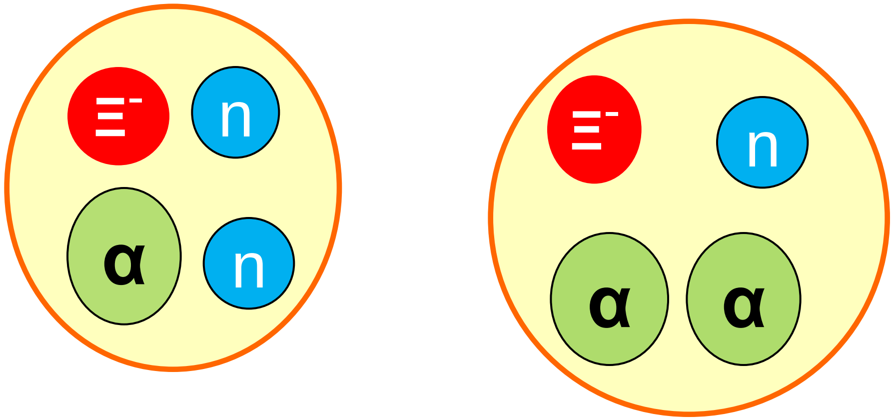
Study of
Ξ hypernuclei and ΞN interaction

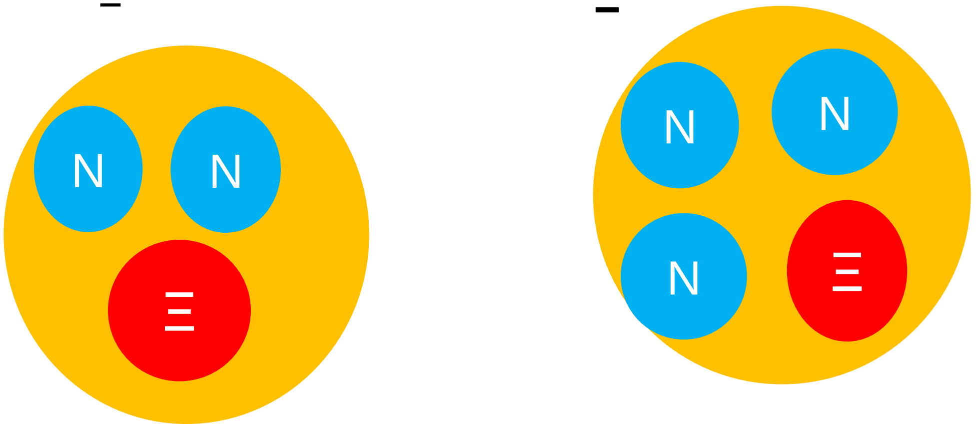
E. Hiyama (Tohoku Univ./RIKEN)

Outline

- Introduction
- double Λ Hypernuclei
- Ξ Hypernuclei



$^{7}_{\Xi^-}$H (T=3/2) $^{10}_{\Xi^-}$Li (T=1)



- conclusion

Major goals of hypernuclear physics

To understand baryon-baryon interactions

Fundamental and important for the study of nuclear physics

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, for the study of YN and YY interactions, the systematic investigation of the structure of light hypernuclei is one of the important way.

(it is planned to perform YN scattering data at J-PARC.)

Once YN and YY interactions are determined, we can predict interesting phenomena which cannot be imagined so far. In addition, we could study inner part of neutron stars which have been observed.

Strategy to determine YN and YY interactions from the studies of light hypernuclear structure

YN and YY interactions

based on meson theory: Nijmegen, Ehime, Julich・・

based on constituent quark model: Kyoto-Niigata,・・

① Use

③ Suggest to improve

using a few-body method

My role

Accurate calculation of hypernuclear structure

Few-body, cluster model, shell model, …..

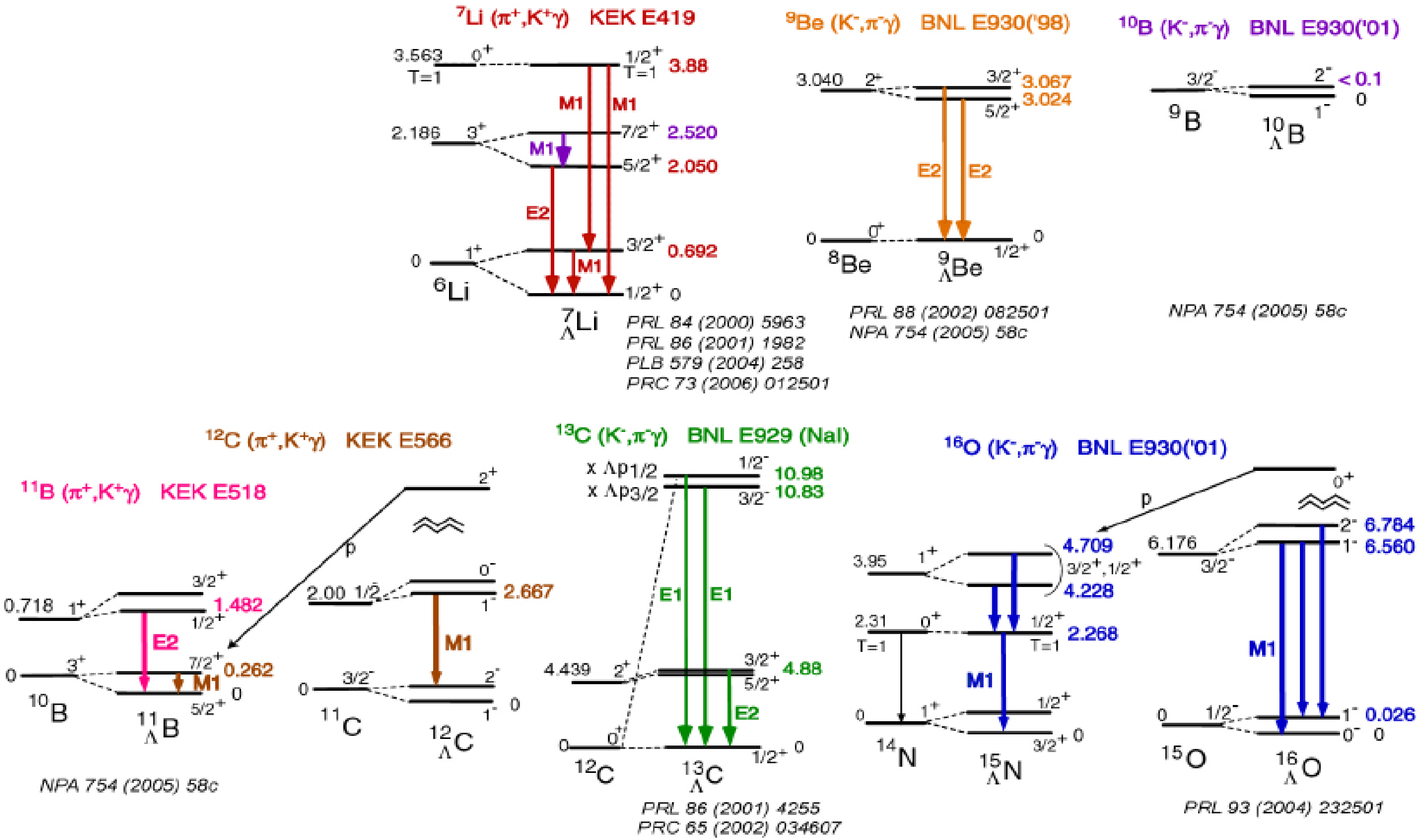
② Compare theoretical results with experimental data

X No direct information

Spectroscopy experiments

- High-resolution γ-ray spectroscopy experiment
  by Tamura and his collaborators
- Emulsion experiment
  by Nakazawa and his collaborators

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

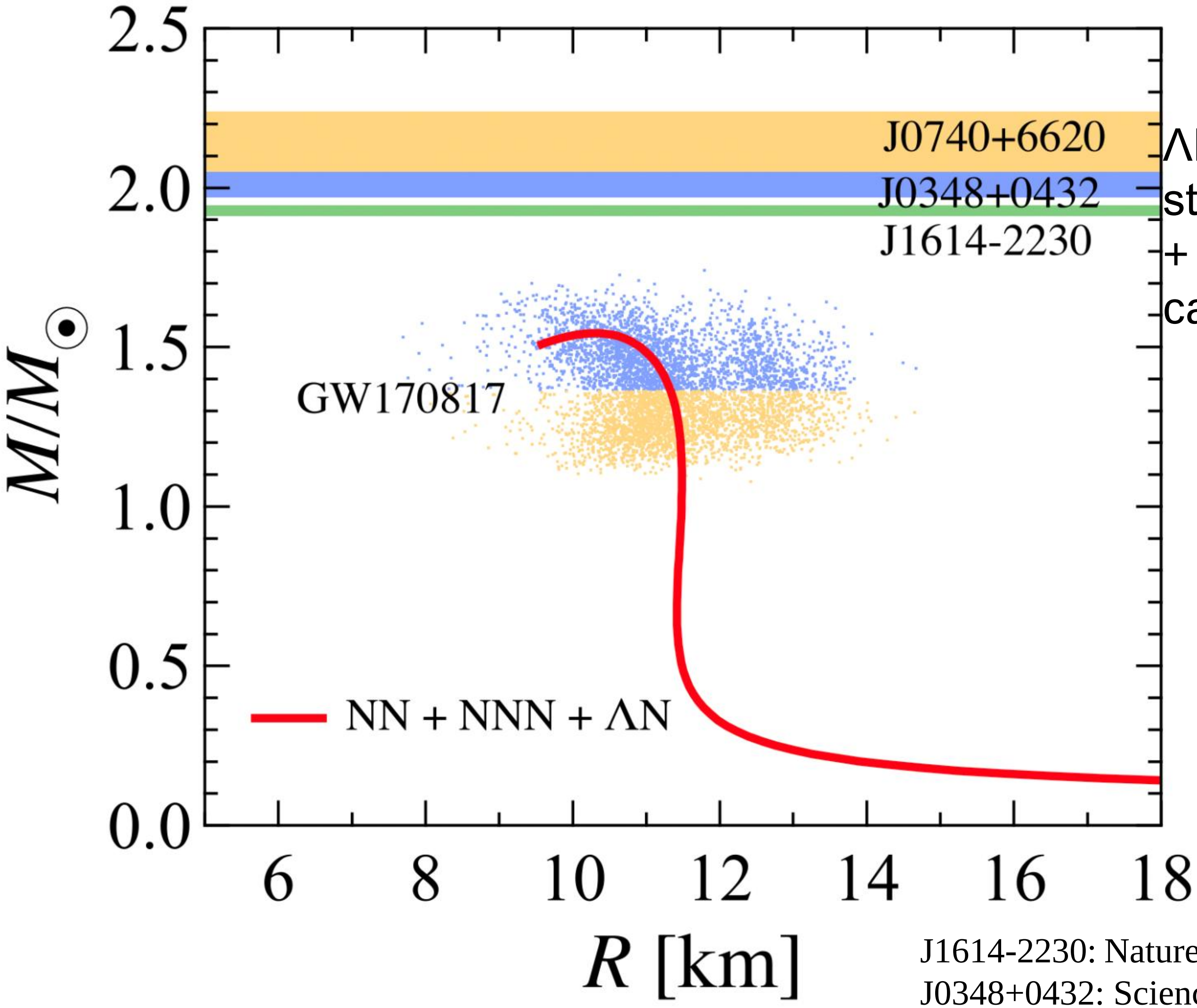


$$V_{\Lambda N} = V_0 + \boldsymbol{\sigma}_\Lambda \cdot \boldsymbol{\sigma}_N V_{\sigma\cdot\sigma} + \mathbf{L}\cdot(\mathbf{s}_\Lambda + \mathbf{s}_N)V_{\mathrm{SLS}} + \mathbf{L}\cdot(\mathbf{s}_\Lambda - \mathbf{s}_N)V_{\mathrm{ALS}} + S_{12}V_{\mathrm{tensor}} + \cdots$$

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

Mass-Radius Relation of Neutron Stars

2021



ΛN interaction updated by structure study of Λ hypernuclei + EoS by cluster variational calculation done by Togashi

Still, the maximum mass of neutron star is less than twice of solar mass.

J1614-2230: Nature 467 (2010) 1081, APJ 832 (2016) 167
J0348+0432: Science 340 (2013) 1233232
J0740+6620: Nat. Astron. (2019)
GW170817: PRL 121 (2018) 161101

Hyperon puzzle

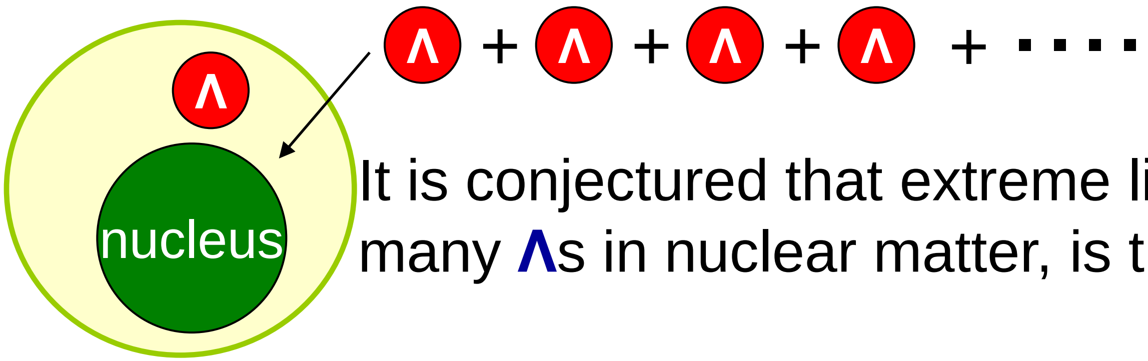
missing part of YN interaction: ΛN-ΣN coupling

S=-2 hypernuclei

and

YY interaction

What is the structure when one or more Λs are added to a nucleus?



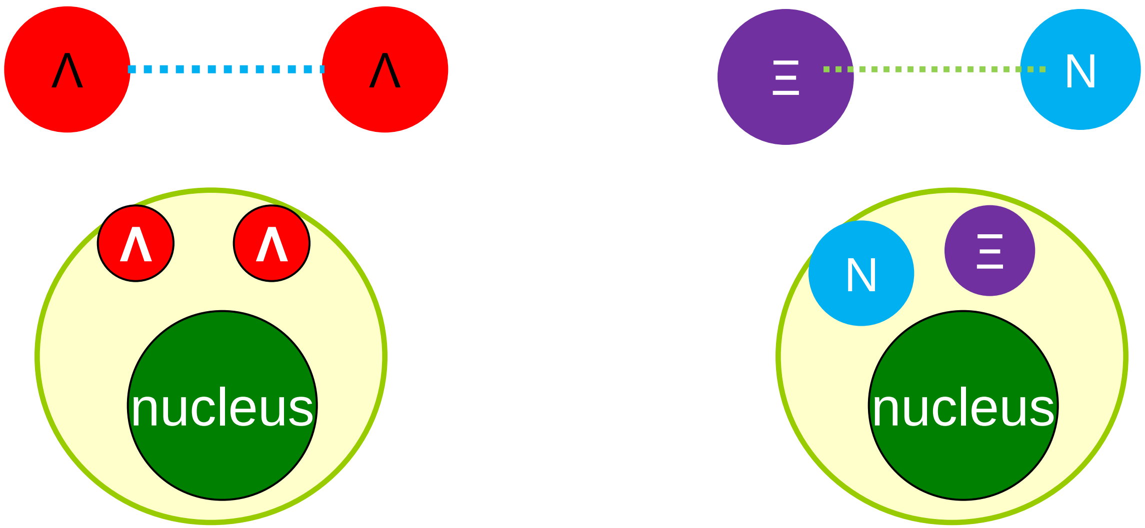
It is conjectured that extreme limit, which includes many Λs in nuclear matter, is the core of a neutron star.

