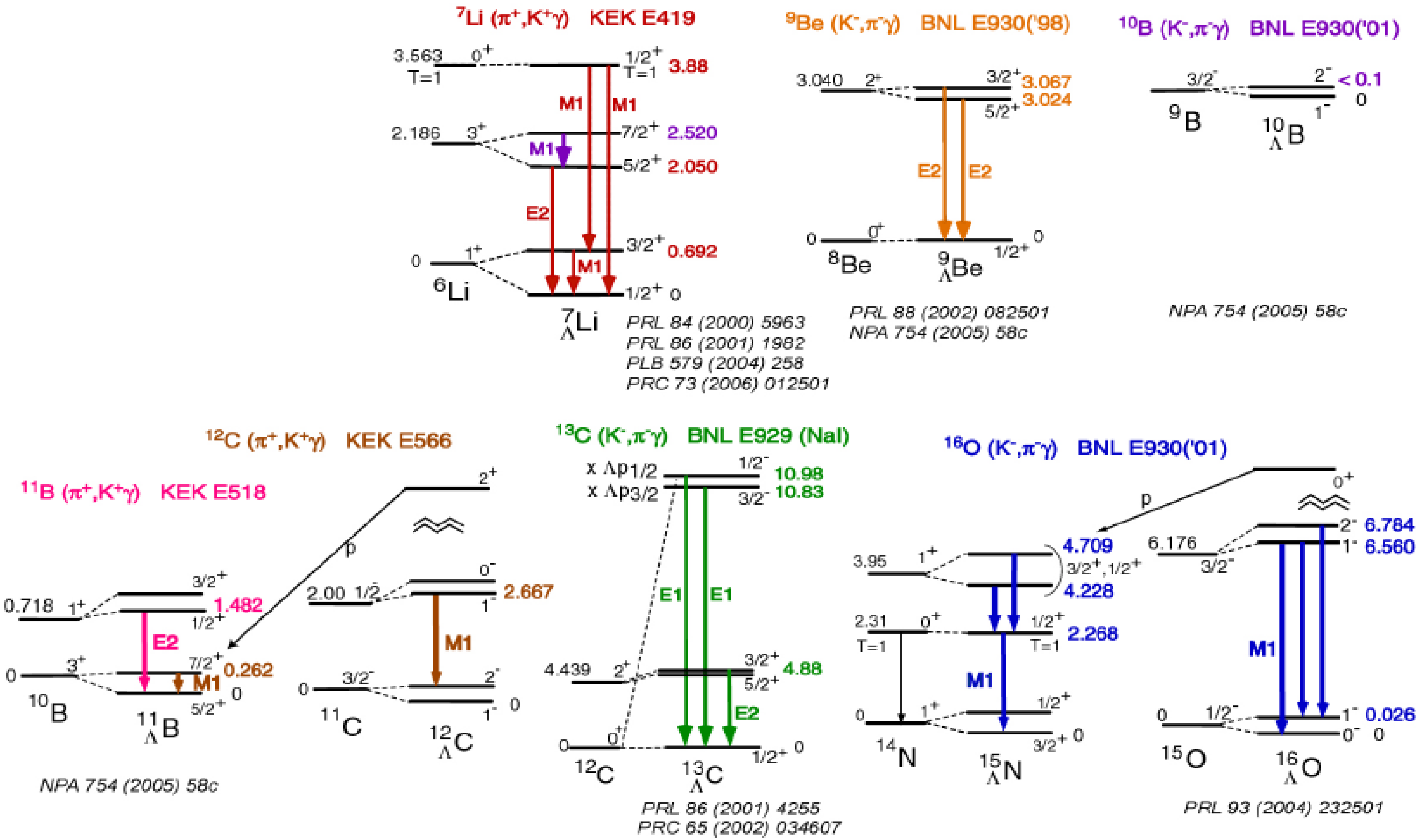
・**NO** YY scattering data

YN and YY potential models so far proposed
(ex. Nijmegen, Julich, Kyoto-Niigata) have large ambiguity.

Therefore, as a substitute for the 2-body limited YN and non-existent YY scattering data,

the systematic investigation of the structure of light hypernuclei is essential.

Hypernuclear γ-ray data since 1998 (figure by H.Tamura)



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

- Millener (p-shell model),
- Hiyama (few-body)

In S= -1 sector,
what are the open questions in YN interaction?

(1) Charge symmetry breaking

(2) ΛN－ΣN coupling

J-PARC : Day-1 experiment　　　　JLAB

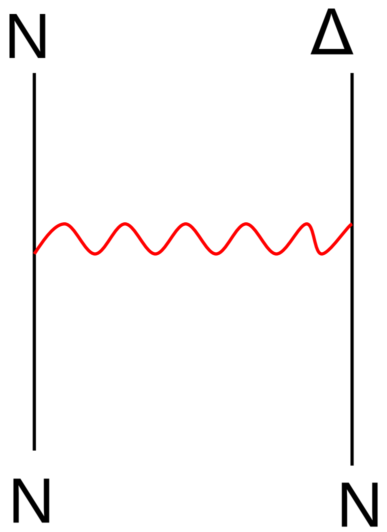
・E13 “γ-ray spectroscopy of light hypernuclei”
by Tamura and his collaborators

$^{11}_{\Lambda}B$　　$^{4}_{\Lambda}He$

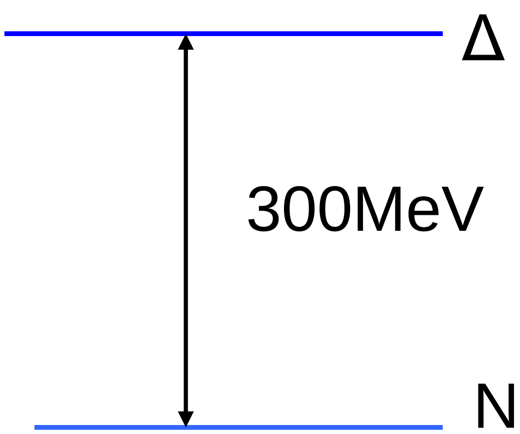
・E10 “Study on Λ-hypernuclei with the doubleCharge-Exchange reaction”
by Sakaguchi , Fukuda and his collaboratiors

$^{9}_{\Lambda}He$　　$^{6}_{\Lambda}H$

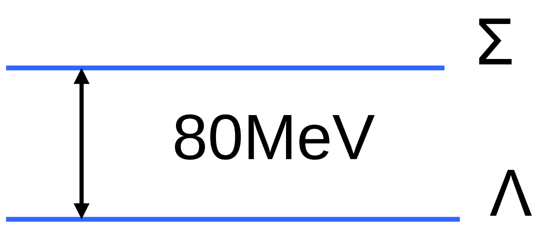
Non-strangeness nuclei

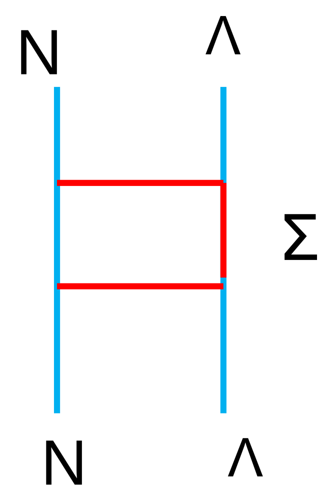


Nucleon can be converted into Δ. However, since mass difference between nucleon and Δ is large, then probability of Δ in nucleus is not large.



On the other hand, the mass difference between Λ and Σ is much smaller, then Λ can be converted into Σ particle easily.

