Hadron Interaction and exotics

Emiko Hiyama (Tohoku Univ./RIKEN)

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.

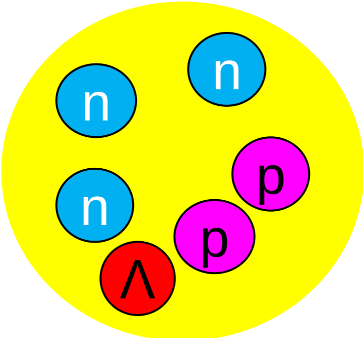
Therefore, for the study of YN and YY interactions, the systematic investigation of the structure of light hypernuclei is one of the important way.

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

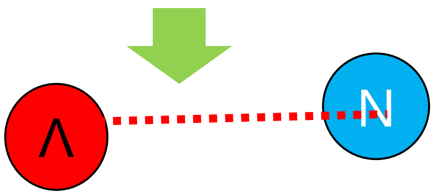
Once YN and YY interactions are determined, we can predict interesting phenomena which cannot be imagined so far. In addition, we could study inner part of neutron stars which have been observed.

Since 1998

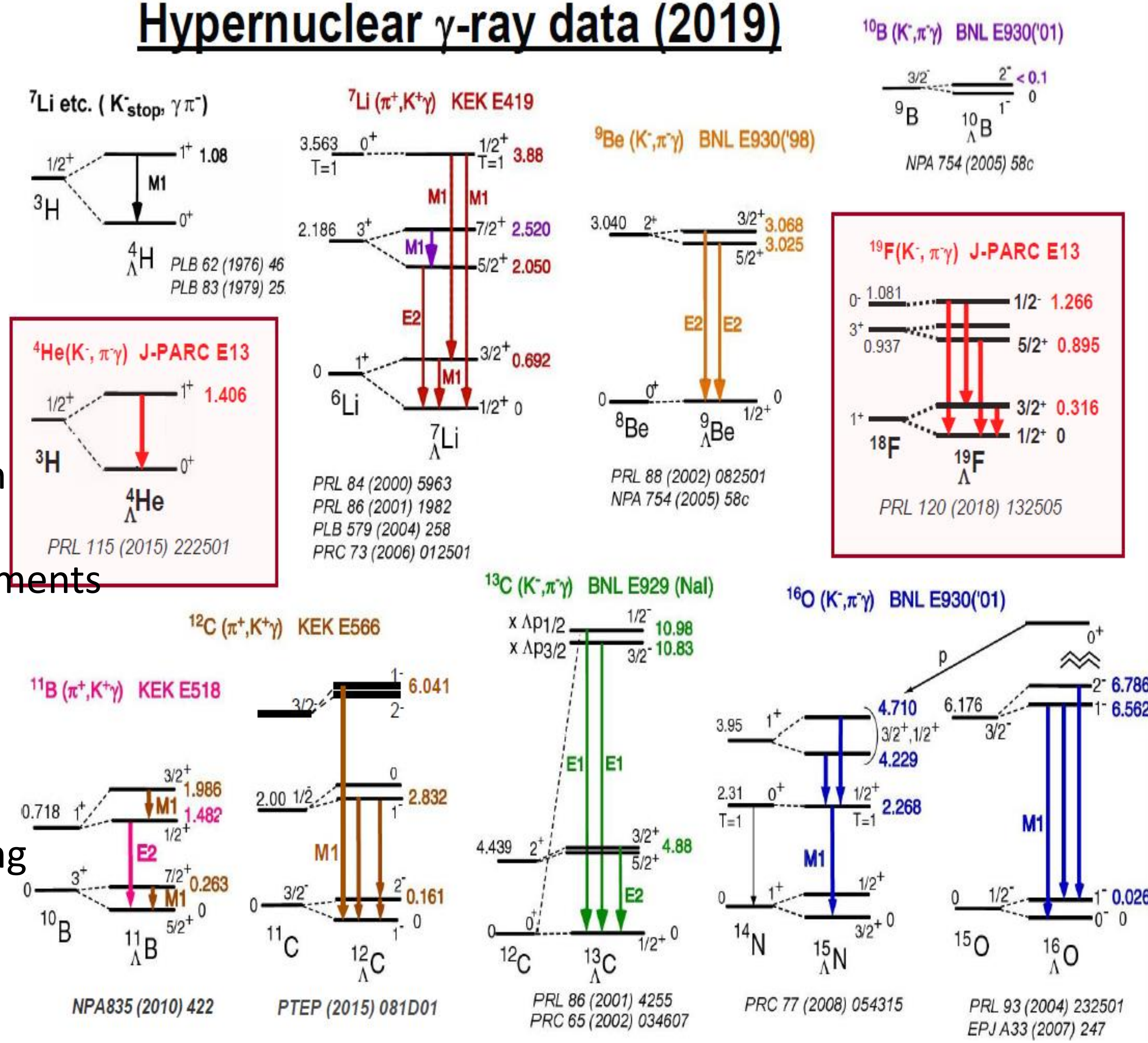
Hypernuclear γ-ray data (2019)