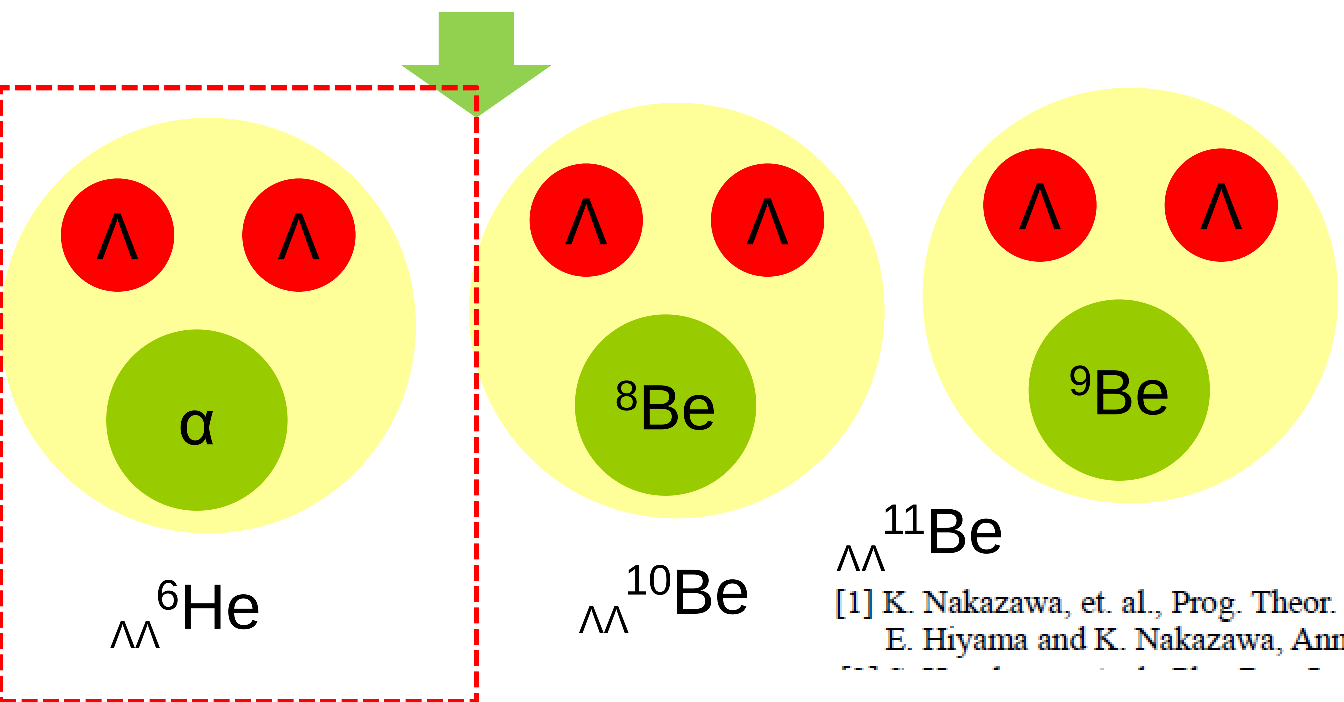
In this meaning, the sector of S=-2 nuclei , double Λ hypernuclei and Ξ hypernuclei is just the entrance to the multi-strangeness world.

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.

Next step: S=-2 sector



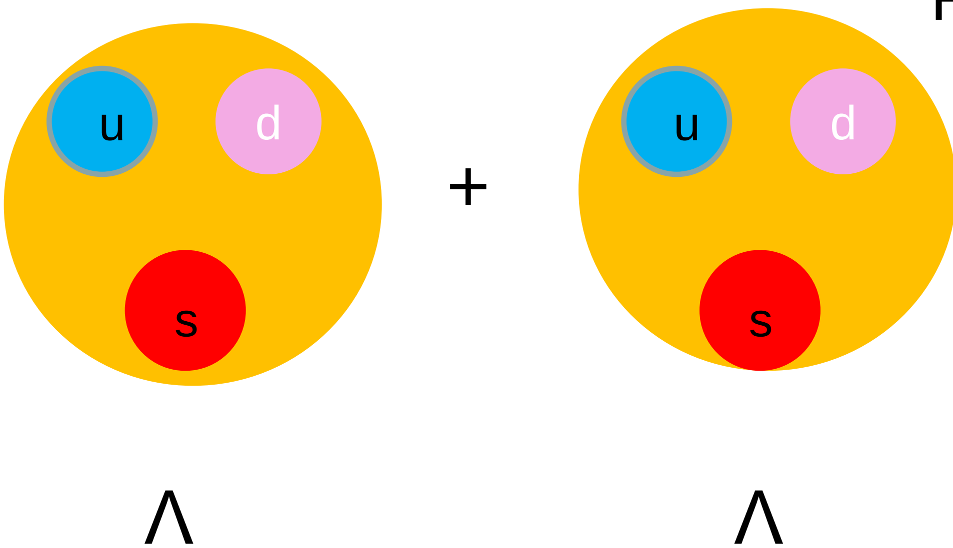


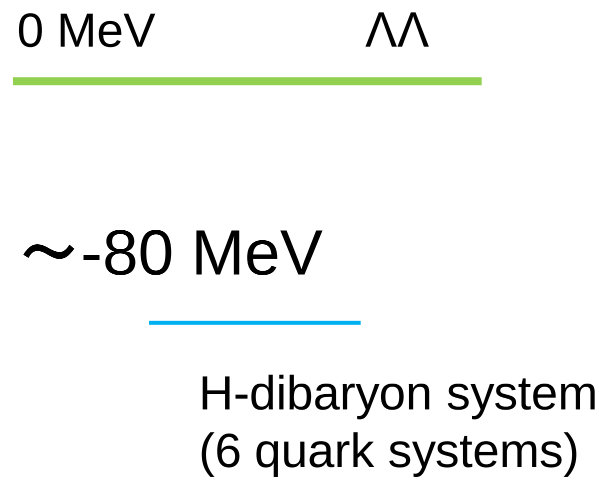
$^1S_0$ of ΛΛ interaction attractive

[1] K. Nakazawa, et. al., Prog. Theor. Exp. Phys. **2015**, 033D02 (2015),
E. Hiyama and K. Nakazawa, Ann. Rev. Nucl. Part. Sci. **68**, 131 (2018).

Study of ΛΛ interaction is interesting for the search of H-dibaryon system.

R. L. Jaffe, PRL38, 195 (1977)





After his prediction, many experimental efforts have been done to search such a system.

For instance,
H. Ejiri et al., PLB 228, (1989), 24, double weak decays

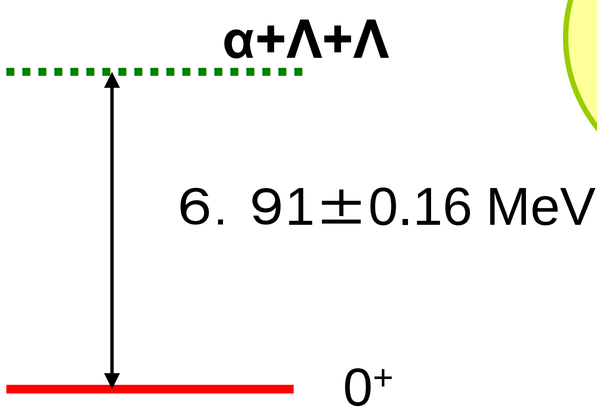
$$d \to H + \beta^+ + \nu,\ {}^{10}Be \to {}^{8}Be + H,\ {}^{72,70}Ge + H + \gamma,\ {}^{127}I \to {}^{125}I + H + \gamma \text{ and } {}^{127}I \to {}^{125}Te + H + \beta^+ + \nu$$

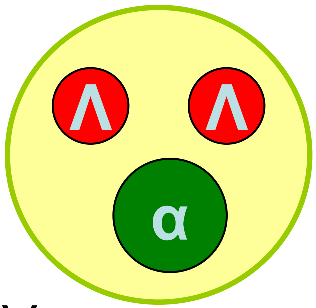
Also, it is important to know attraction of ΛΛ interaction.=>binding energy of double Λ hypernuclei

In 2001, the epoch-making data has been reported by the KEK-E373 experiment.

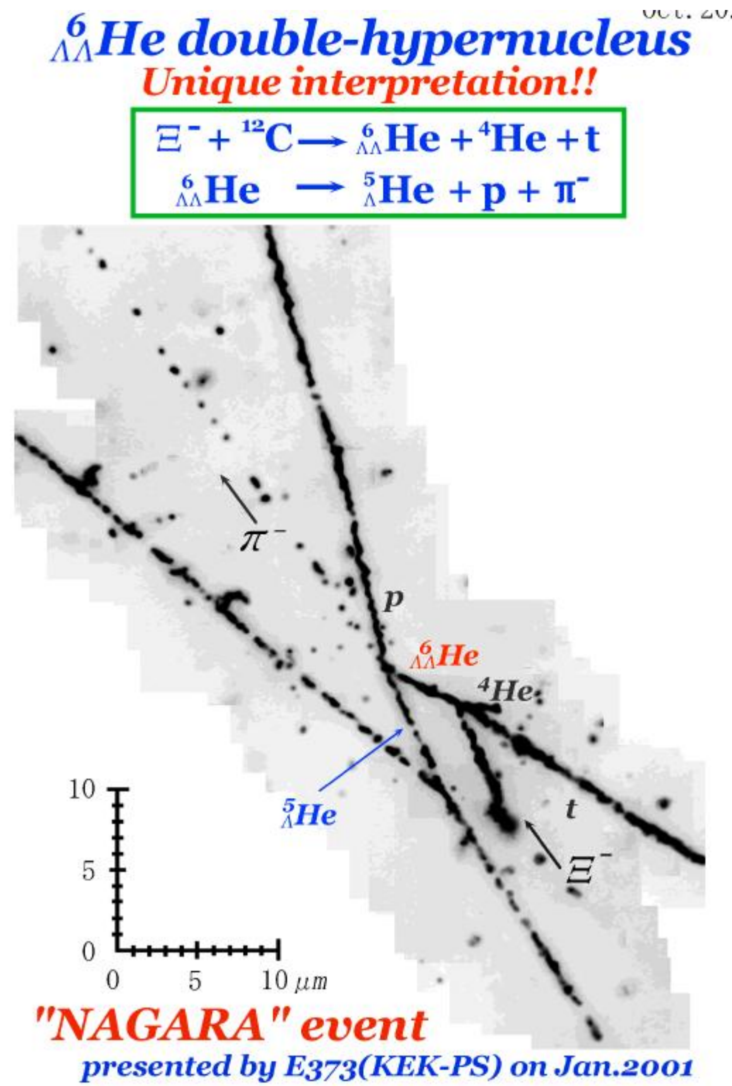
Observation of $^{6}_{\Lambda\Lambda}$He

Uniquely identified without ambiguity for the first time





$^{6}_{\Lambda\Lambda}$**He**



H. Takahashi *et al.*, PRL 87, 212502-1 (2001)

$^{6}_{\Lambda\Lambda}$**He**

Strategy of how to determine YY interaction from the study of light hypernuclear structure

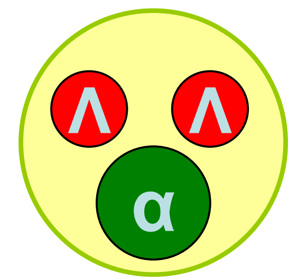
We understand that attraction of ΛΛ interaction is too weak to make H-dibaryon system bound.

YY interaction
Nijmegen model D

① **Use**

③ **Suggest reducing the strength of spin-independent force by half**

${}^{6}_{\Lambda\Lambda}\mathrm{He}$



Accurate structure calculation

② **compare between the theoretical result and the experimental data of the biding energy of ${}^{6}_{\Lambda\Lambda}\mathrm{He}$**

④ **prediction of new** double Λ hypernuclei

Spectroscopic experiments
Emulsion experiment (KEK-E373)
by Nakazawa and his collaborators

・E07 Approved proposal at J-PARC

"Systematic Study of double strangness systems at J-PARC"

by Nakazawa and his collaborators(done in 2018)

It is difficult to determine
- (1) spin-parity
- (2) whether the observed state is the ground state or an excited state

My theoretical contribution using few-body calculation

Emulsion experiment $\longleftrightarrow$ **comparison** **Theoretical calculation**

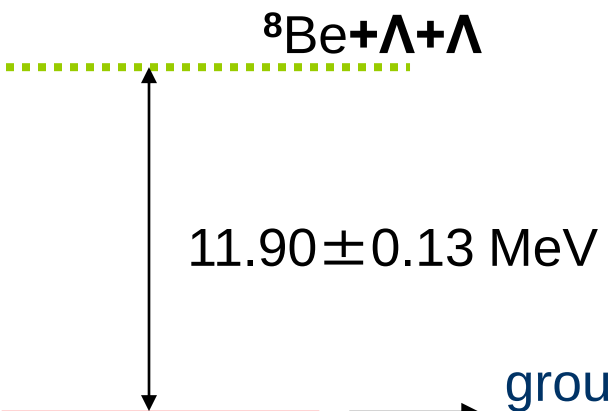
input: ΛΛ interaction to reproduce the observed binding energy of $_{\Lambda\Lambda}{}^{6}$He

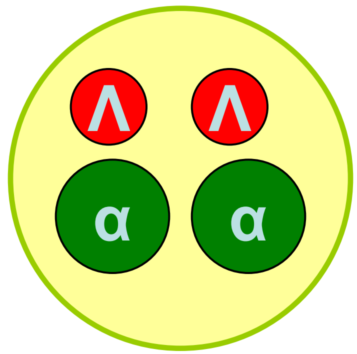
↓

the identification of the state

Successful example to determine spin-parity of double Λ hypernucleus --- Demachi-Yanagi event for $^{10}_{\Lambda\Lambda}\mathrm{Be}$

Observation of $^{10}_{\Lambda\Lambda}\mathrm{Be}$ --- KEK-E373 experiment

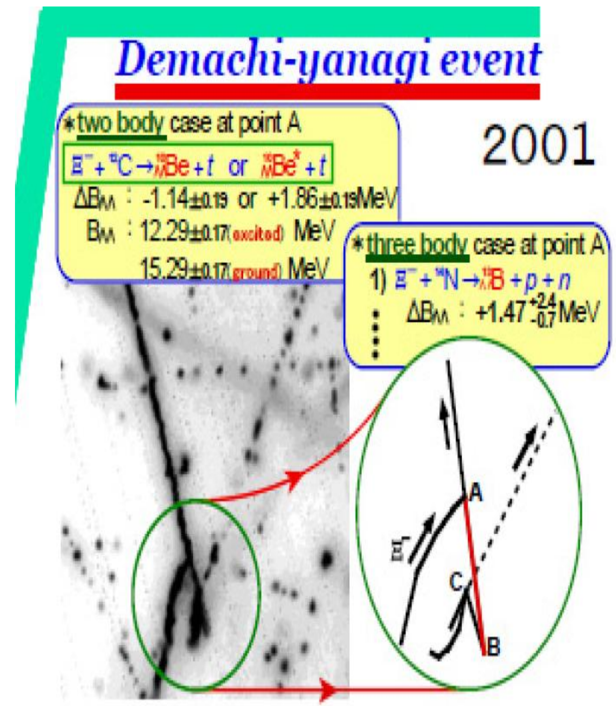




$^{10}_{\Lambda\Lambda}\mathrm{Be}$

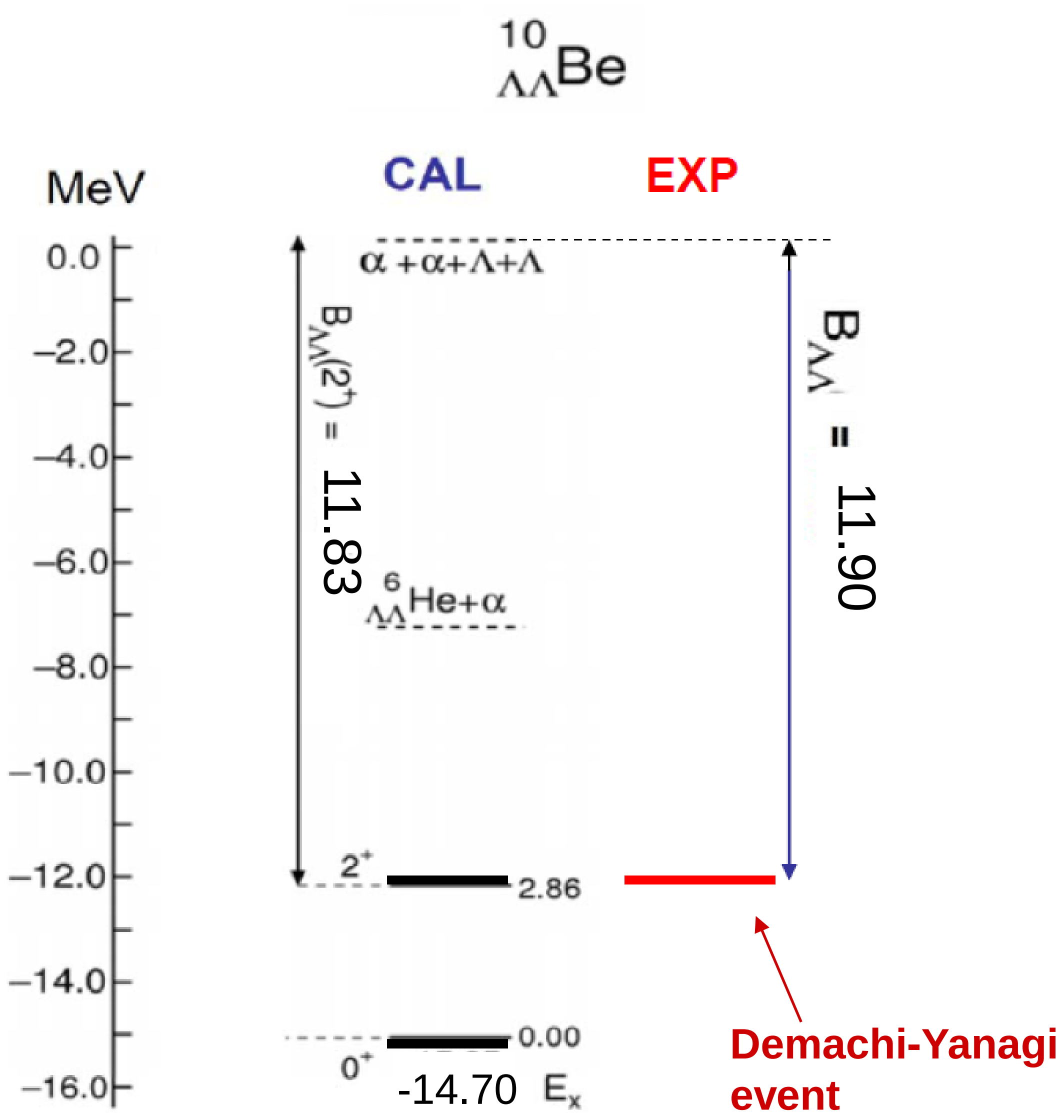
ground state ?
excited state ?