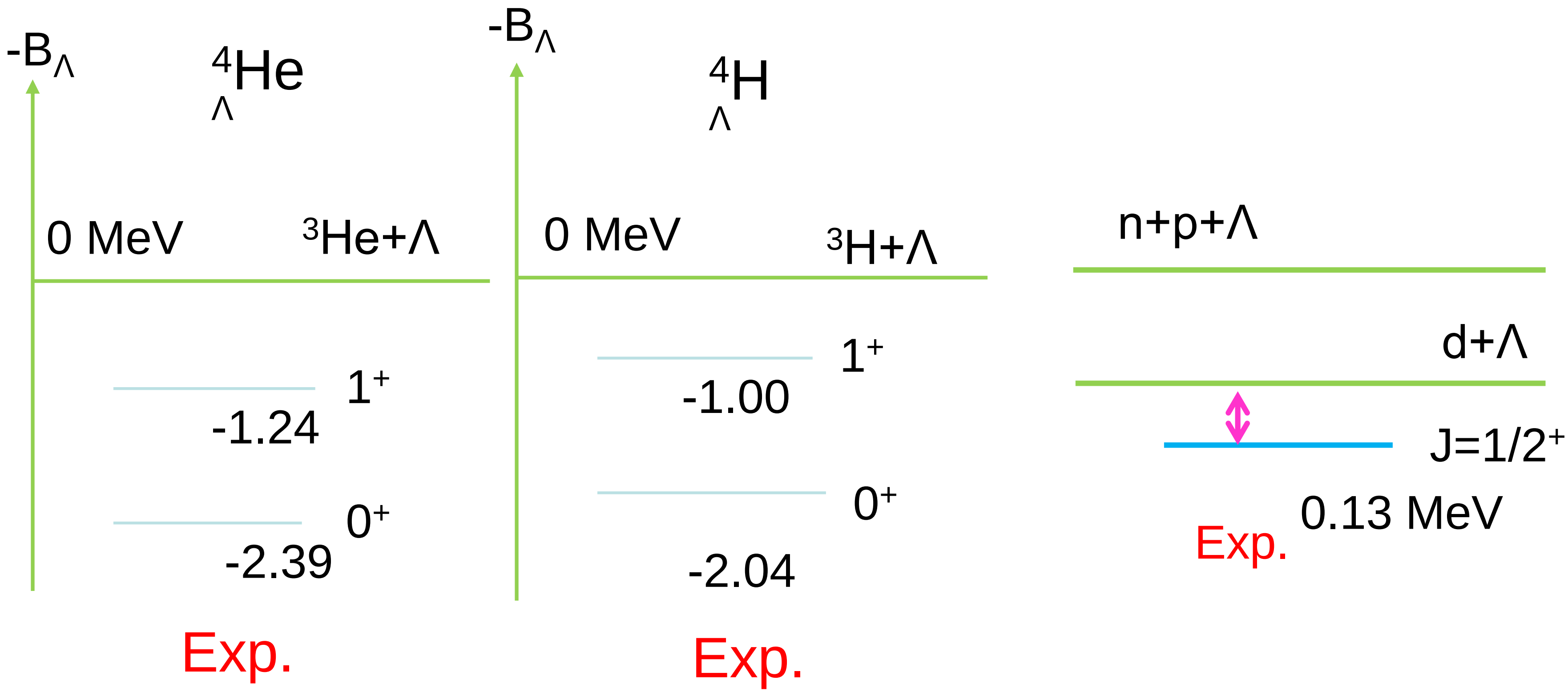


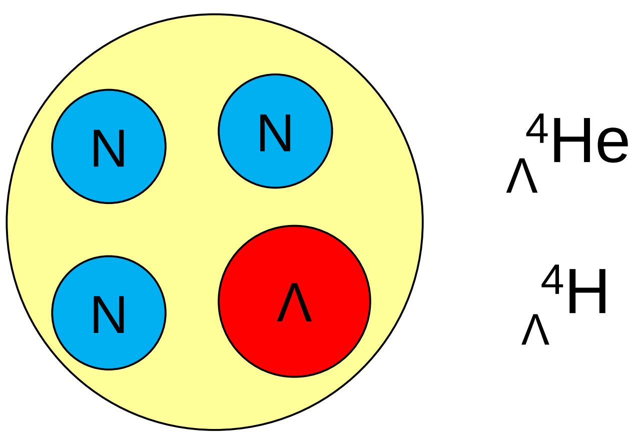


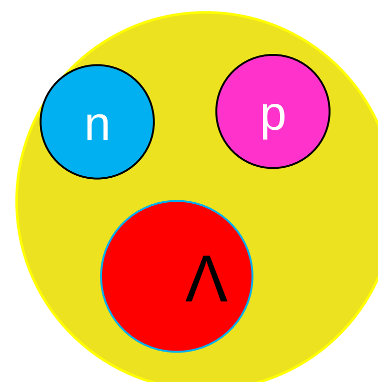
Interesting Issues for the ΛN-ΣN particle conversion in hypernuclei

(1)How large is the mixing probability of the Σ particle in the hypernuclei?

(2) How important is the ΛN—ΣN coupling in the binding energy of the Λ hypernuclei?







$^3_\Lambda$H (hyper-triton)

These hypernuclei are suited for studying ΛN-ΣN coupling.

PHYSICAL REVIEW C 88, 041001(R) (2013)

Search for evidence of $^{3}_{\Lambda}n$ by observing $d + \pi^-$ and $t + \pi^-$ final states in the reaction of $^{6}\mathrm{Li} + {}^{12}\mathrm{C}$ at 2A GeV

C. Rappold,[1,2,*] E. Kim,[1,3] T. R. Saito,[1,4,5,†] O. Bertini,[1,4] S. Bianchin,[1] V. Bozkurt,[1,6] M. Kavatsyuk,[7] Y. Ma,[1,4] F. Maas,[1,4,5]
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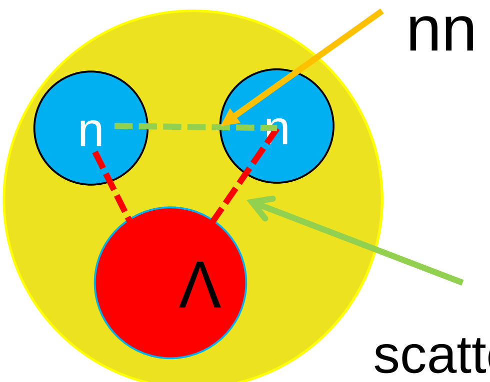
(HypHI Collaboration)

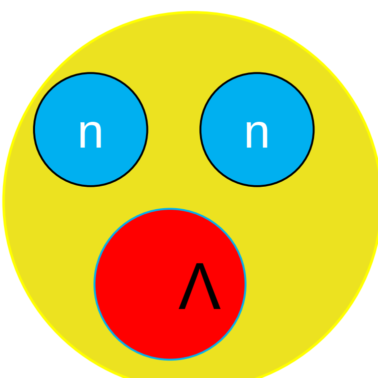


nnΛ breakup threshold

?
They did not report the binding energy.

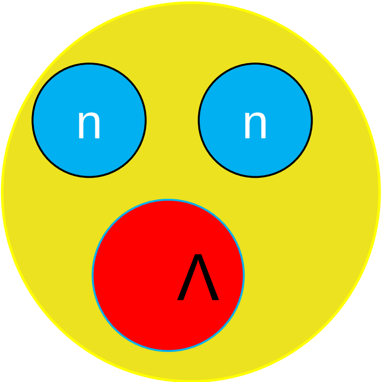
Observation of nnΛ system (2013)
This is also important to get information on ΛN-ΣN coupling.

three-body calculation of $^{3}_{\Lambda}n$



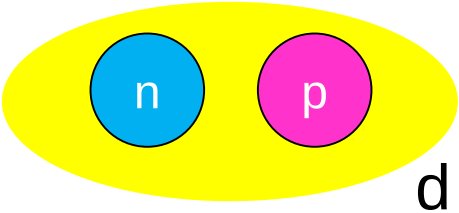
E. Hiyama, S. Ohnishi, B.F. Gibson, and T. A. Rijken, PRC89, 061302(R) (2014).

What is interesting to study nnΛ system?

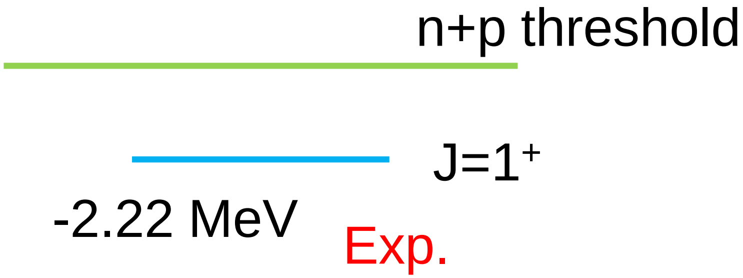


S=0

The lightest nucleus to have a bound state is deuteron.



d



S=-1 (Λ hypernucear sector)

n+p+Λ

Lightest hypernucleus to have a bound state

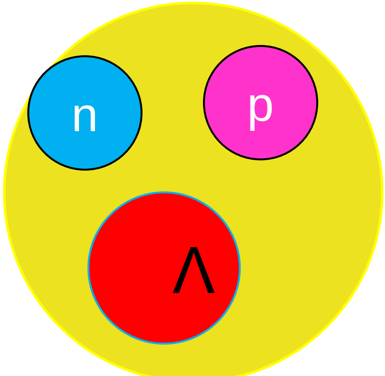
d+Λ

$^3_\Lambda$H (hyper-triton)

0.13 MeV

$J=1/2^+$

Exp.