Ab-initio calculation
Shell model calculation
+
High-resolution experiments

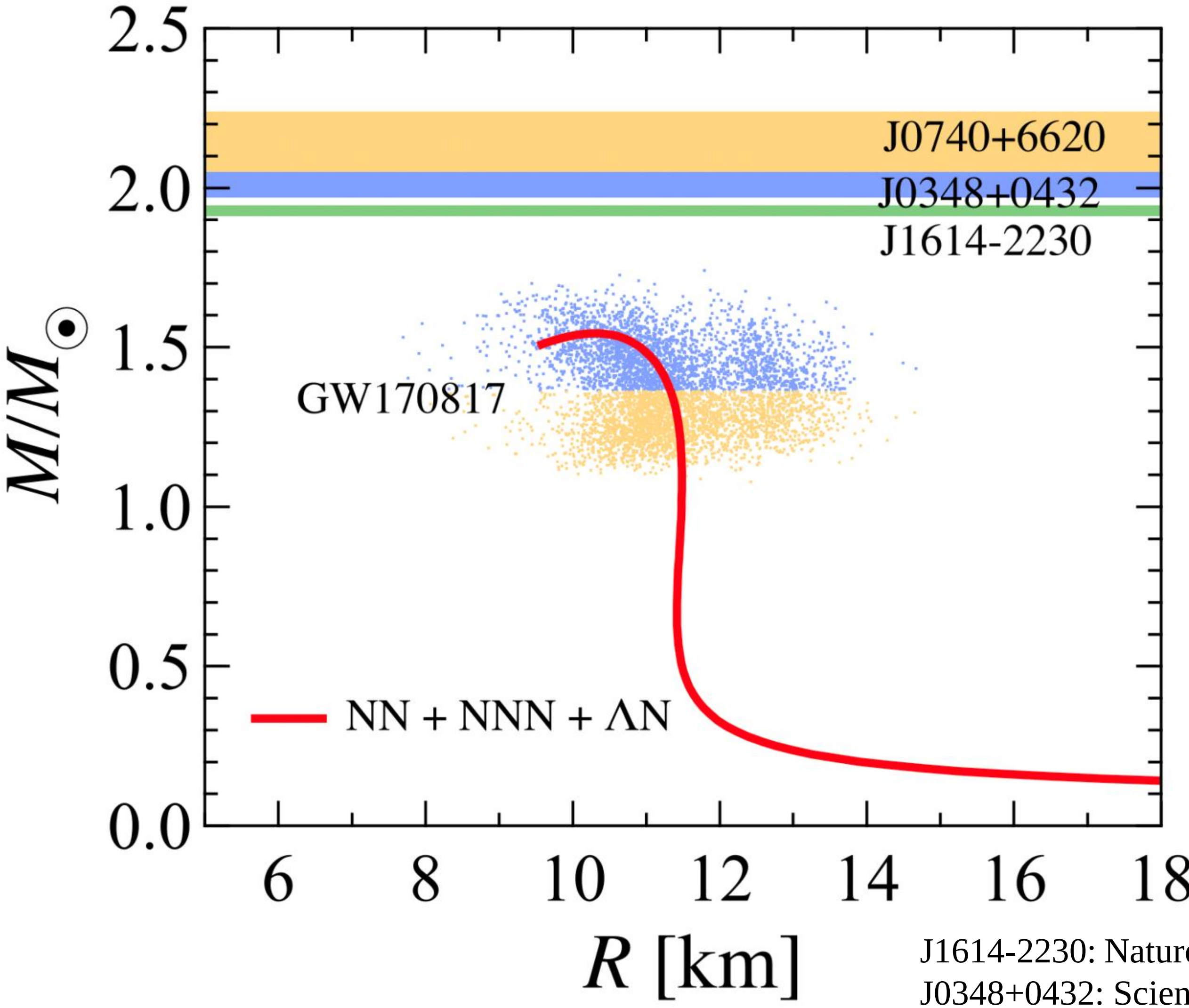


We have been obtaining information on ΛN two-body interaction.



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

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

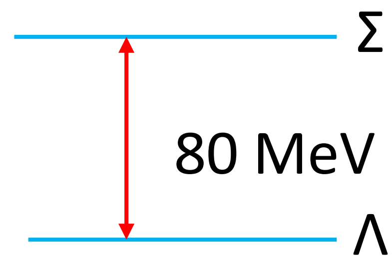
Hyperon puzzle