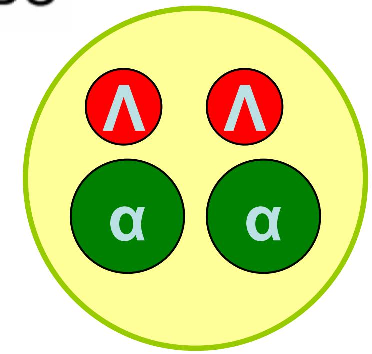
$^{10}_{\Lambda\Lambda}\mathrm{Be}$



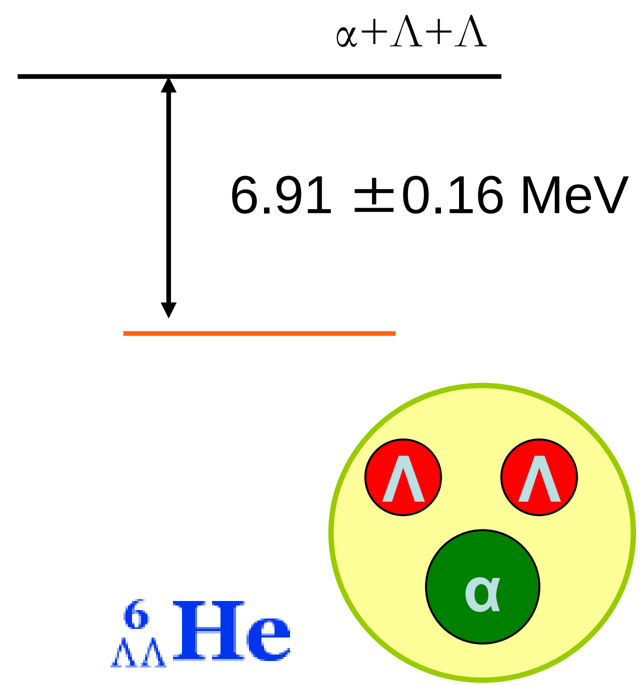
Demachi-Yanagi event

Successful interpretation of spin-parity of $^{10}_{\Lambda\Lambda}\mathrm{Be}$



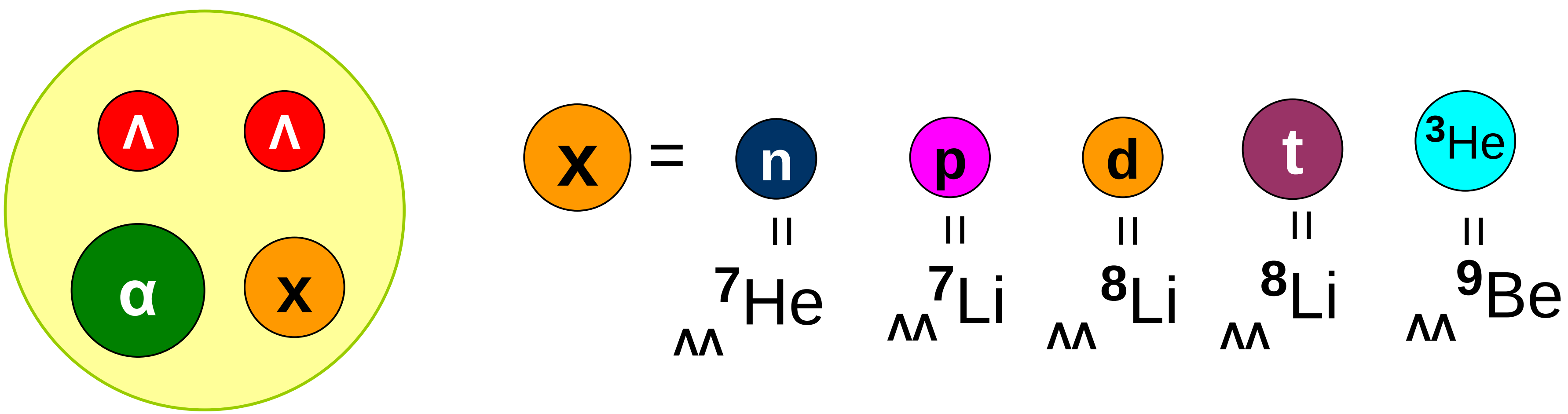


E. Hiyama, M. Kamimura,T.Motoba,
T. Yamada and Y. Yamamoto
Phys. Rev. 66 (2002) , 024007



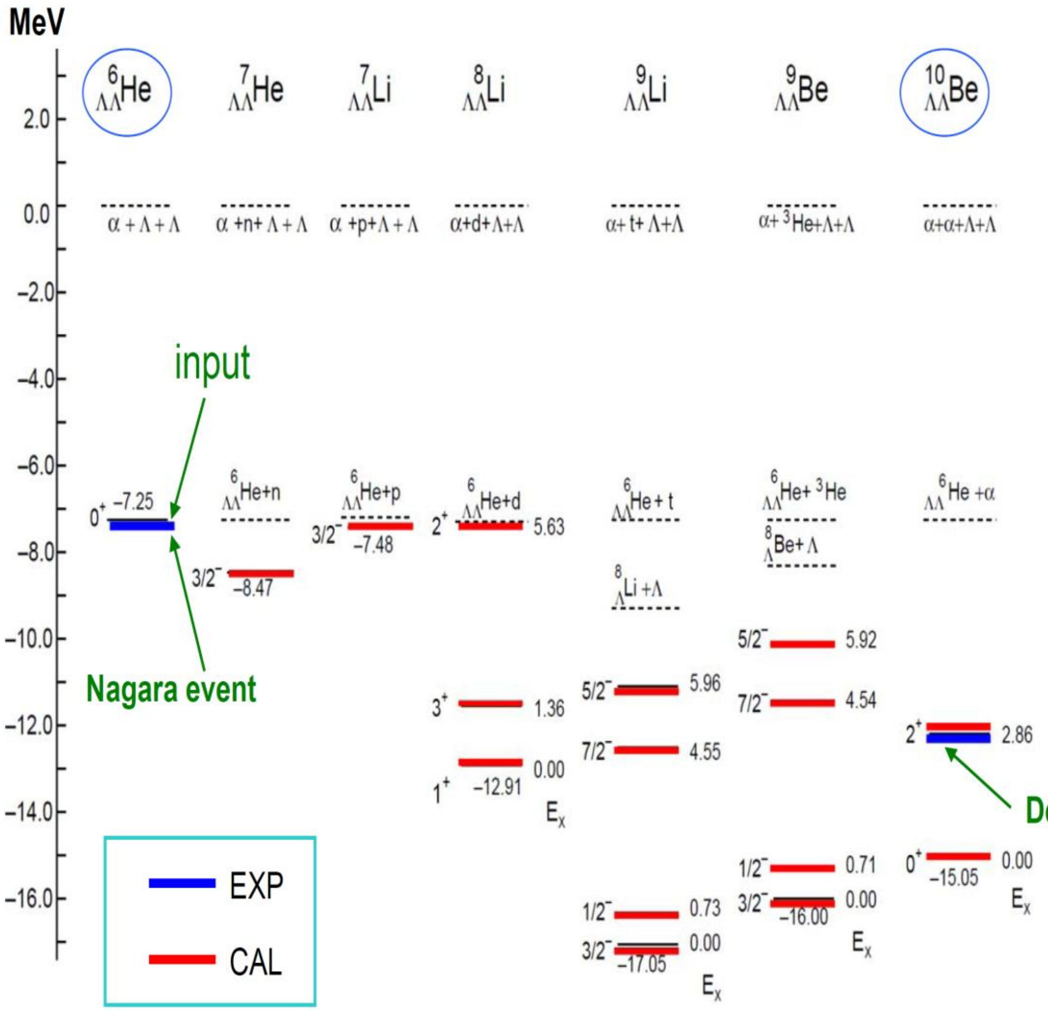
Hoping to observe new double **Λ** hypernuclei in future experiments, I predicted level structures of these double **Λ** hypernuclei within the framework of the α+x+**Λ**+**Λ** 4-body model.

E. Hiyama, M. Kamimura, T. Motoba, T.Yamada and Y. Yamamoto
Phys. Rev. C66, 024007 (2002)



Spectroscopy of ΛΛ-hypernuclei

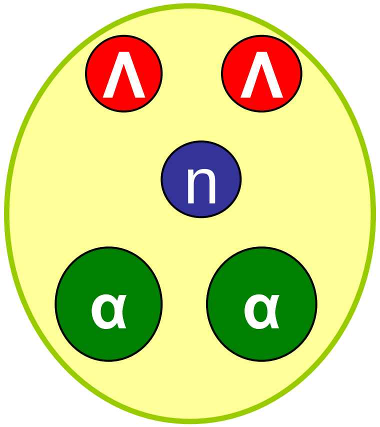
E. Hiyama, M. Kamimura,T.Motoba, T. Yamada and Y. Yamamoto
Phys. Rev. 66 (2002) , 024007



A≳11
ΛΛ hypernuclei

new data
(2009)
(2019)

I have been looking forward to having new data in this mass-number region.



${}^{11}_{\Lambda\Lambda}\mathrm{Be}$

$\boxed{\mathbf{B_{\Lambda\Lambda}} = 20.49 \pm 1.15 \text{ MeV}}$

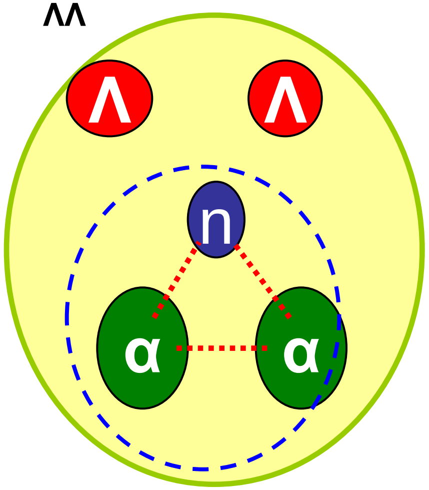
H. Ekawa et al.
PTEP 2019, 021D02
(2019)

In 2019 : $B_{\Lambda\Lambda} = 19.07 \pm 0.1$ MeV

Important issues:

2) Can we reproduce the observed biding energy of the event ?

$^{11}_{\Lambda\Lambda}$Be



Core nucleus, ^{9}Be is well described as

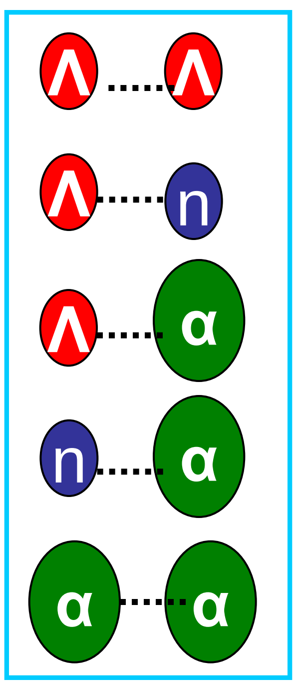
α +α + n three-cluster model.

Then, $^{11}_{\Lambda\Lambda}$Be is considered to be suited for studying with α +α + n +Λ +Λ 5-body model.

Difficult 5-body calculation:

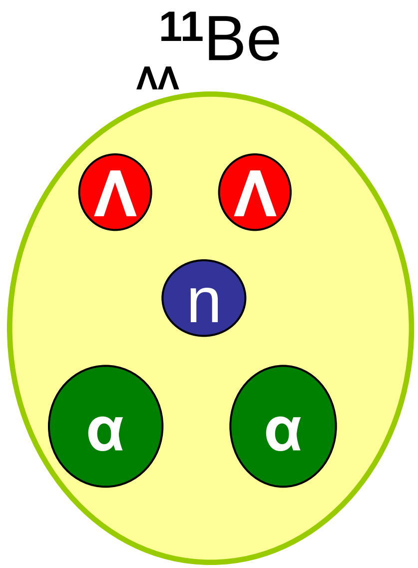
1) 3 kinds of particles (**α**, Λ, **n**)

2) 5 different kinds of interactions



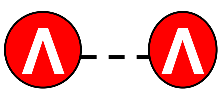
3) Pauli principle between **α** and **α**, and between **α** and **n**

But, I have succeeded in performing this calculation.

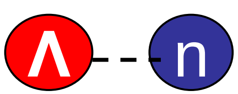


5-body calculation of $^{11}_{\Lambda\Lambda}$Be (Hida event)

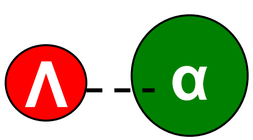
The core nucleus ^{9}Be has been extensively studied with the $\alpha + \alpha + n$ microscopic 3-body cluster model. ($V_{\alpha\alpha}V_{,n\alpha}$)



$V_{\Lambda\Lambda}$: the same one used in reproducing the observed binding energy of $^{6}_{\Lambda\Lambda}$He



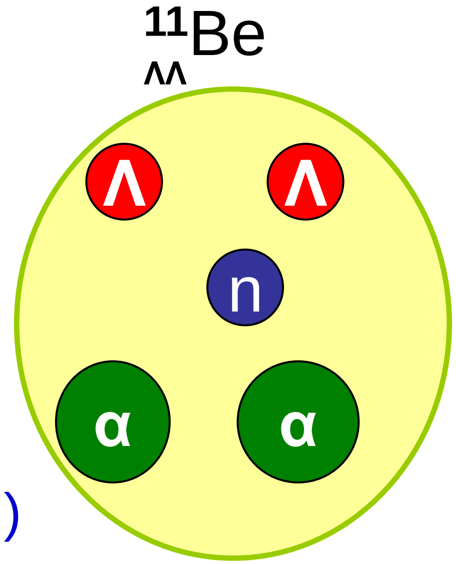
$V_{\Lambda n}$: Nijgemen soft core '97f



$V_{\Lambda\alpha}$: the same as the one used in $^{6}_{\Lambda\Lambda}$He (obtained by folding Nijgemen soft core '97f into the α-cluster density; local plus non-local potentials)

5-body calculation of $^{11}_{\Lambda\Lambda}$Be

$$(H - E)\,\Psi_{JM}({}^{11}_{\Lambda\Lambda}\mathrm{Be}) = 0$$



A variational method:

Gaussian Expansion Method (GEM)

(review paper) E. H., Y. Kino and M. Kamimura,
Prog. Part. Nucl. Phys., 51 (2003) 223.