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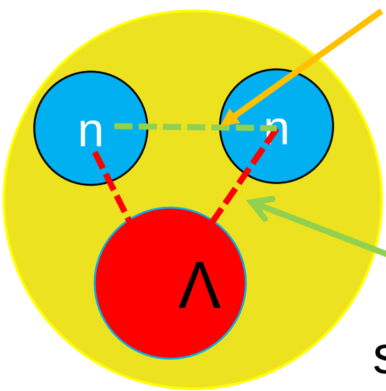


nn unbound

scattering length:-2.68fm

nnΛ breakup threshold

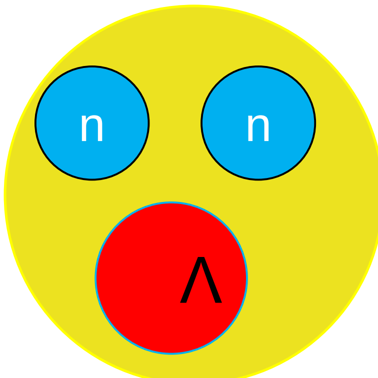
?
They did not report the binding energy.

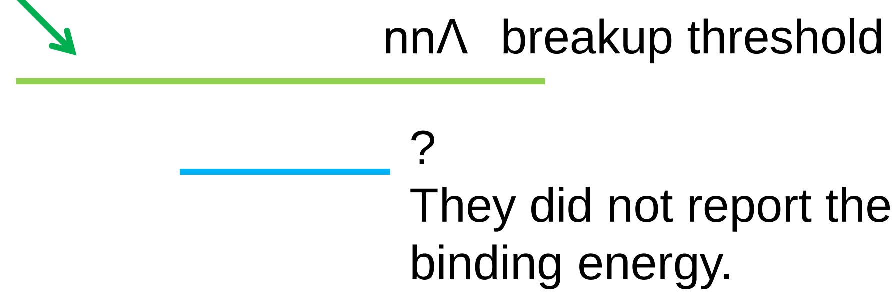
Observation of nnΛ system (2013)
One of the lightest bound hypernuclei

Theoretical important issue:

Do we have bound state for nnΛ system?

If we have a bound state for this system, how much is binding energy?





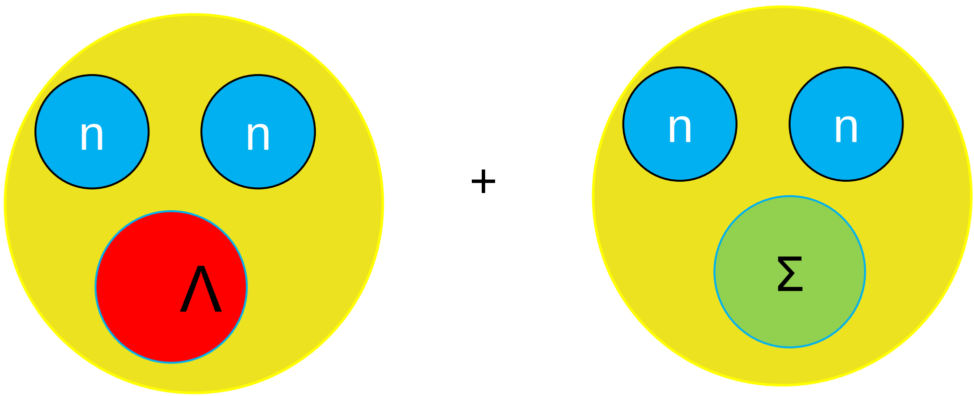
NN interaction : to reproduce the observed binding energies of ^{3}H and ^{3}He

NN: AV8 potential

We do not include 3-body force for nuclear sector.

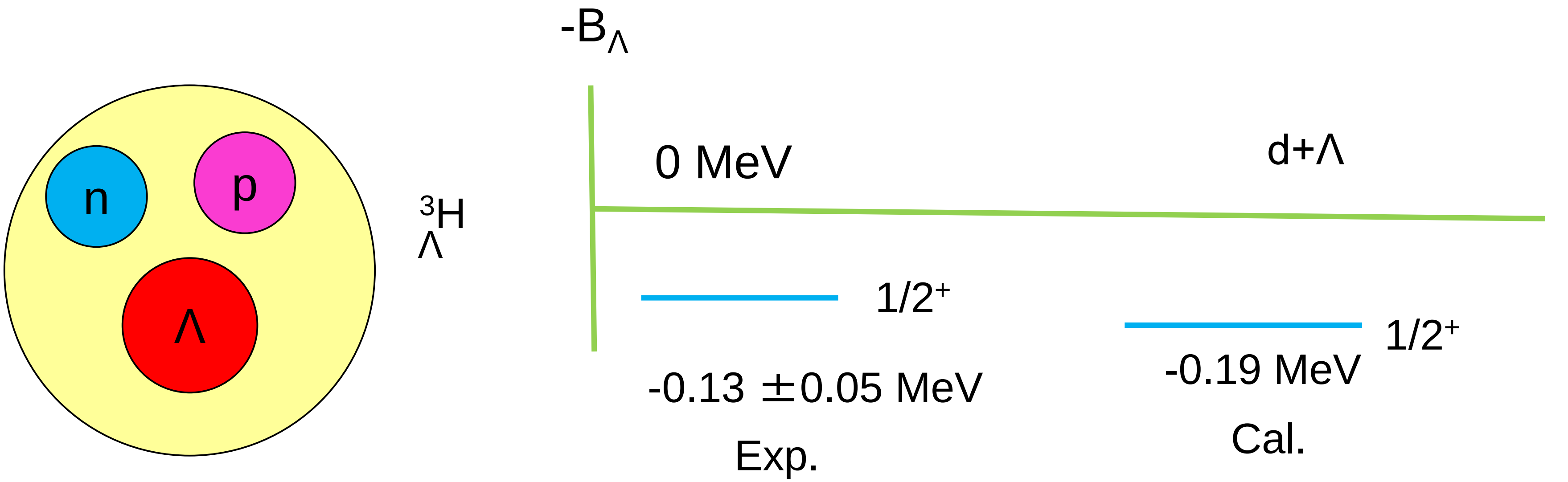
How about YN interaction?