missing part of YN interaction: ΛN-ΣN coupling

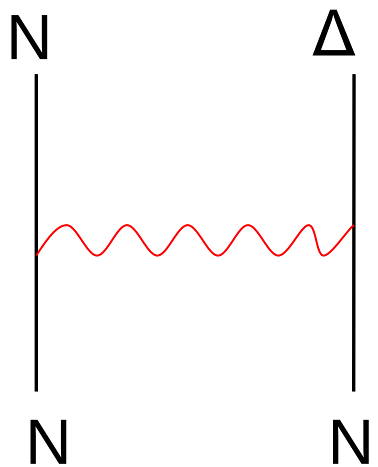
ΛN—ΣN coupling

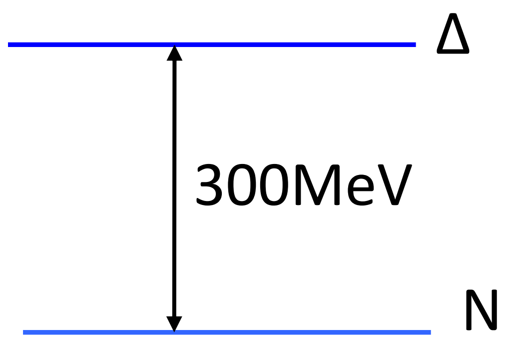
S=-1

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



Non-strangeness sector





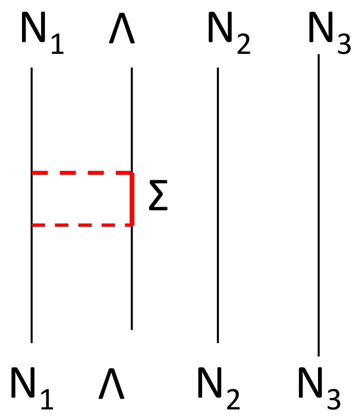
Probability of Δ in nuclei is not large.

ΛN-ΣN coupling is key issue to construct YN two-body interaction completely.