expansion coefficient

$$\Psi_{JM}({}^{11}_{\Lambda\Lambda}\mathrm{Be}) = \sum_{c} \sum_{\boldsymbol{\beta}_5} A^{(c)}_{\boldsymbol{\beta}_5}\, \Phi^{(c)}_{JM,\boldsymbol{\beta}_5} \,(\text{5-body basis})$$

specifies many sets of Jacobi coordinates

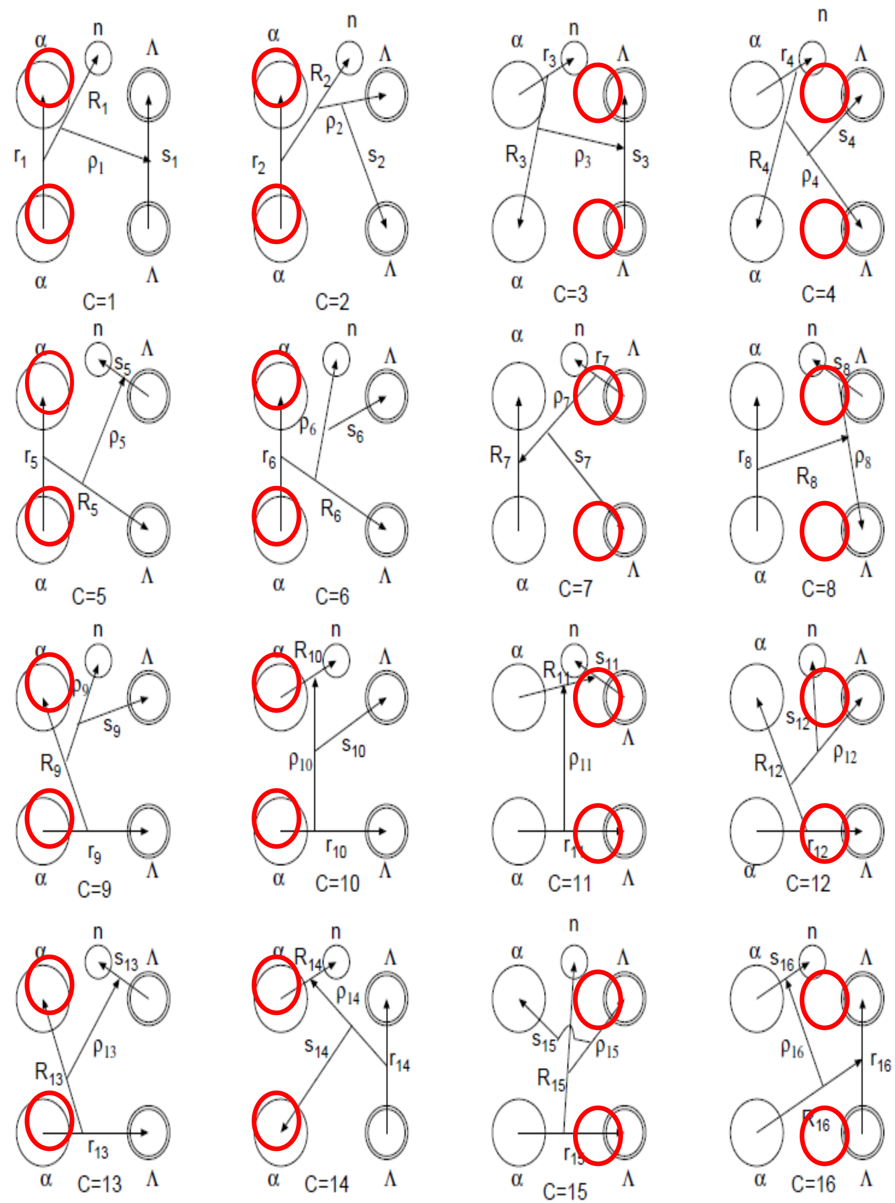
specifies 5-body basis functions of each Jacobi-coordinate set

Some of important Jacobi corrdinates of the α+ α+ n + Λ+ Λ system.

Two αparticles are symmetrized.

Two Λparticles are antisymmetrized.

120 sets of Jacobi coordinates are employed.



An example of 5-body basis function:

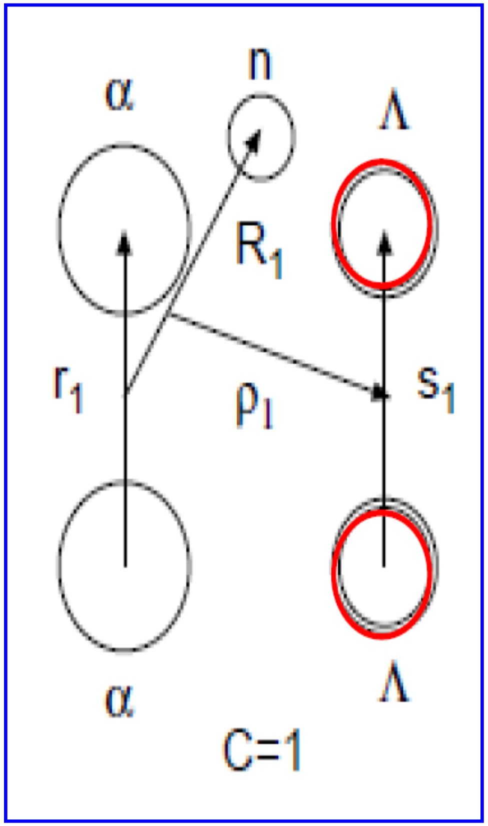
$$\Psi^{(c)}_{JM,\boldsymbol{\beta}_5}(\text{5-body basis}) = \Big[\overbrace{\big[\big[[\phi^{(c)}_{nl}(\mathbf{r}_c)\,\psi^{(c)}_{NL}(\mathbf{R}_c)]_I\,\varphi^{(c)}_{n'l'}(\boldsymbol{\rho}_c)\big]_K\,\Phi^{(c)}_{N'L'}(\mathbf{S}_c)\big]_L}^{\text{5-body spatial function}} \times \underbrace{\big[[\chi_{\frac{1}{2}}(\Lambda)\chi_{\frac{1}{2}}(\Lambda)]_\Sigma\,\chi_{\frac{1}{2}}(n)\big]_S}_{\text{spin function}}\Big]_{JM}$$

$$\begin{cases} c=1 & \text{(a Jacobi coordinate set)} \\ \boldsymbol{\beta}_5 = \{\underbrace{n\,N\,n'\,N'}, \underbrace{l\,L\,l'\,L', I\,K\,L}, \overbrace{\Sigma S}^{\text{spin}}\} \end{cases}$$

specify radial dependence

(shown below)

specify angular momenta



Form of each basis function

5-body spatial function

$$\overbrace{\Big[\,\Big[\,[\underline{\phi_{nl}^{(c)}(\mathbf{r}_c)}\,\psi_{NL}^{(c)}(\mathbf{R}_c)]_I\,\varphi_{n'l'}^{(c)}(\boldsymbol{\rho}_c)\Big]_K\,\Phi_{N'L'}^{(c)}(\mathbf{S}_c)\Big]_L}^{\text{5-body spatial function}}$$

Gaussian for radial part : $\phi_{nlm}(\mathbf{r}) = r^l\, e^{-(r/r_n)^2} Y_{lm}(\widehat{\mathbf{r}})$

geometric progression
for Gaussian ranges : $r_n = r_1 a^{n-1} \qquad (n = 1 - n_{\max})$

Similarly for the
other basis : $\psi_{NLM}^{(c)}(\mathbf{R}_c) \quad \varphi_{n'l'm'}^{(c)}(\boldsymbol{\rho}_c) \quad \Phi_{N'L'M'}^{(c)}(\mathbf{S}_c)$

Use of this type gaussian basis is known to be very suitable
for describing simultaneously both the short-range correlations and
long-range tail behaviour of few-body systems;

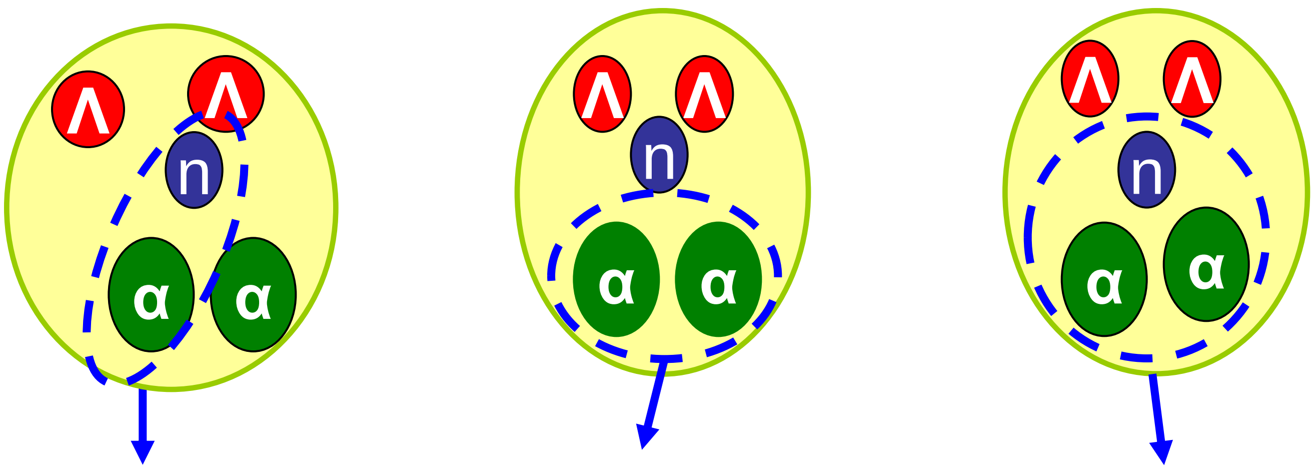
This is precisely
shown in $\longrightarrow$

Gaussian Expansion Method (GEM)
(review paper) E. H., Y. Kino and M. Kamimura,
Prog. Part. Nucl. Phys., 51
(2003) 223.

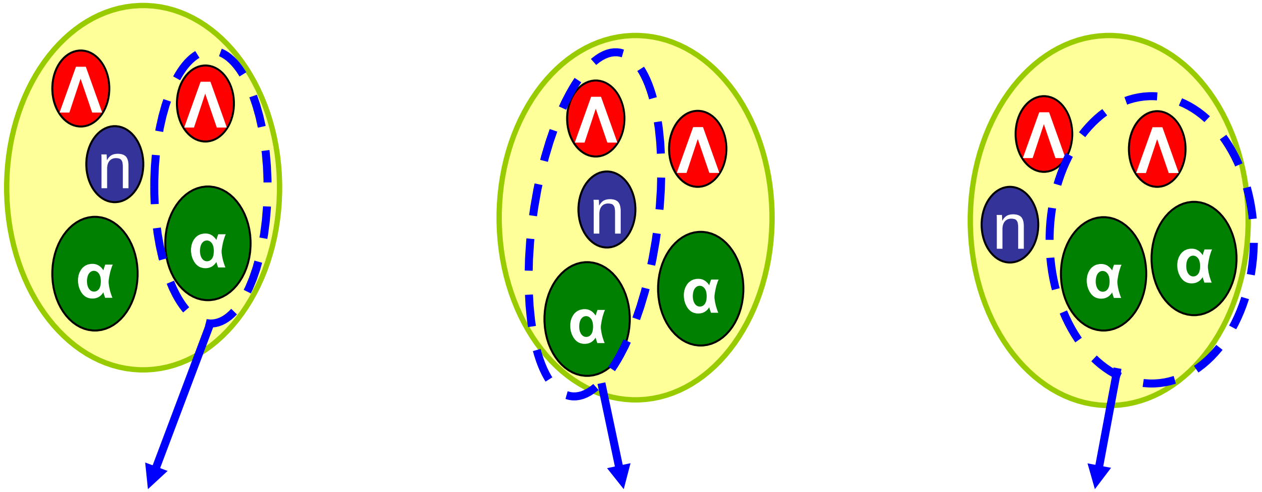
Before doing full 5-body calculation,
it is important and necessary to reproduce the observed binding energies of all the sets of subsystems in $^{11}_{\Lambda\Lambda}\mathrm{Be}$.

In our calculation, this was successfully done using the

same interactions for the following 9 subsystems:



$^{5}\mathrm{He}\ (3/2^-)$	$^{8}\mathrm{Be}\ (0^+)$	$^{9}\mathrm{Be}\ (3/2^-)$
CAL : +0.80 MeV	CAL : +0.09 MeV	CAL : -1.57 MeV
EXP : +0.80 MeV	EXP : +0.09 MeV	EXP : -1.57 MeV

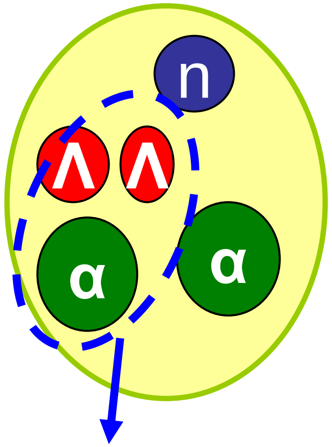


$^{5}_{\Lambda}\mathrm{He}\ (1/2^{-})$	$^{6}_{\Lambda}\mathrm{He}\ (1^{-})$	$^{9}_{\Lambda}\mathrm{Be}\ (1/2^{+})$
CAL : -0.32 MeV	CAL : -3.29 MeV	CAL : -6.64 MeV
EXP : -0.32 MeV	EXP : -3.29 MeV	EXP : -6.62 MeV

(The energy is measured from the full-breakup threshold

of each subsystem)