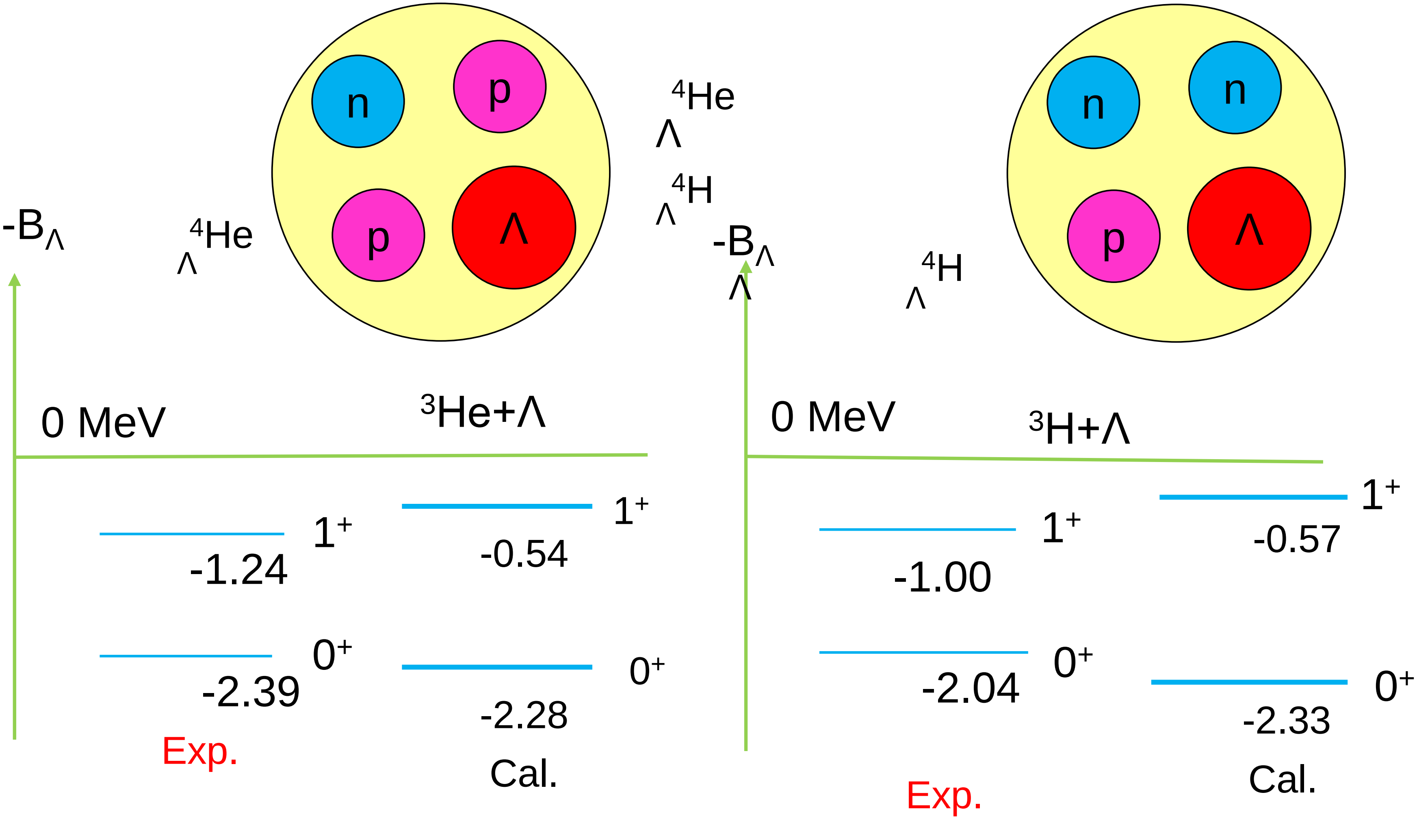
To take into account of Λ particle to be converted into Σ particle, we should perform below calculation using realistic hyperon(Y)-nucleon(N) interaction.



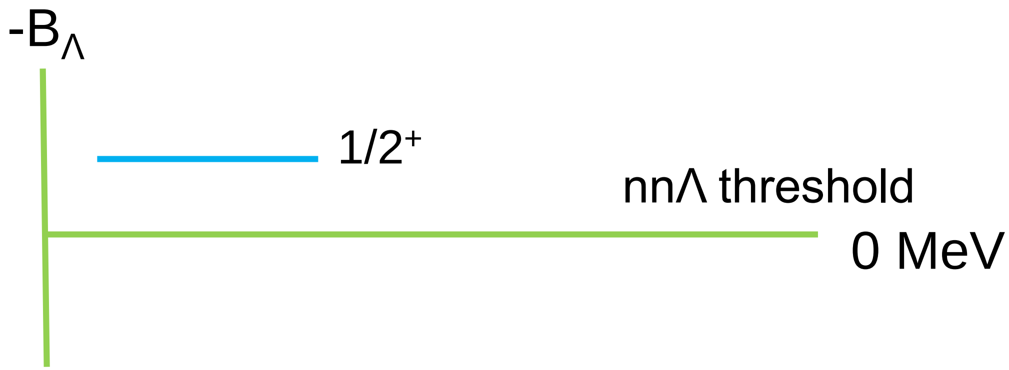
YN interaction: Nijmegen soft core '97f potential (NSC97f) proposed by Nijmegen group

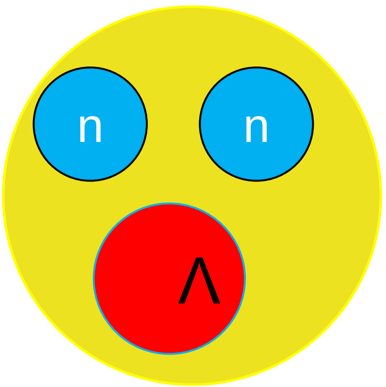
reproduce the observed binding energies of $^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$ and $^{4}_{\Lambda}He$


n
p
Λ
$^{3}_{\Lambda}H$
$-B_{\Lambda}$
0 MeV
d+Λ
1/2+
-0.13 ±0.05 MeV
Exp.
1/2+
-0.19 MeV
Cal.



What is binding energy of nnΛ?

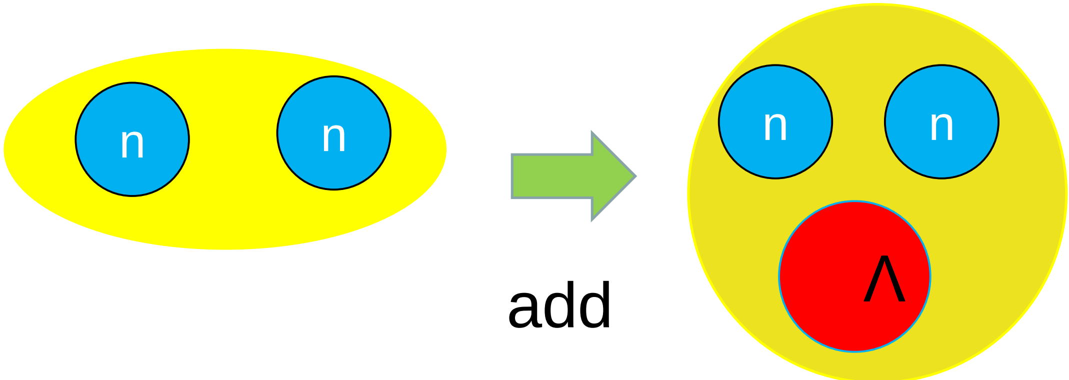




We have no bound state in nnΛ system.
This is inconsistent with the data.

In this way, we have no possibility to have a bound state for nnΛ system. Then, I hope that confirm experiment of this system will be peformed Again at GSI or J-PARC facility using heavy ion collision beam in the future.

Now, we have a question. If we add more two neutrons In this system, what happen?



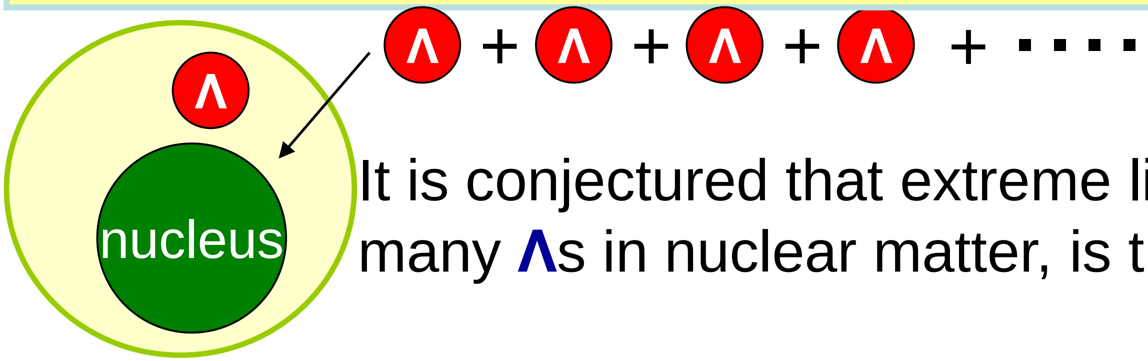
S=-2 hypernuclei

and

YY interaction

So far, we have discussed about single Λ hypernuclei.

What is the structure when one or more **Λ**s are added to a nucleus?



It is conjectured that extreme limit, which includes many **Λ**s in nuclear matter, is the core of a neutron star.

In this meaning, the sector of S=-2 nuclei , double **Λ** hypernuclei and **Ξ** hypernuclei is just the entrance to the multi-strangeness world.

However, we have hardly any knowledge of the YY interaction because there exist no YY scattering data.

Then, in order to understand the YY interaction, it is crucial to study the structure of double **Λ** hypernuclei and **Ξ** hypernuclei.