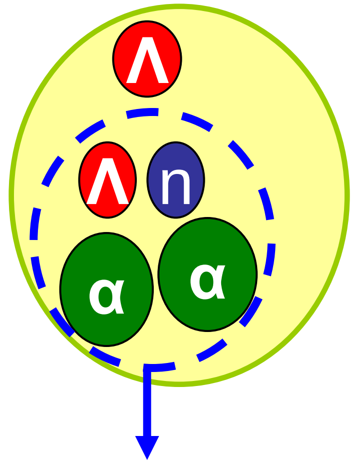
← adjusted | predicted →



$^{6}_{\Lambda\Lambda}\mathrm{He}\ (0^{+})$

CAL (0^{+}): -6.93 MeV

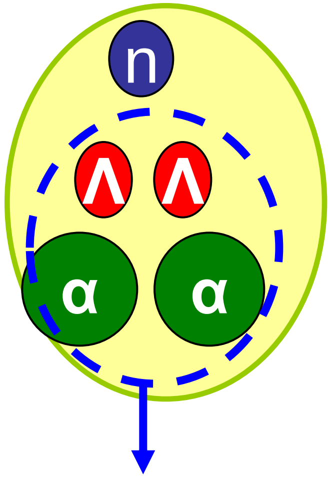
EXP (0^{+}): -6.93 MeV



$^{10}_{\Lambda}\mathrm{Be}\ (1^{-})$

CAL : -10.64 MeV

EXP : -10.64 MeV



$^{10}_{\Lambda\Lambda}\mathrm{Be}\ (0^{+}, 2^{+})$

CAL (2^{+}): -10.96 MeV

EXP (2^{+}): -10.98 MeV

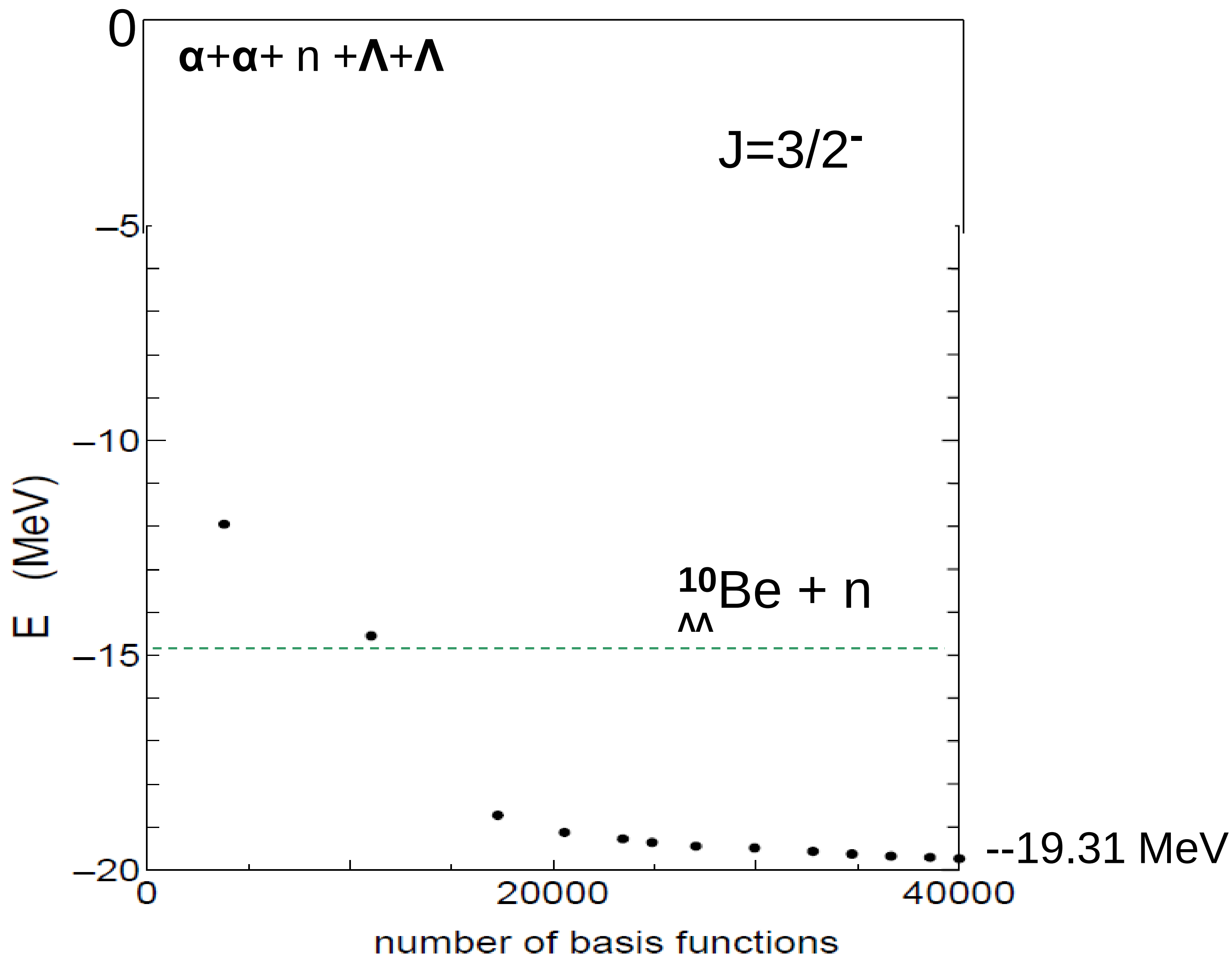
CAL (0^{+}): -14.74 MeV

EXP (0^{+}): -14.69 MeV

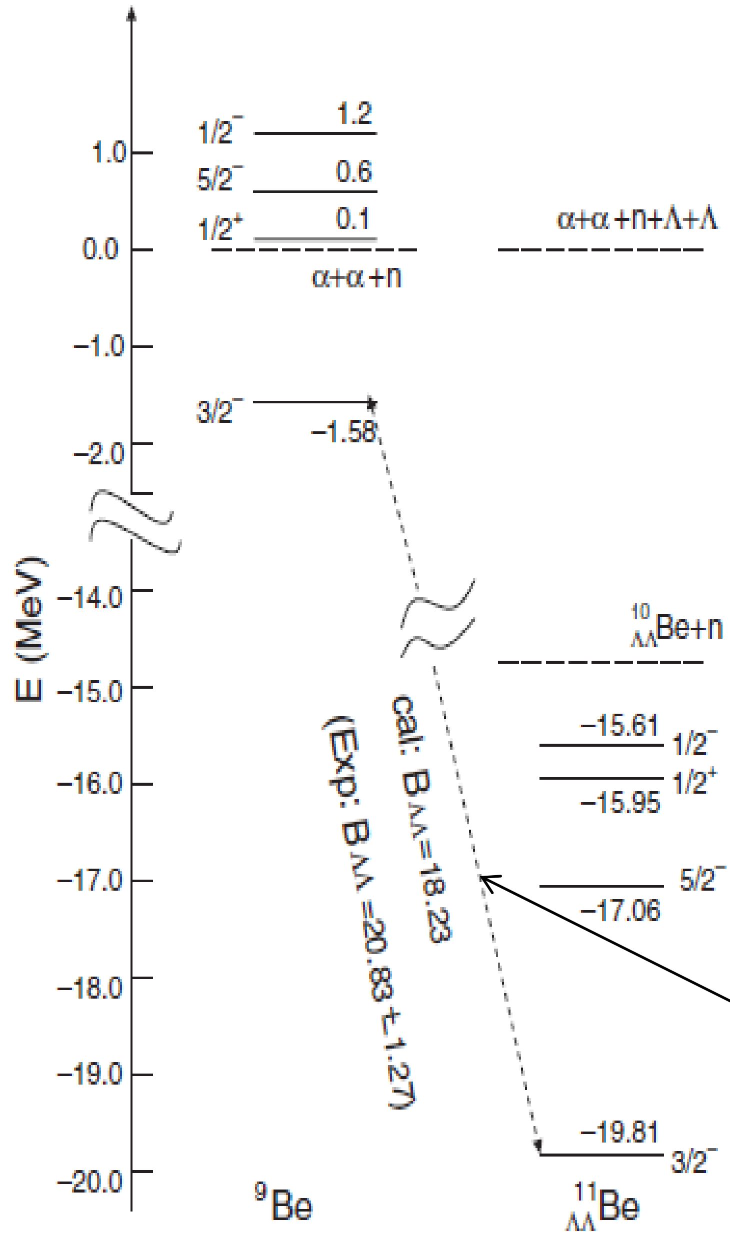
All the potential parameters have been adjusted in the 2- and 3-body subsystems.

Therefore, energies of these 4-body susbsystems and the 5-body system $^{11}_{\Lambda\Lambda}\mathrm{Be}$ are predicted with no adjustable pameters.

Convergence of the ground-state energy of the α+α+ n +Λ+Λ 5-body system ($^{11}_{\Lambda\Lambda}$Be)



$^{11}_{\Lambda\Lambda}$Be

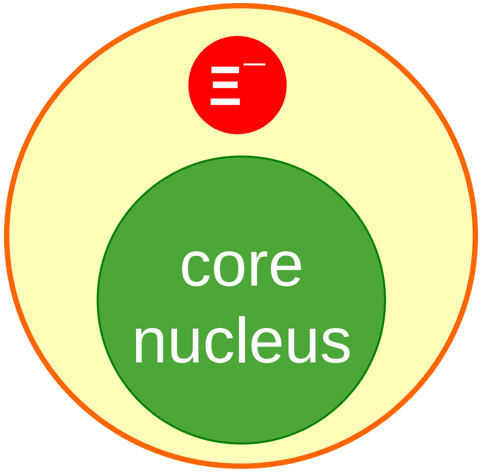


New data:

19.07 ± 0.11 MeV

H. Ekawa et al.
PTEP 2019, 021D02
(2019)

Ξ hypernuclei



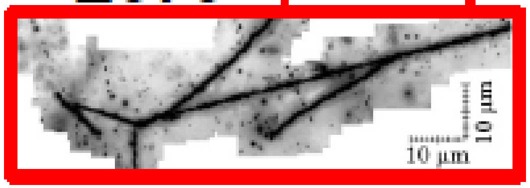
For the study of ΞN interaction, it is important to study the structure of Ξ hypernuclei.

However, so far there was no observed Ξ hypernucleus. Therefore, we do not know that ΞN interaction is attractive or repulsive.

If we observe Ξ hypernuclei as bound states, we understand ΞN interaction should be attractive. Thus, we have been searching bound Ξ hypernclei experimentally.

The first measurement of bound Ξ hypernucleus, ^{14}N-Ξ.

E373 KISO



^{14}N-Ξ-

0 MeV

-1.03 ± 0.18 MeV
or
3.87 ± 0.21 MeV

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

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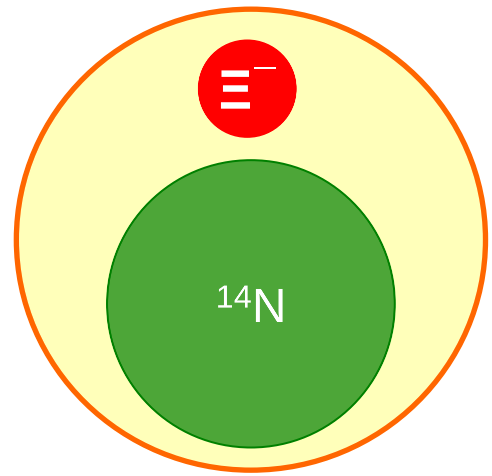
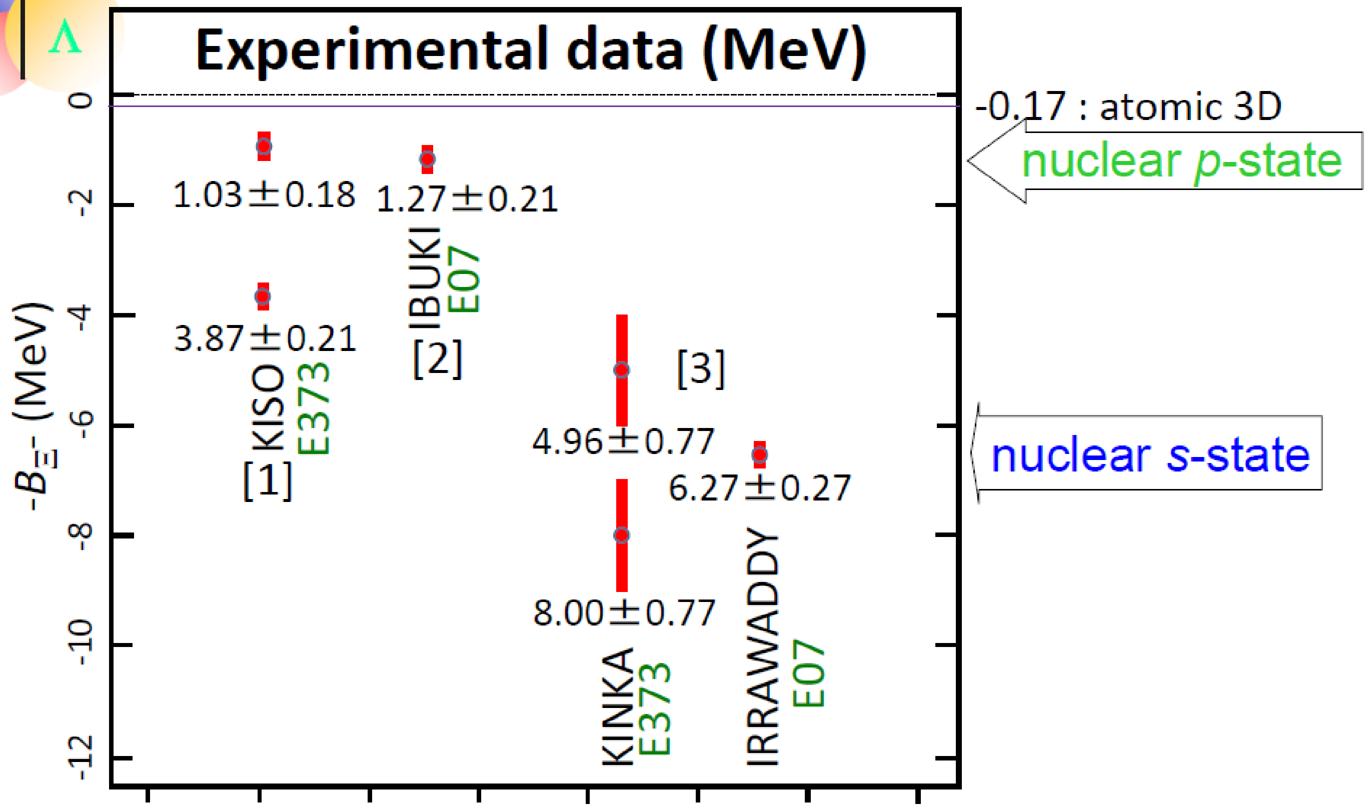


We understood Ξ-nuclear potential should be attractive.

Level scheme of Ξ hypernucleus ($^{15}_{\Xi}C$ [Ξ^--^{14}N])

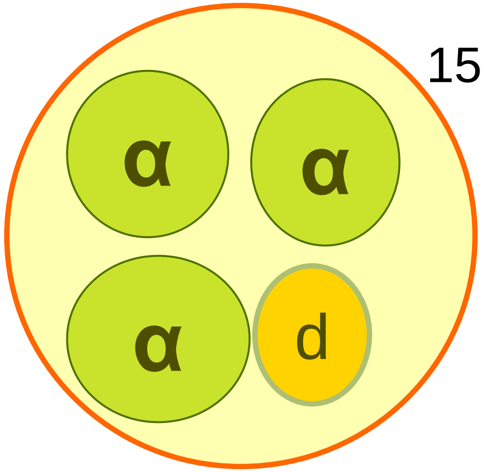


[1] K. Nakazawa, et. al., Prog. Theor. Exp. Phys. **2015**, 033D02 (2015),
E. Hiyama and K. Nakazawa, Ann. Rev. Nucl. Part. Sci. **68**, 131 (2018).
[2] S. Hayakawa, et. al., Phy. Rev. Lett., **126**, 062501 (2021).
[3] M. Yoshimoto, et. al., Prog. Theor. Exp. Phys. **2021**, 073D02 (2021).

Slide by Nakazawa

After observation of Kiso event, they observed several events of ^{14}N-Ξ hypernucleus.
Some are observed as excited state and some are observed as ground state.

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



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

In this way, we are finding to have bound states in these systems and then we shall get information that $V_{\Xi N}$ itself is attractive.

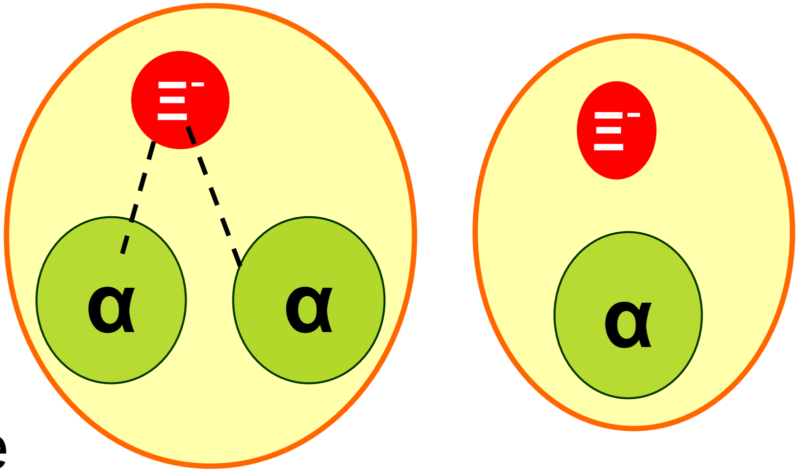
All of the terms contribute to binding energy of $^{15}{}_{\Xi}C$ (^{14}N is not spin-, isospin- saturated).

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

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

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

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



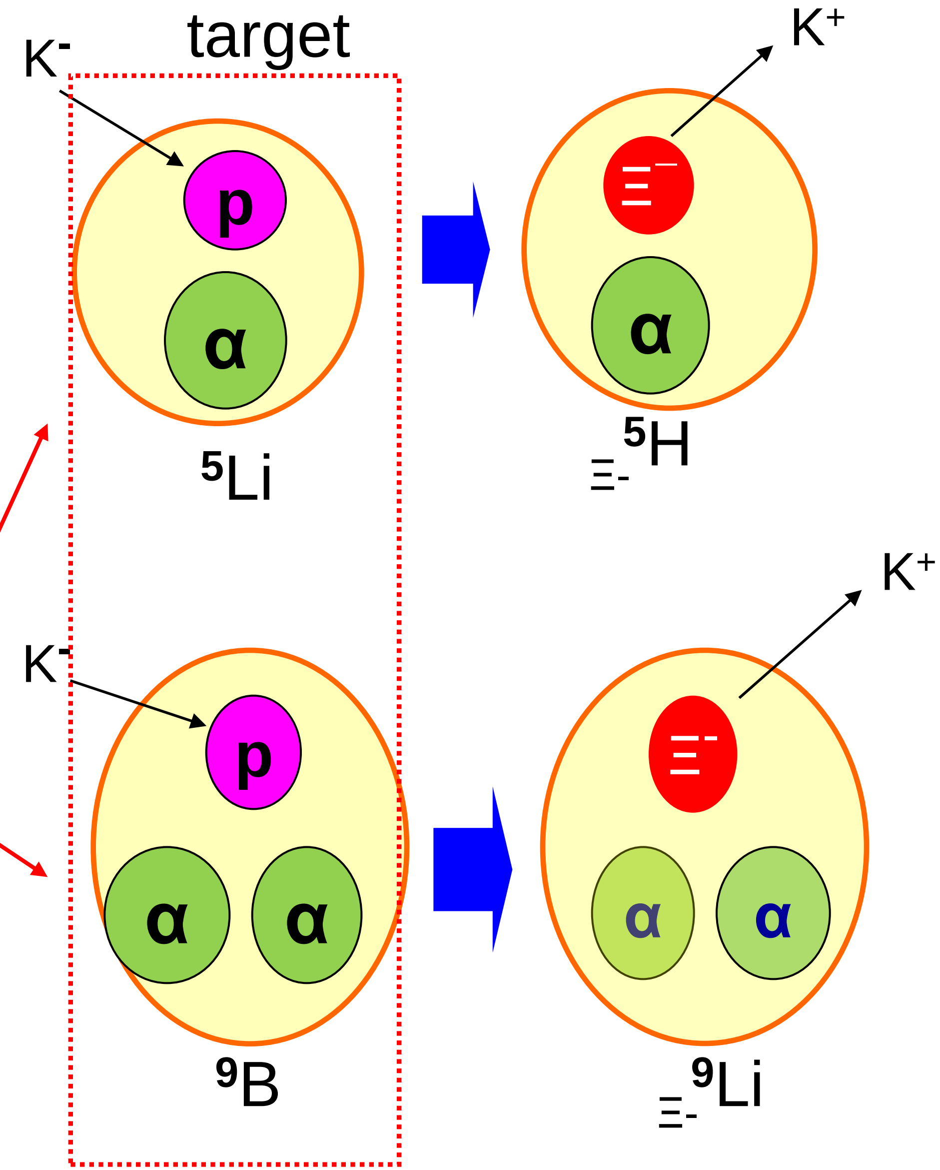
problem : there is NO target to produce them by the (K^-, K^+) experiment .

Because, ･･･

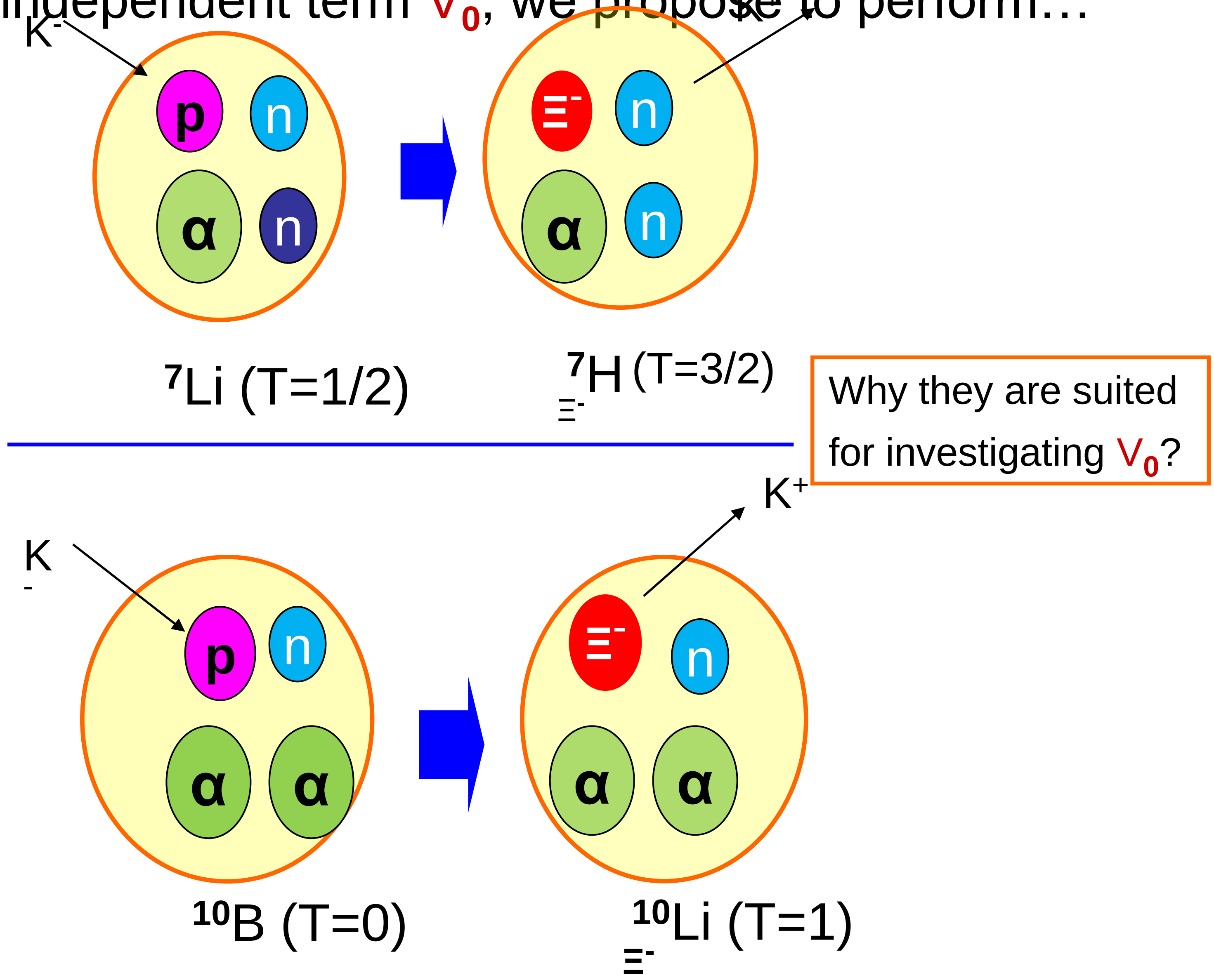
To produce **αΞ⁻** and **ααΞ⁻** systems by (K^-, K^+) reaction,

These systems are unbound.

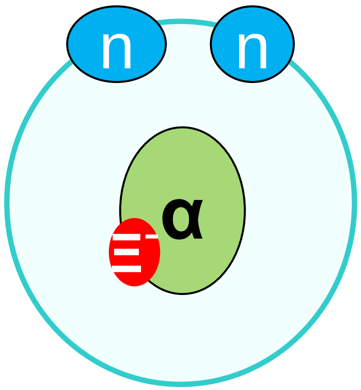
Then, we cannot use them as targets.



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



(more realistic illustration)

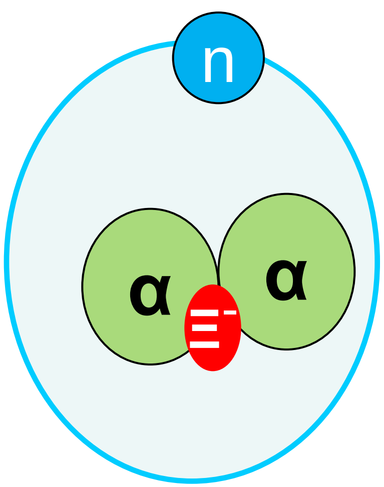


${}^{7}_{\Xi^-}\mathrm{H}$ (T=3/2)

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

Valence neutrons n are located in p-orbit, whereas Ξparticle Ξ^- is located in 0s-orbit.

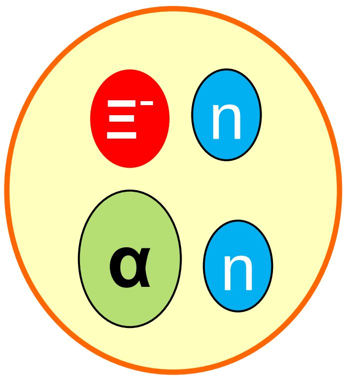
Then, distance between Ξ and **n** is much larger than the interaction range of Ξ and **n**.



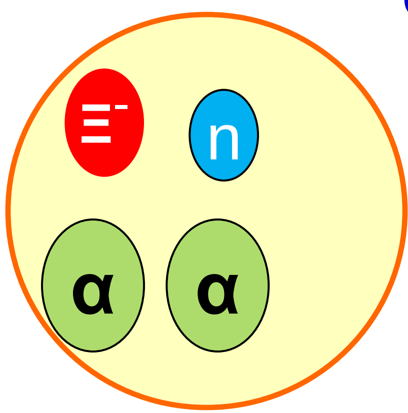
${}^{10}_{\Xi^-}\mathrm{Li}$ (T=1)

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

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



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



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

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.

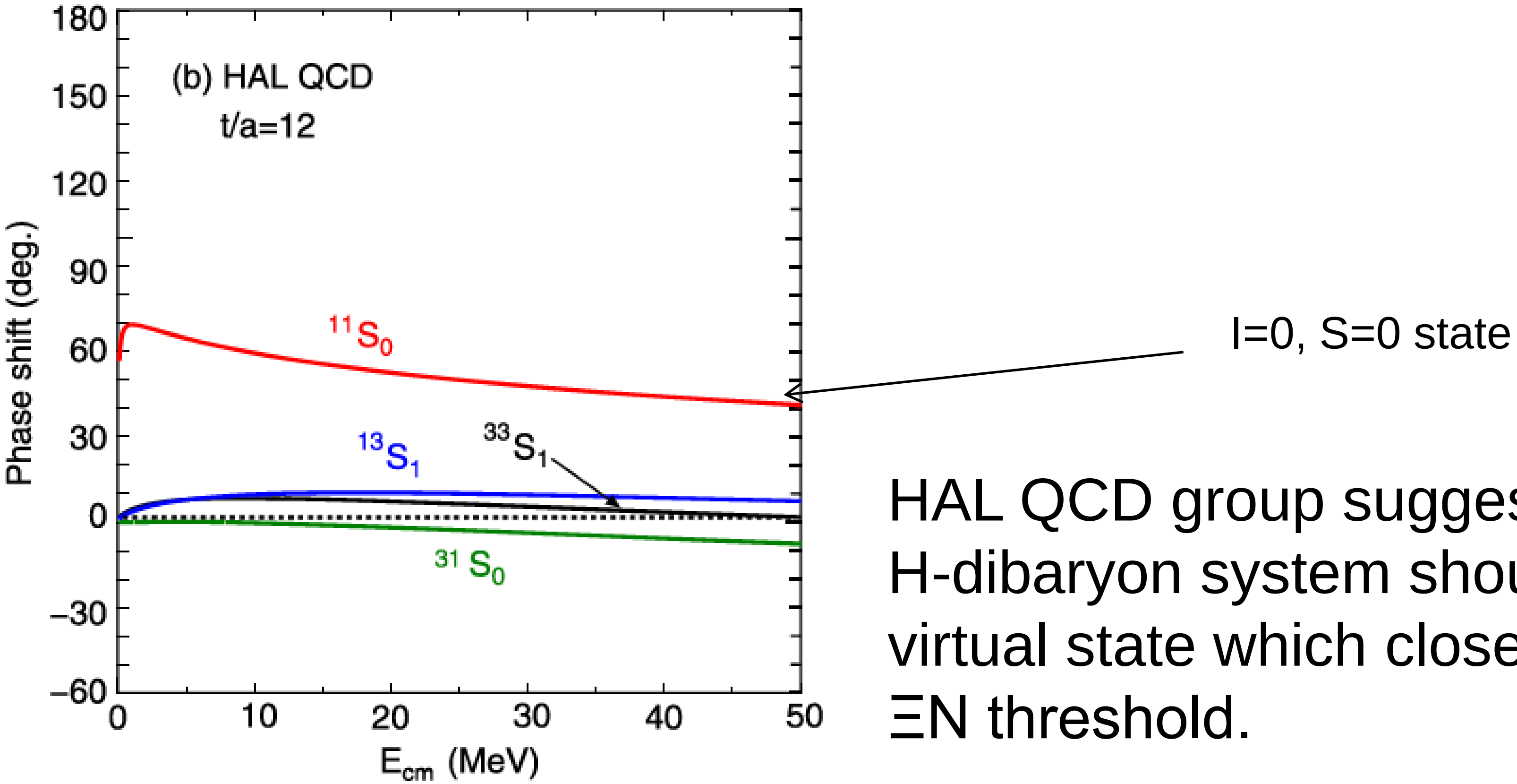
We employ ESC04 and ND.

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

HAL potential

$$V_{\Xi N}=V_0(r)+(\sigma_\Xi\cdot\sigma_N)V_s(r)+(\tau_\Xi\cdot\tau_N)V_t(r)+(\sigma_\Xi\cdot\sigma_N)(\tau_\Xi\cdot\tau_N)V_{ts}(r)$$

All terms are central parts only.



HAL QCD group suggests H-dibaryon system should be virtual state which close to ΞN threshold.

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

V(T,S)	ESC04	ND	HAL
T=0, S=1	strongly attractive (a bound state)	weakly attractive	Weakly attractive
T=0, S=0	weakly repulsive		Strongly attractive
T=1, S=1	weakly attractive		Weakly attractive
T=1, S=0	weakly repulsive		Weakly repulsive

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

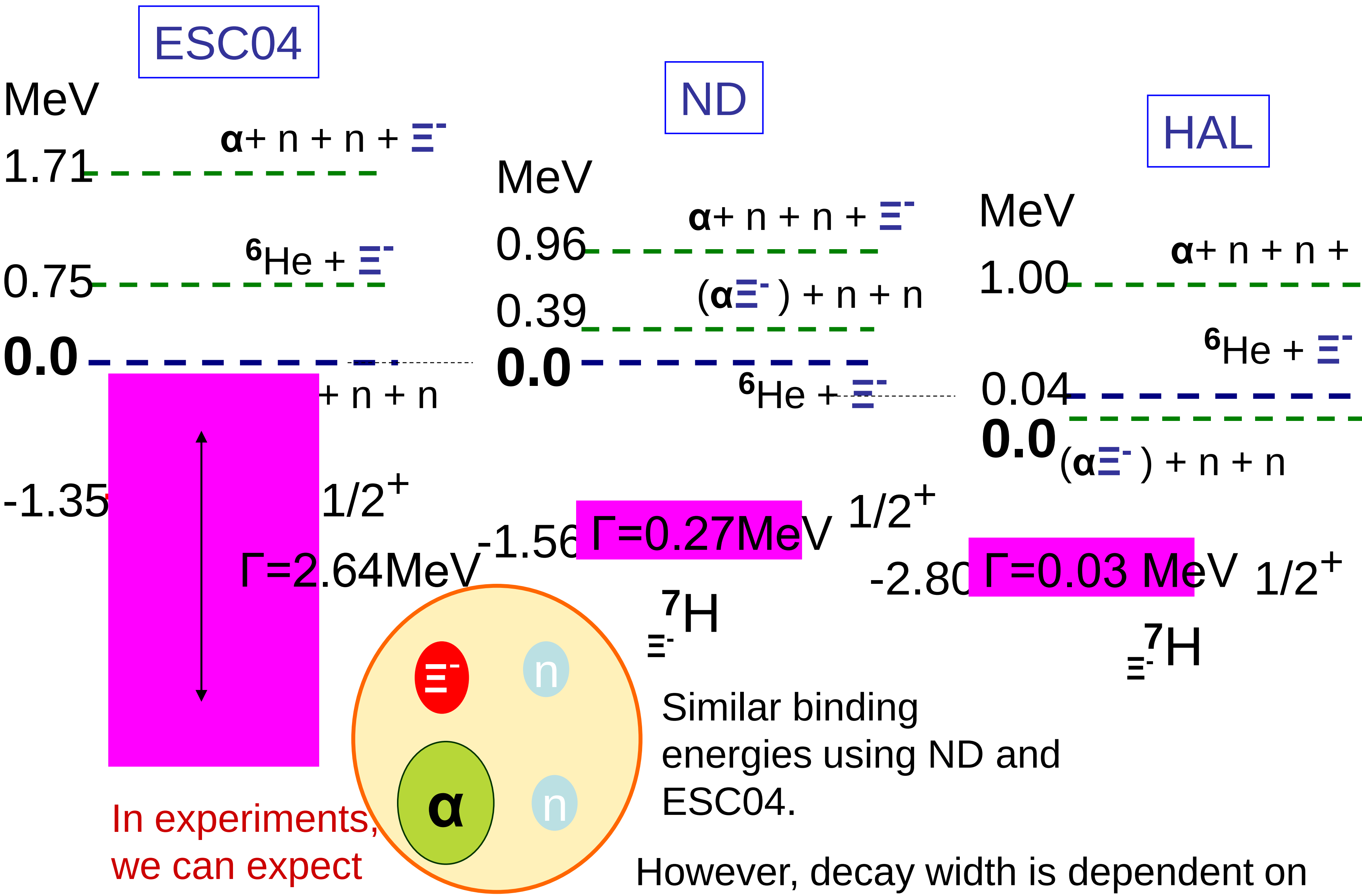
we find that the spin- and isospin-averaged property,

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

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

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

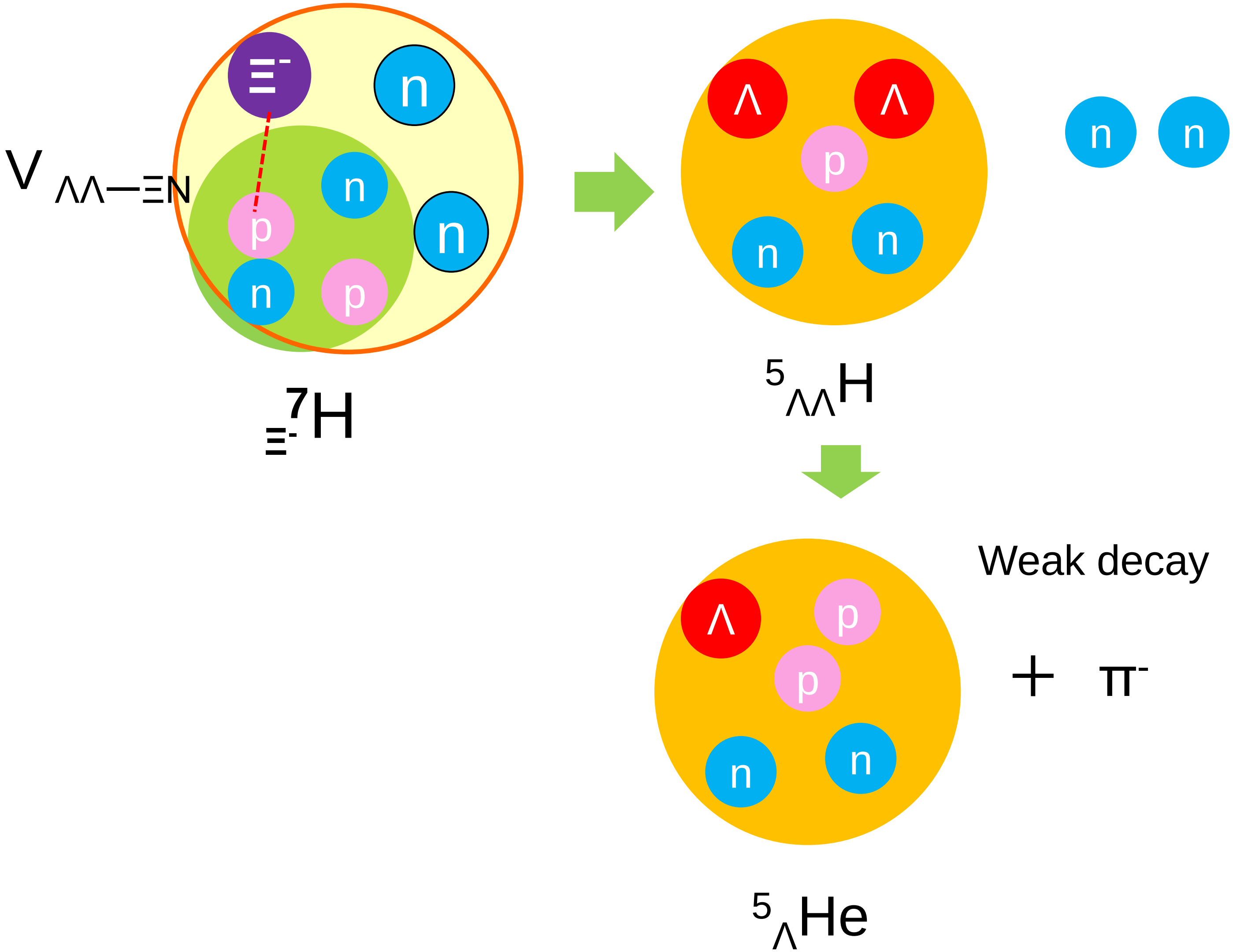
E. Hiyama et al.,
PRC**78** (2008) 054316



In experiments,
we can expect
a bound state.