PTEP

Prog. Theor. Exp. Phys. **2015**, 033D02 (11 pages)
DOI: 10.1093/ptep/ptv008

The first evidence of a deeply bound state of Xi^{-}–^{14}N system

K. Nakazawa[1,*], Y. Endo[1], S. Fukunaga[2], K. Hoshino[1], S. H. Hwang[3], K. Imai[3], H. Ito[1], K. Itonaga[1], T. Kanda[1], M. Kawasaki[1], J. H. Kim[4], S. Kinbara[1], H. Kobayashi[1], A. Mishina[1], S. Ogawa[2], H. Shibuya[2], T. Sugimura[1], M. K. Soe[1], H. Takahashi[5], T. Takahashi[5], K. T. Tint[1], K. Umehara[1], C. S. Yoon[4], and J. Yoshida[1]

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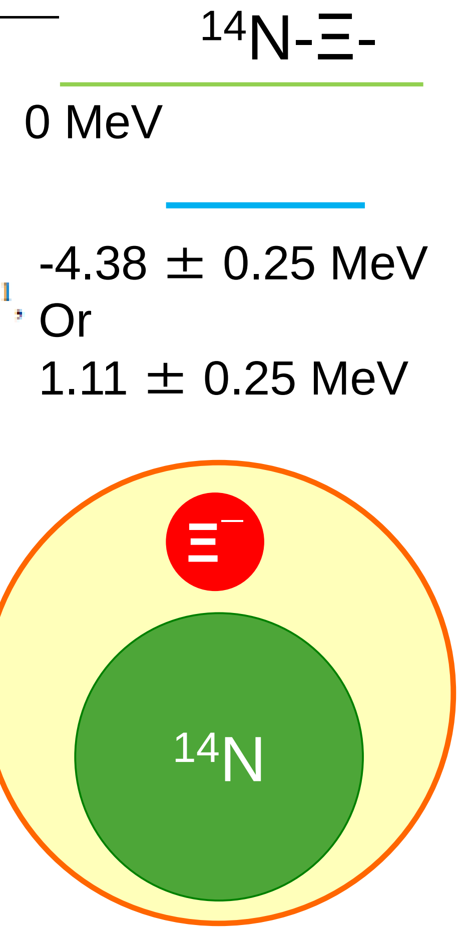
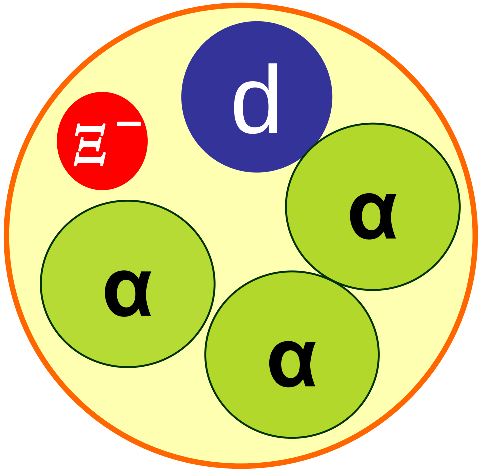


Recently, we observed bound Ξ hypernucleus, for the first time in the world. Next, it is important to predict theoretically what kinds of Ξ hypernuclei will exist as bound states.

^{14}N-Ξ^- ($^{15}_{\Xi}C$)observation by KEK-E373 experiment

What part's information of the ΞN interaction do we extract?

$$V_{\Xi N} = V_0 + \boldsymbol{\sigma}\cdot\boldsymbol{\sigma}\, V_{\sigma\cdot\sigma} + \boldsymbol{\tau}\cdot\boldsymbol{\tau}\, V_{\tau\cdot\tau} + (\boldsymbol{\sigma}\cdot\boldsymbol{\sigma})(\boldsymbol{\tau}\cdot\boldsymbol{\tau})\, V_{\sigma\cdot\sigma\ \tau\cdot\tau}$$



$^{15}_{\Xi^-}C$

All of the terms contribute to binding energy of $^{15}_{\Xi^-}C$ (^{14}N is not spin-, isospin- saturated).

Then, even if we observe this system as a bound state, we shall get only information that $V_{\Xi N}$ itself is attractive.

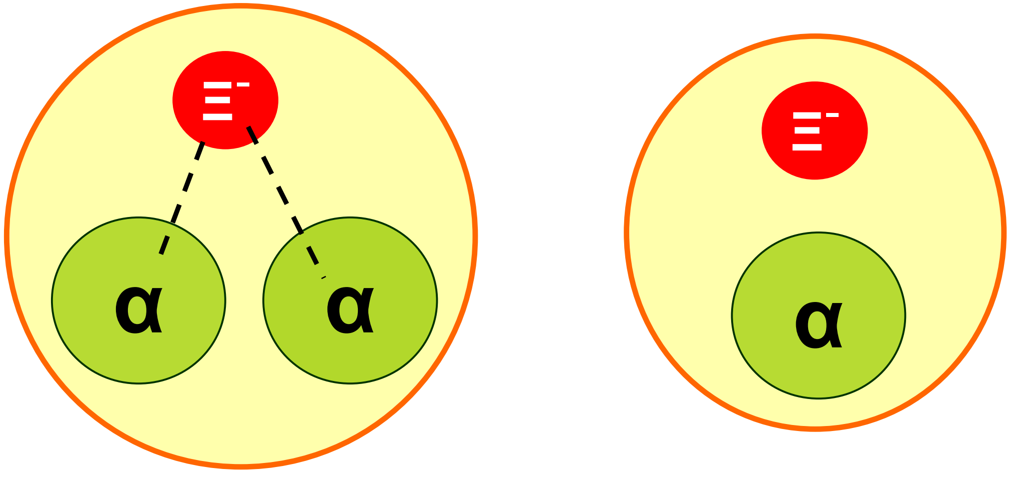
Therefore, next,

we want to know desirable strength of V_0, the spin-,isospin-independent term.

$$V_{\Xi N} = V_0 + \boldsymbol{\sigma}\cdot\boldsymbol{\sigma}\, V_{\sigma\cdot\sigma} + \boldsymbol{\tau}\cdot\boldsymbol{\tau}\, V_{\tau\cdot\tau} + (\boldsymbol{\sigma}\cdot\boldsymbol{\sigma})(\boldsymbol{\tau}\cdot\boldsymbol{\tau})\, V_{\sigma\cdot\sigma\ \tau\cdot\tau}$$

In order to obtain useful information about V_0,
the following systems are suited, because

the $(\boldsymbol{\sigma}\cdot\boldsymbol{\sigma})$, $(\boldsymbol{\tau}\cdot\boldsymbol{\tau})$ and $(\boldsymbol{\sigma}\cdot\boldsymbol{\sigma})$ $(\boldsymbol{\tau}\cdot\boldsymbol{\tau})$ terms of $V_{\Xi N}$ vanish by folding them into the **α**-cluster wave function that are spin-, isospin-satulated.



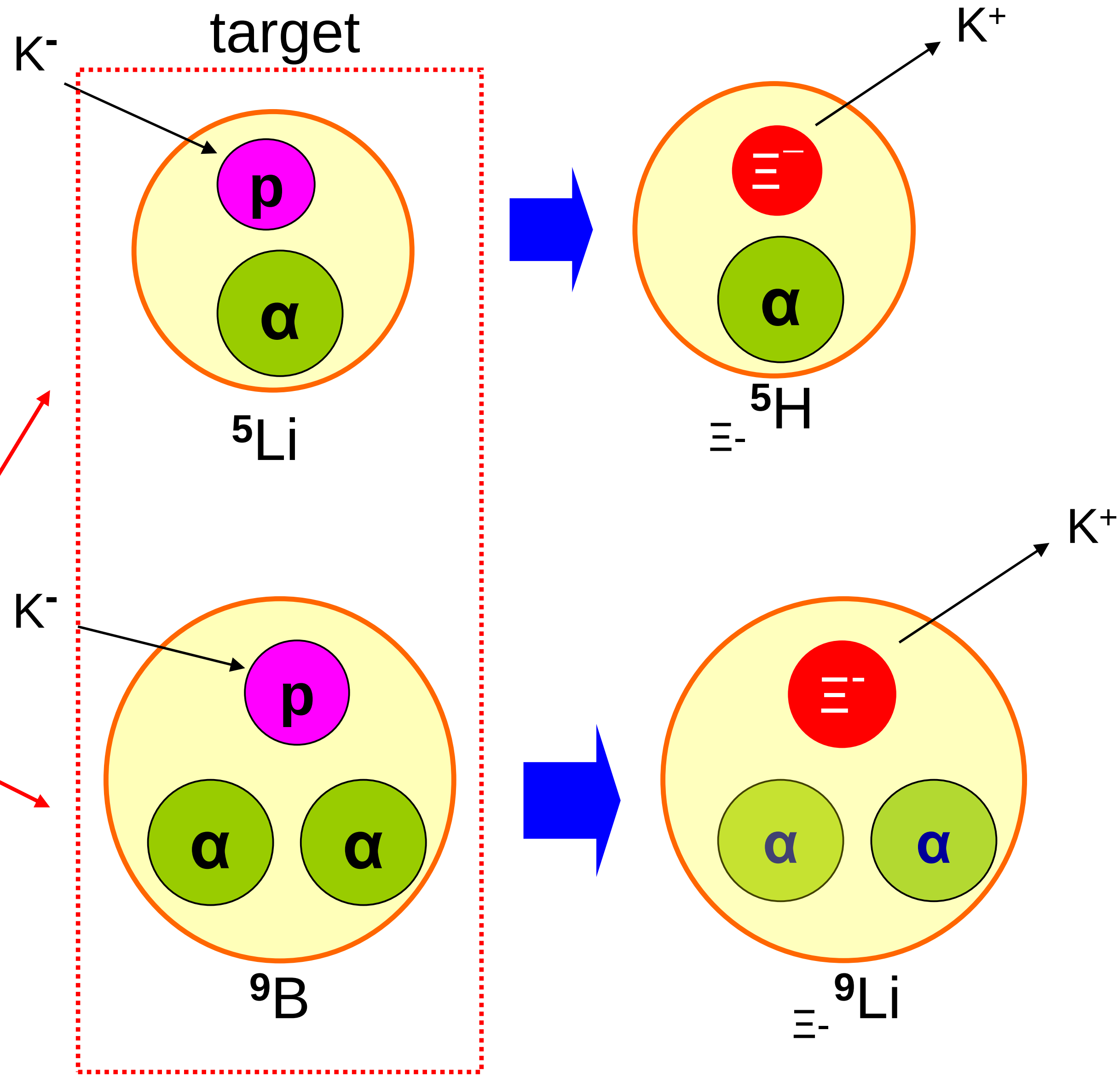
problem : there is NO target to produce them by the (K^-, K^+) experiment .

Because, ･･･

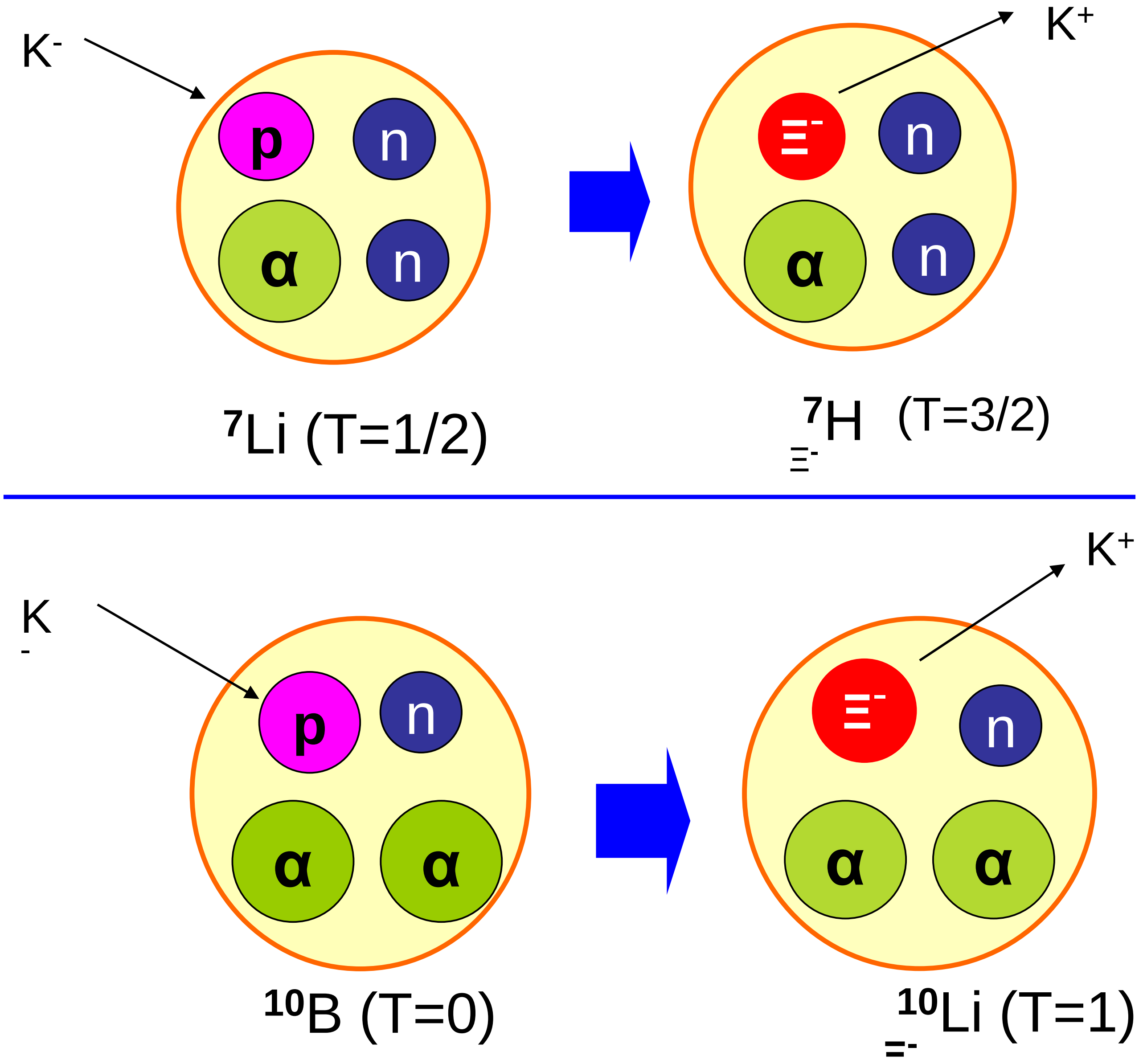
To produce **αΞ⁻** and **ααΞ⁻** systems by (K^-, K^+) reaction,

These systems are unbound.

Then, we cannot use them as targets.



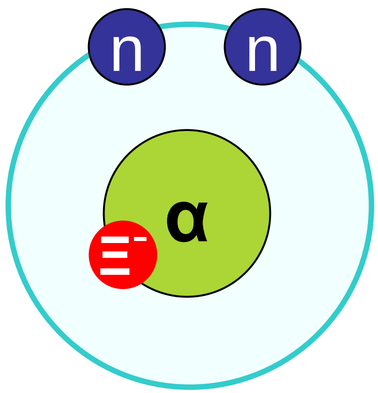
As the second best candidates to extract information about the spin-, isospin-independent term V_0, we propose to perform…



Why they are suited for investigating V_0?

(more realistic illustration)

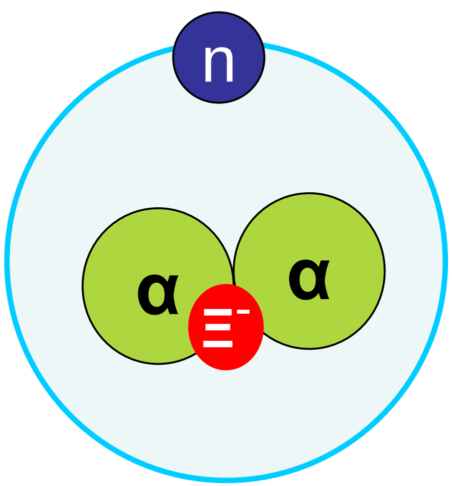
Core nucleus ^{6}He is known to be halo nucleus. Then, valence neutrons are located far away from α particle.



$^{7}_{\Xi^-}$H (T=3/2)

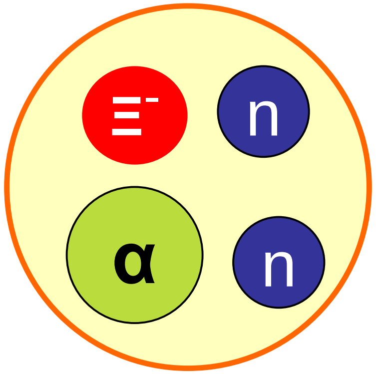
Valence neutrons (n) are located in p-orbit, whereas Ξ particle (Ξ-) is located in 0s-orbit.