Similar binding
energies using ND and
ESC04.

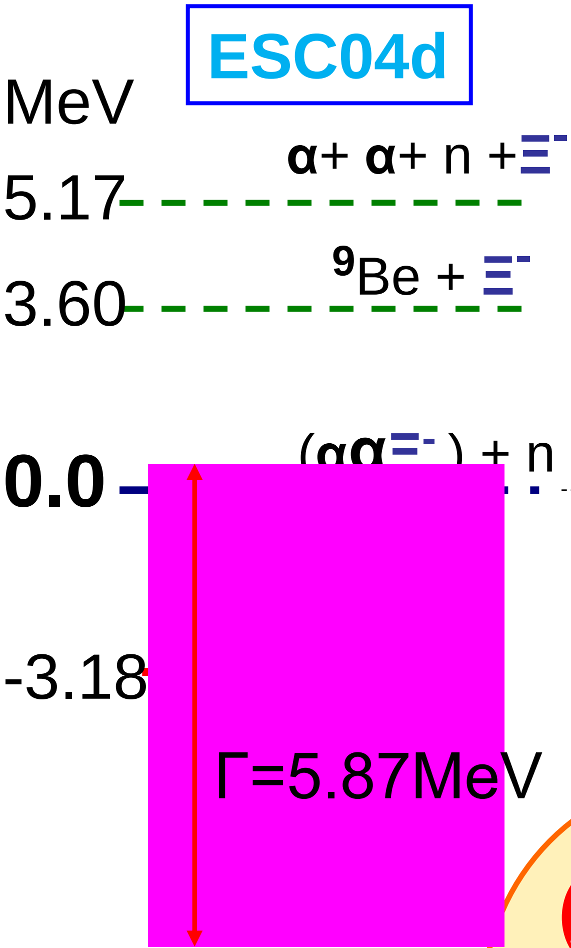
However, decay width is dependent on
on employed ΞN potential

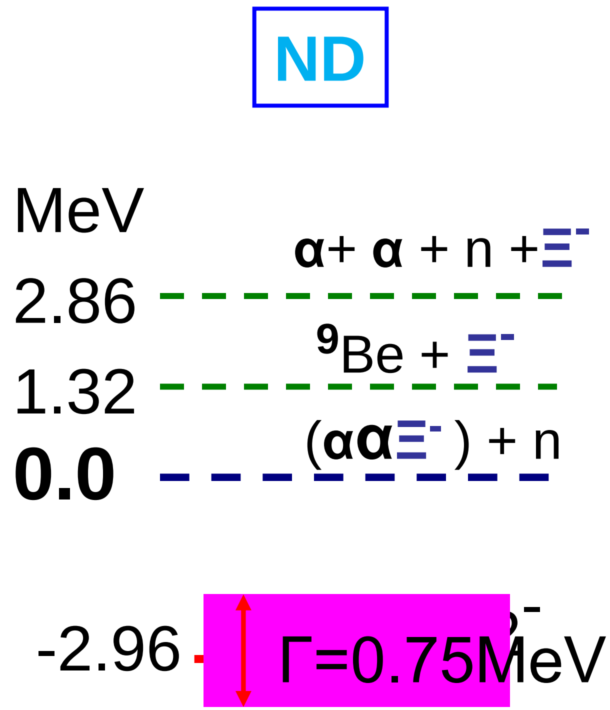


J-PARC P-75 spokesperson: H. Fujioka (TIT)

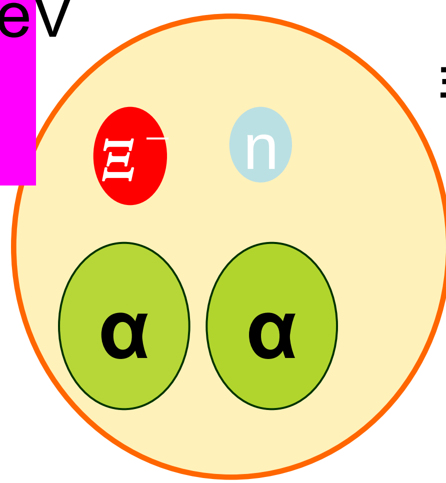
4-body calculation of $^{10}_{\Xi^-}$Li

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





$^{10}_{\Xi^-}$Li



Similar binding energies using ND and ESC04d.

Independent on employed ΞN potential

But, decay width is dependent on employed ΞN interaction.

In experiments, we can expect a bound state.

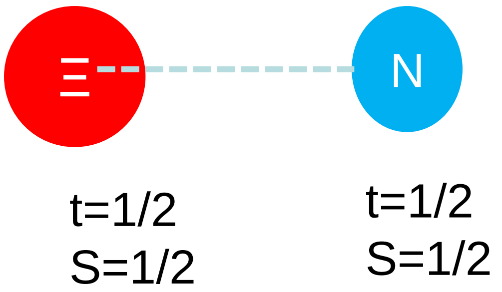
In this way, the binding energies of Ξ hypernuclei with A=7 and 10 are dominated by **$\alpha\Xi$** potential, namely, spin-, and iso-spin independent ΞN interaction（**V_0**）.

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.

Also next, it is interesting to know

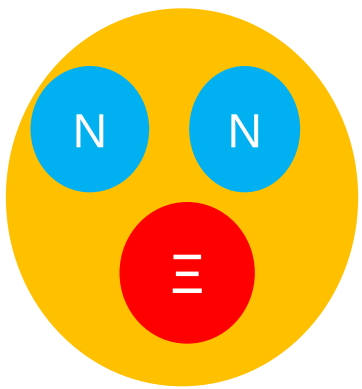
which partial contribution makes attractive for $V_{\Xi N}$ **?**

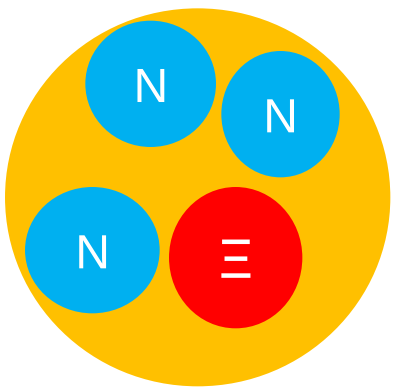
ΞN interaction: T=0, S=0
T=0, S=1
T=1, S=0
T=1, S=1



We want to know which partial wave is attractive or repulsive.

The suited systems to study are s-shell Ξ hypernuclei such as NNΞ and NNNΞ systems.

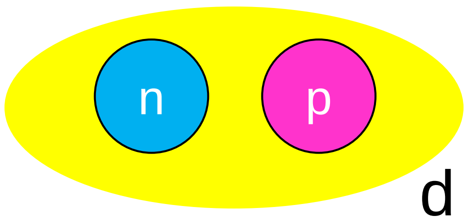




Question: what is the lightest Ξ bound state?

S=0

The lightest nucleus to have a bound state is deuteron.



n+p threshold

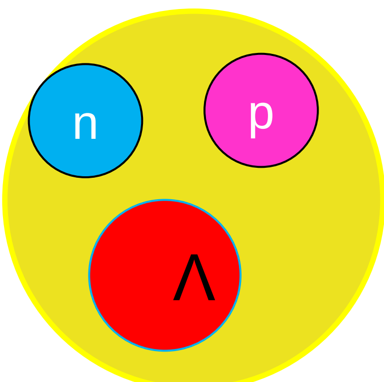
J=1$^+$

-2.22 MeV

Exp.

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.

S=-2

Double Λ hypernuclei:????

Ξ hypernuclei:???

Possible Lightest Ξ Hypernucleus with Modern Ξ*N* Interactions

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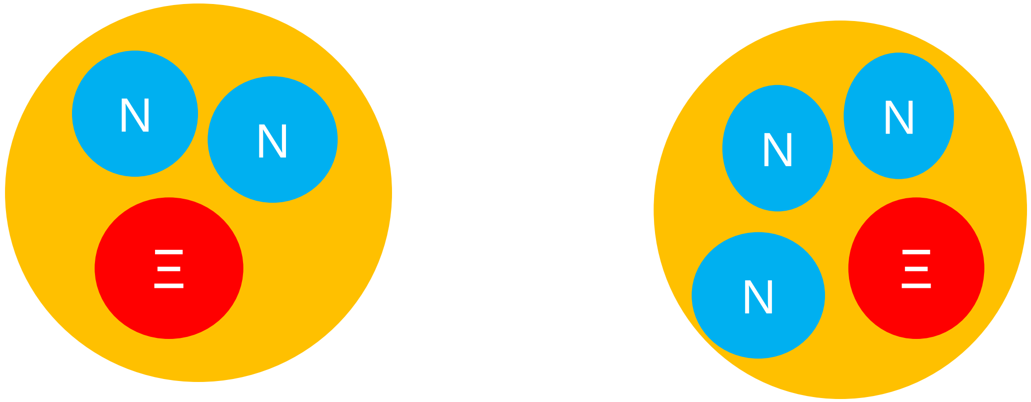
(Received 19 October 2019; revised manuscript received 18 January 2020; accepted 22 January 2020; published 4 March 2020)

Experimental evidence exists that the Ξ-nucleus interaction is attractive. We search for $NN\Xi$ and $NNN\Xi$ bound systems on the basis of the AV8 NN potential combined with either a phenomenological Nijmegen ΞN potential or a first principles HAL QCD ΞN potential. The binding energies of the three-body and four-body systems (below the $d+\Xi$ and ^{3}H$/^3$He $+\,\Xi$ thresholds, respectively) are calculated by a high precision variational approach, the Gaussian expansion method. Although the two ΞN potentials have significantly different isospin (T) and spin (S) dependence, the $NNN\Xi$ system with quantum numbers $(T=0,\ J^\pi=1^+)$



I show my new results of these light systems.

NN interaction: AV8 potential
ΞN interaction :
Nijimegen extended soft core potential (ESC08c)
Realistic potential (only ΞN channel)

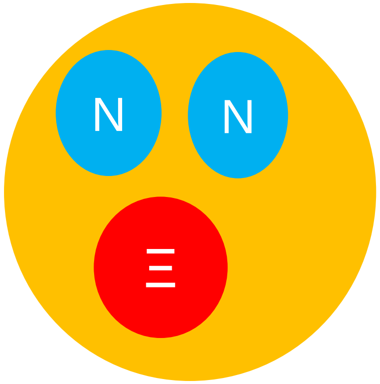
ΞN interaction by HAL collaboration (Lattice QCD calculation)
The potential was made by K. Sasaki, Miyamoto, Hatsuda and Aoki.

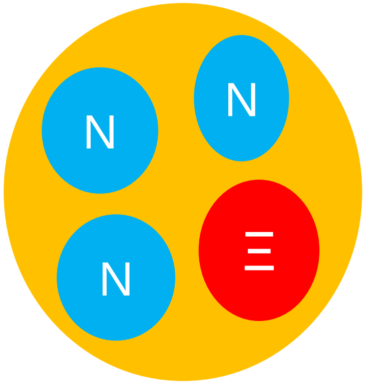
Property of the spin- and isospin-components of ESC08 and HAL

V(T,S)	ESC08c	HAL
T=0, S=1	strongly attractive	Weakly attractive
T=0, S=0	weakly repulsive	Strongly attractive
T=1, S=1	strong attractive	Weakly attractive
T=1, S=0	weakly repulsive	Weakly repulsive

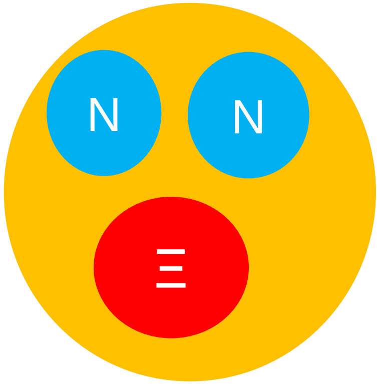
Although the spin- and isospin-components of these two models are very different between them.

It is interesting to see the difference in the energy spectra in s-shell Ξ hypernuclei.

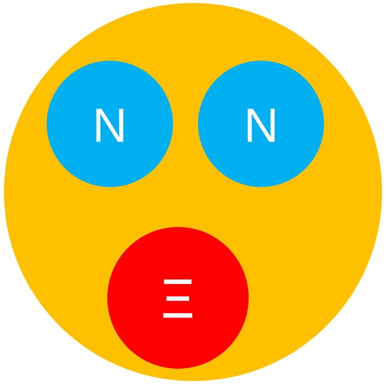




Question: do we have some bound states for these
Three and four-body systems?

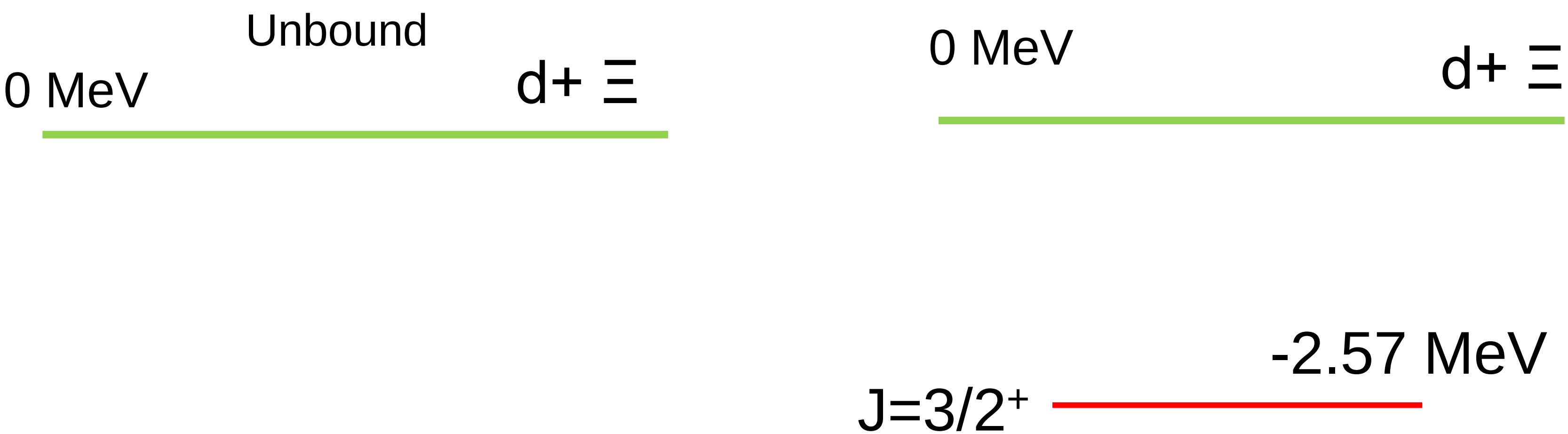


(NN) S=0, or 1
Ξ: ½ => J=1/2+ or 3/2+

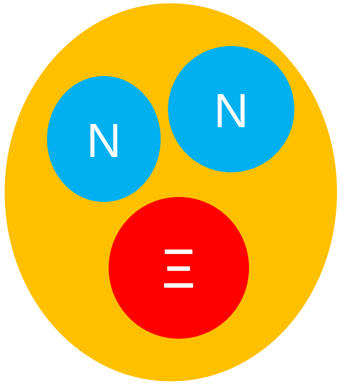


T=1/2, J=1/2$^+$ and J=3/2$^+$

ESC08c



I used the different version of ESC08c (realistic force).
However, I also have two bound states in three-body system.