Then, distance between Ξ and **n** is much larger than the interaction range of Ξ and **n**.

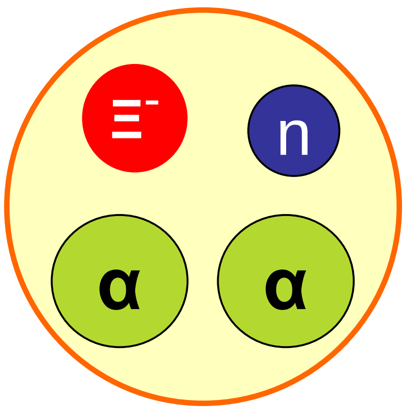


$^{10}_{\Xi^-}$Li (T=1)

Then, αΞ potential, in which only V_0 term works, plays a dominant role in the binding energies of these system.



${}^{7}_{\Xi^-}\mathrm{H}$ (T=3/2)



${}^{10}_{\Xi^-}\mathrm{Li}$ (T=1)

Before the experiments will be done,
we should predict whether these Ξ^--
hypernuclei will be observed as
bound states or not.

Namely, we calculate the binding energies
of these hypernuclei.

ΞN interaction

Only one experimental information about ΞN interaction

Y. Yamamoto, Gensikaku kenkyu 39, 23 (1996),

T. Fukuda *et al*. Phys. Rev. C58, 1306, (1998);

P.Khaustov *et al*., Phys. Rev. C61, 054603 (2000).

Well-depth of the potential between Ξ and ^{11}B: -14 MeV

Among all of the Nijmegen model,

ESC04 (Nijmegen soft core) and ND (Nijmegen Model D)

reproduce the experimental value.

OtherΞN interaction are repulsive or weak attractive.

We employ ESC04 and ND.

The properties of ESC04 and ND are quite different from each other.

Property of the spin- and isospin-components of ESC04 and ND

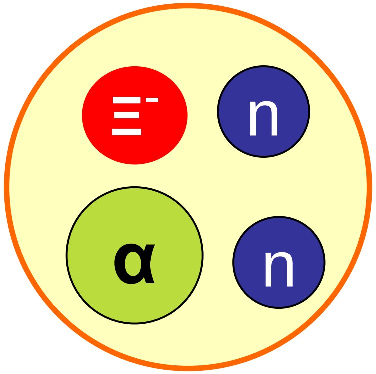
V(T,S)	ESC04	ND
T=0, S=1	strongly attractive (a bound state)	weakly attractive (all four components)
T=0, S=0	weakly repulsive	
T=1, S=1	weakly attractive	
T=1, S=0	weakly repulsive	

Although the spin- and isospin-components of these two models are very different between them (due to the different meson contributions),

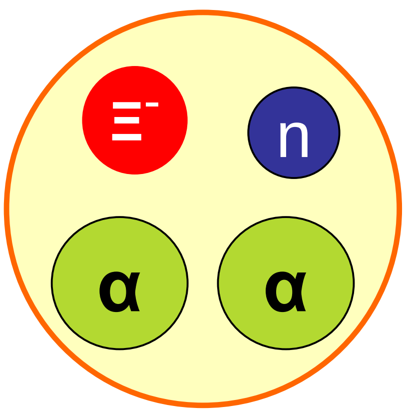
we find that the spin- and isospin-averaged property,

$$V_0 = [\ V(0,0) + 3V(0,1) + 3V(1,0) + 9V(1,1)\ ] / 16,$$

namely, strength of the V_0- term is similar to each other.



${}^{7}_{\Xi^-}$H (T=3/2)



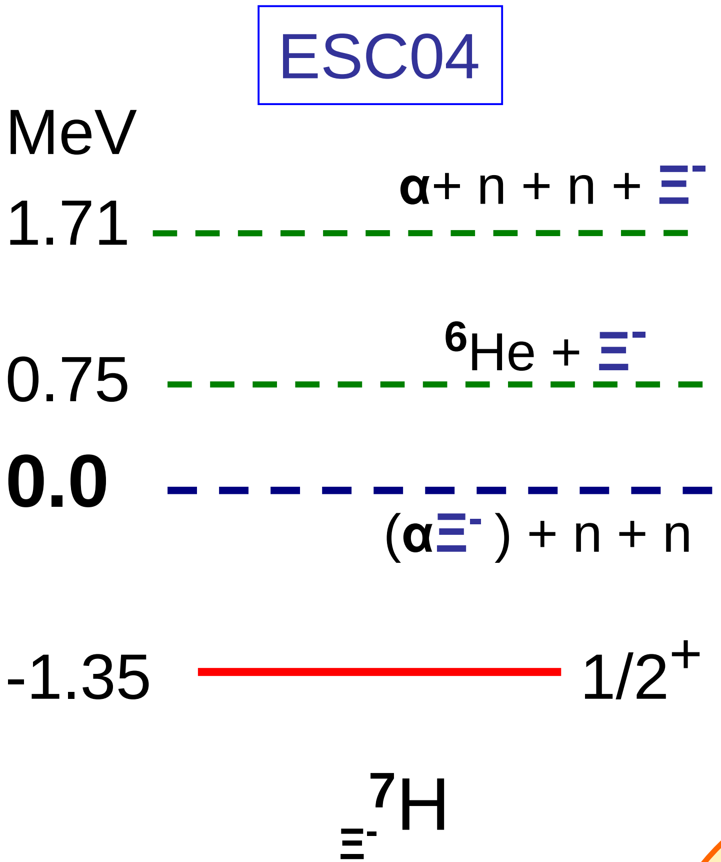
${}^{10}_{\Xi^-}$Li (T=1)

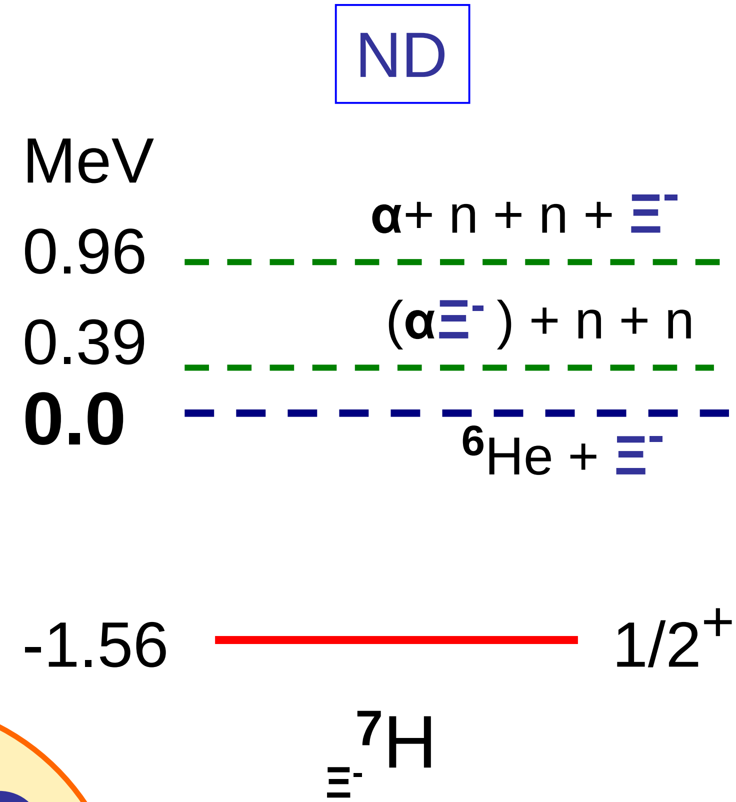
As mentioned before,
αΞ potential, in which only **V_0** term works,
plays a dominant role in the binding
energies of these system.