T=1/2, J=1/2$^+$ and J=3/2$^+$

HAL potential

0 MeV

d+ Ξ

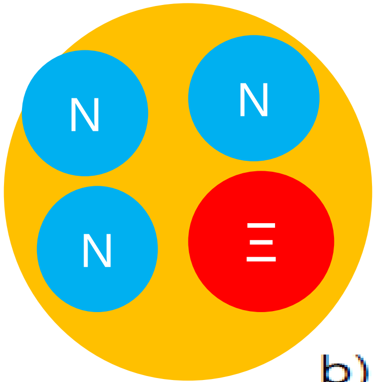
0 MeV

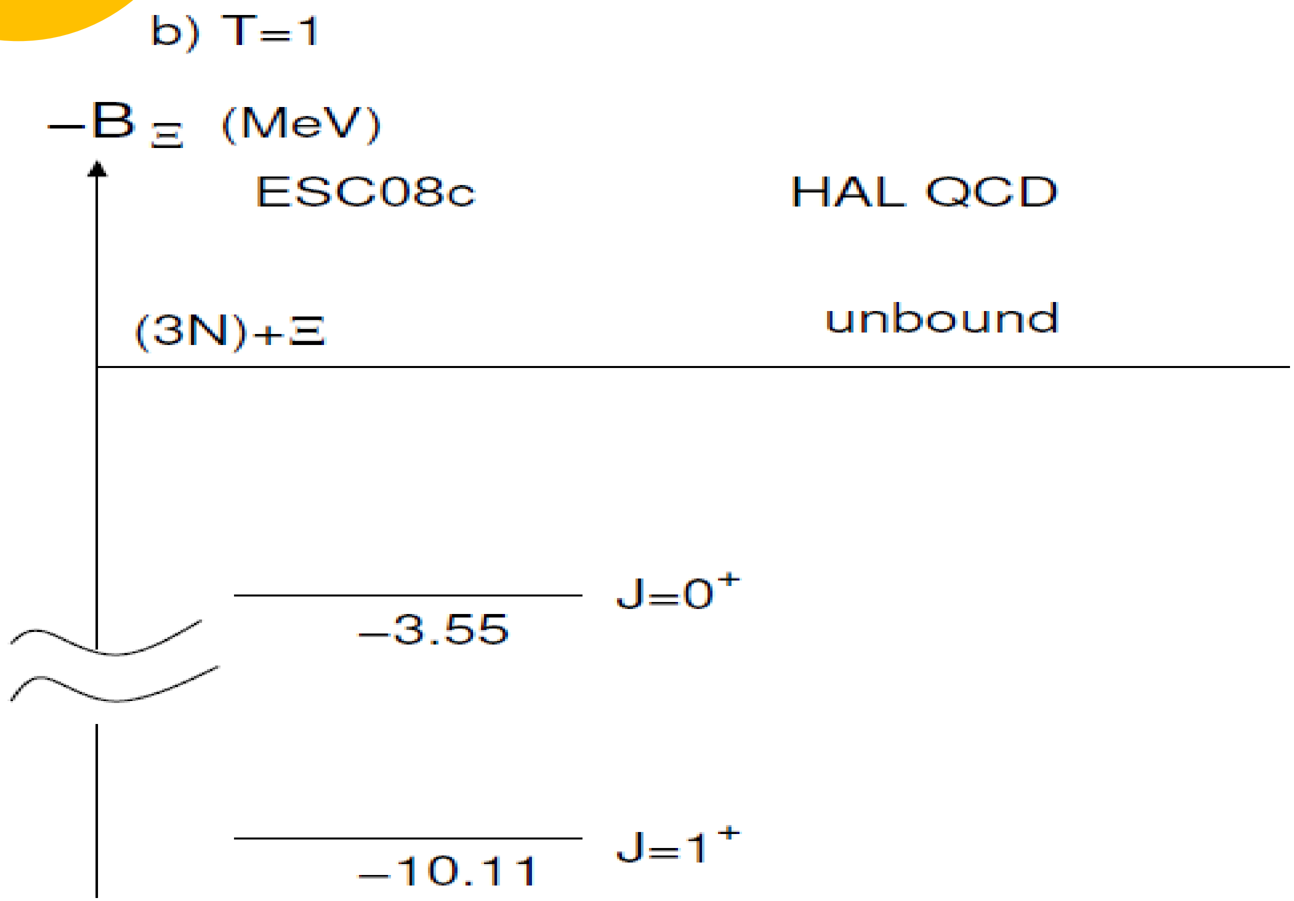
d+ Ξ

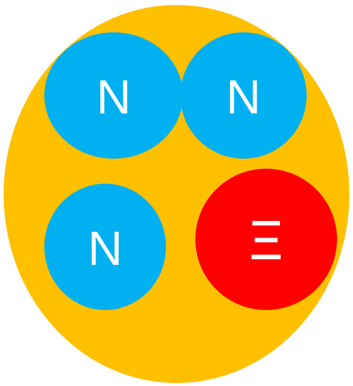
No bound state

J=3/2$^+$

J=1/2+

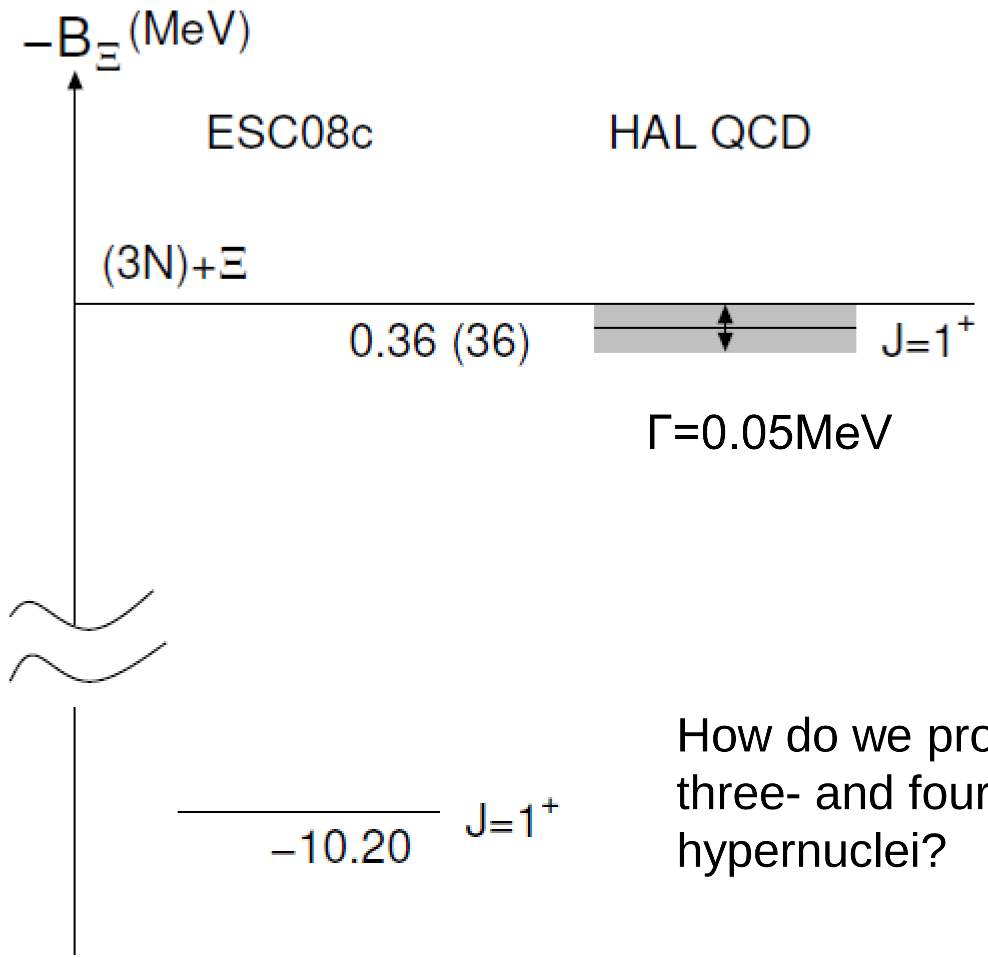

N
N
N
Ξ


b) T=1
−B_Ξ (MeV)
ESC08c
HAL QCD
(3N)+Ξ
unbound
J=0+
−3.55
J=1+
−10.11

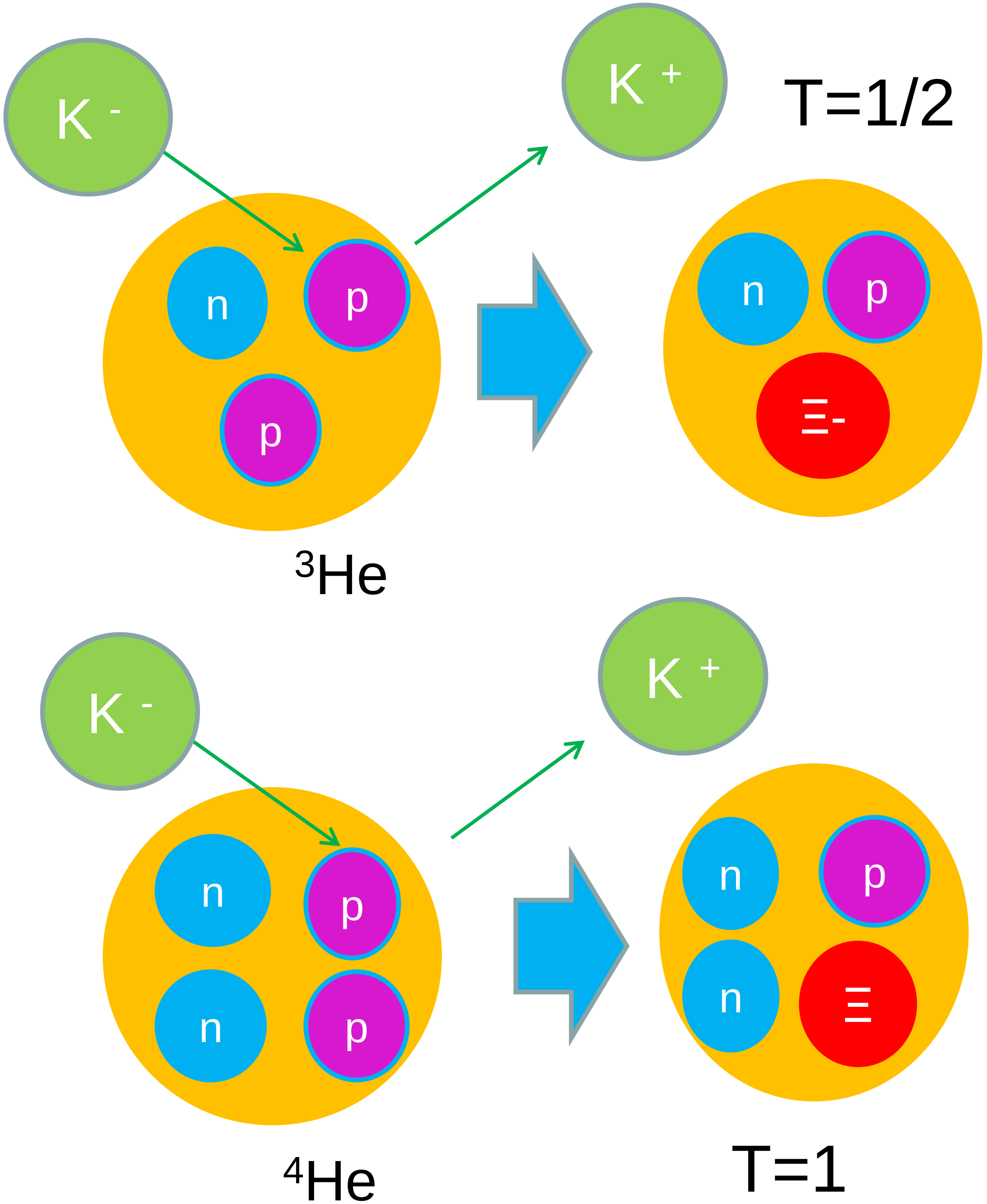


Four-body Ξ system is the lightest bound system.
Tetra-Ξ bound system

a) T=0



How do we produce three- and four-body Ξ hypernuclei?



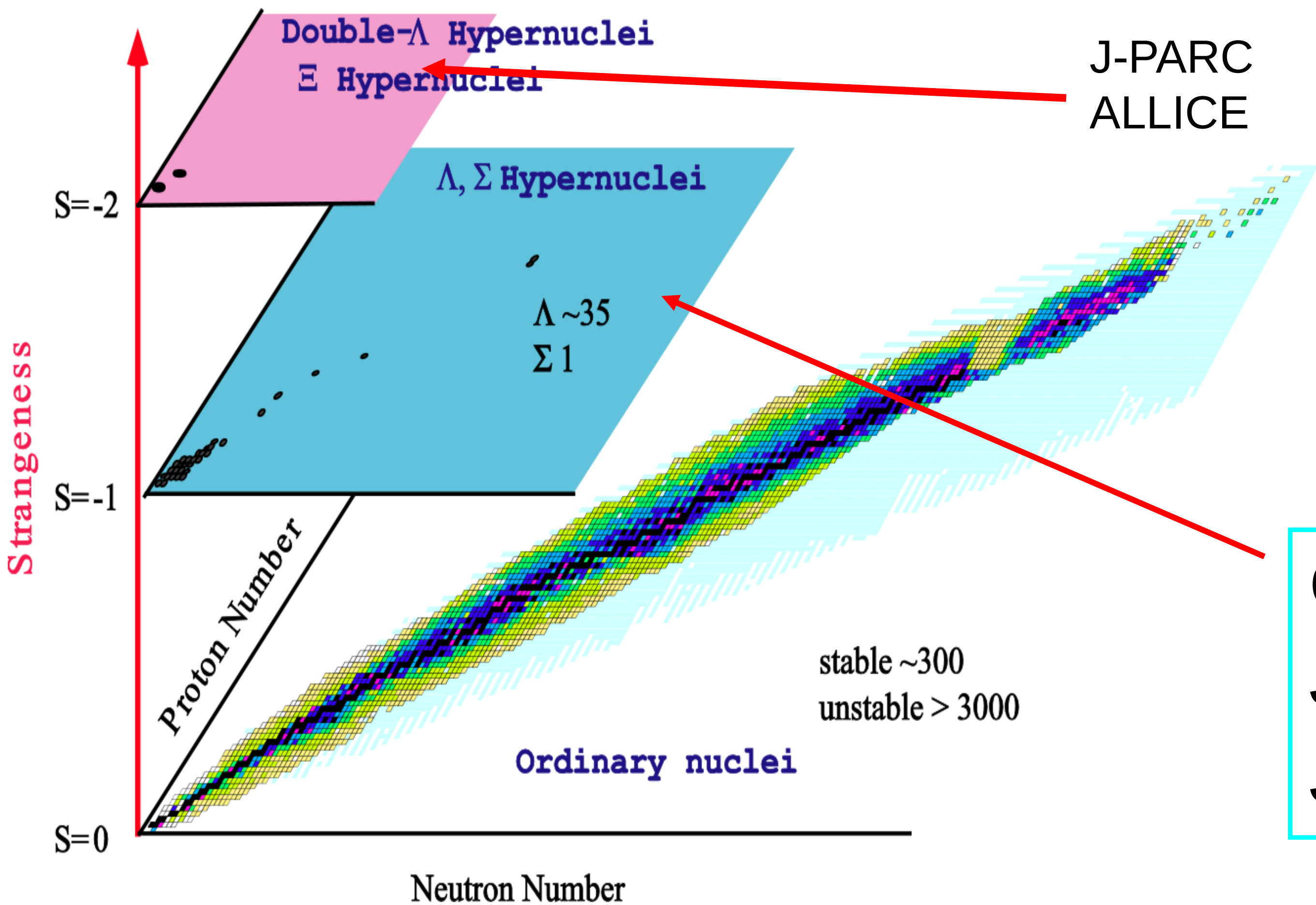
Using 3He and 4He target,
It might be possible
to produce NNΞ and NNNΞ
systems by (K^-,K^+) reaction.

Another way is a heavy ion
collision by ALLICE(CERN).

Concluding remark

Multi-strangeness system
such as Neutron star

Three-Dimensional Nuclear Chart



J-PARC
ALLICE

GSI
JLab
J-PARC

Thank you!