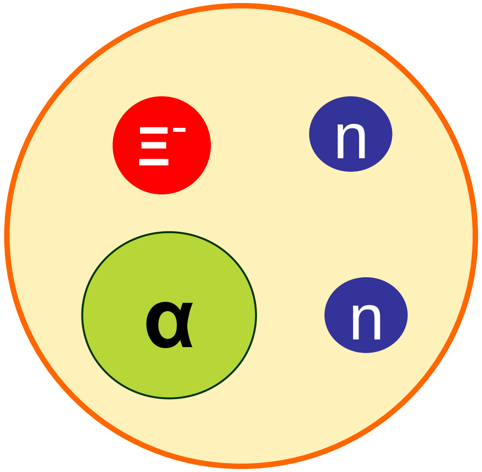
Therefore, interestingly,
we may expect to have similar binding
energies between ESC04 and ND,
although the spin- and isospin-components
are very different between the two.

4-body calculation of ${}^{7}_{\Xi^-}H$

E. Hiyama et al.,
PRC**78** (2008) 054316







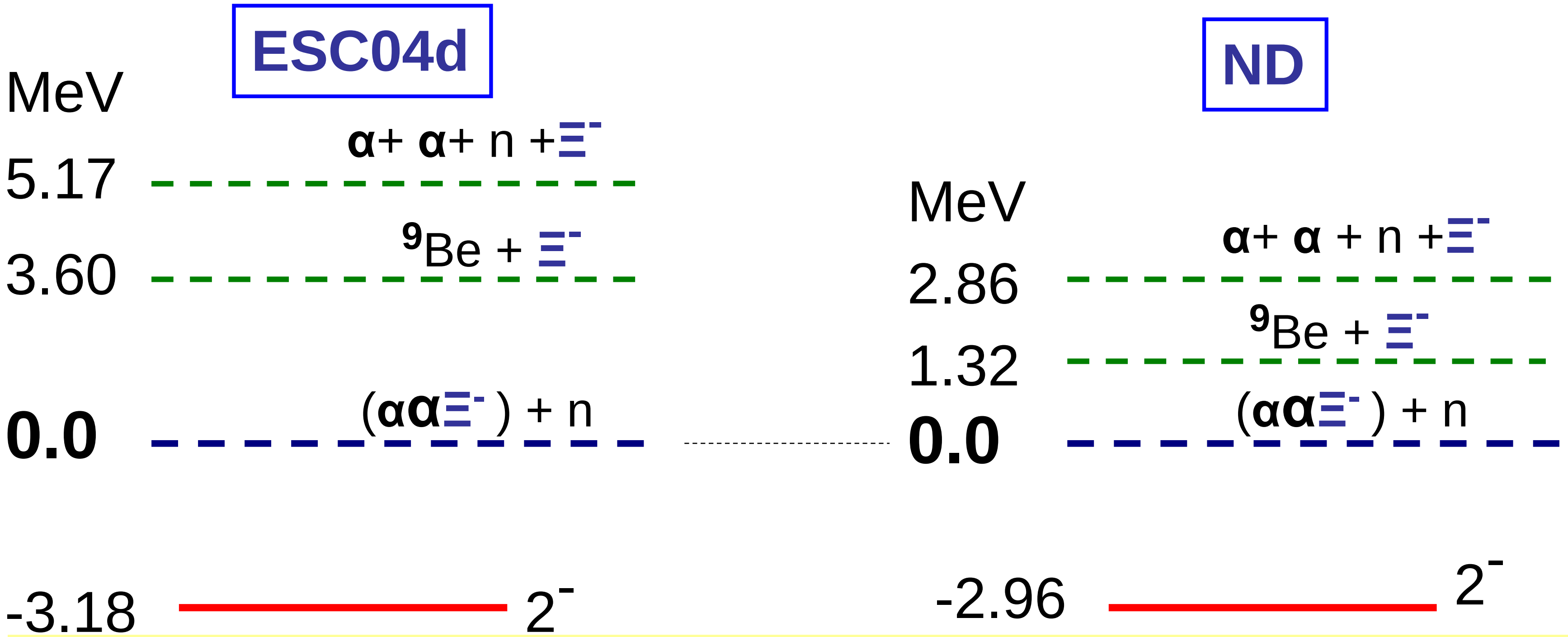
In experiments, we can expect a bound state.

Similar binding energies using ND and ESC04.

Independent on employed ΞN potential

4-body calculation of $^{10}_{\Xi^-}Li$

E. Hiyama et al., PRC**78** (2008) 054316

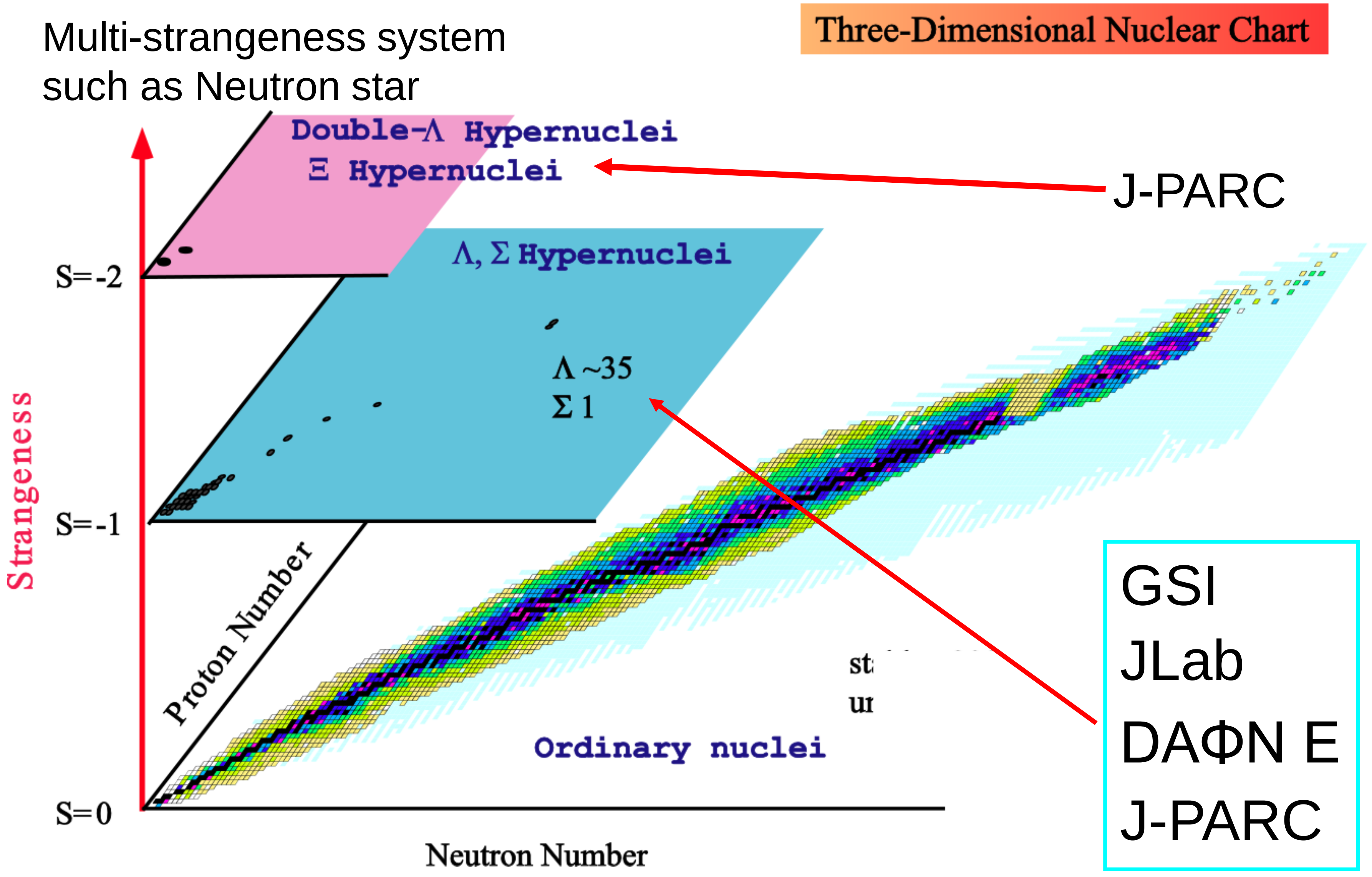


In this way, the binding energies of Ξ hypernuclei with A=7 and 10 are dominated by αΞ potential, namely, spin-, and iso-spin independent ΞN interaction (V_0).

Then, to get information about this part, we propose to perform the (K^-,K^+) experiment by using ^{7}Li and ^{10}B targets at J-PARC.

Concluding remark

Multi-strangeness system
such as Neutron star



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Thank you!