Role of the ΛN-ΣN interaction

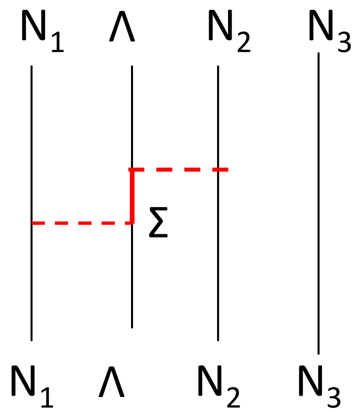
・ Three-body effect

①



Effective two-body force

②



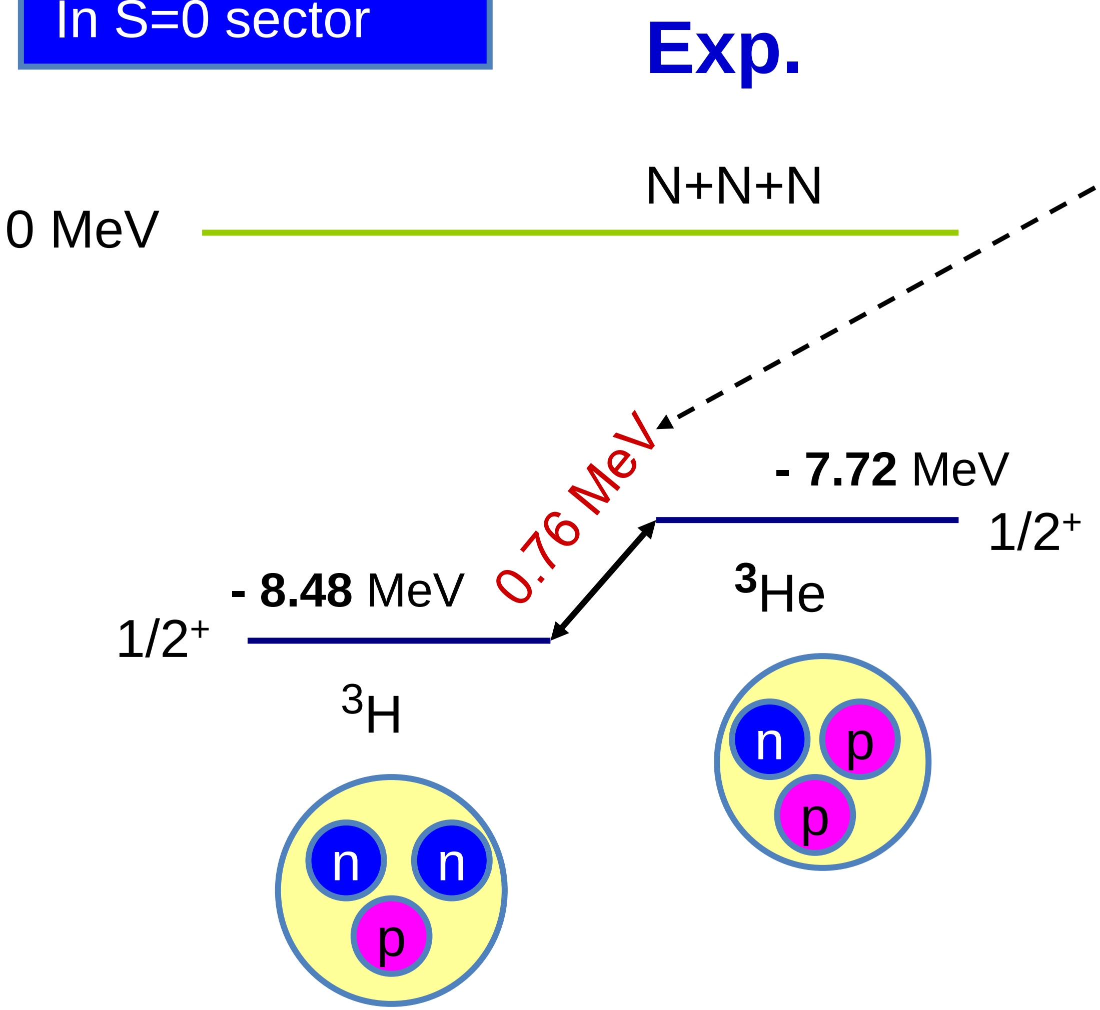
Three-body force

In the neutron matter or neutron star, three-body force might play important role.

・Charge symmetry breaking effect

Charge Symmetry breaking

In S=0 sector

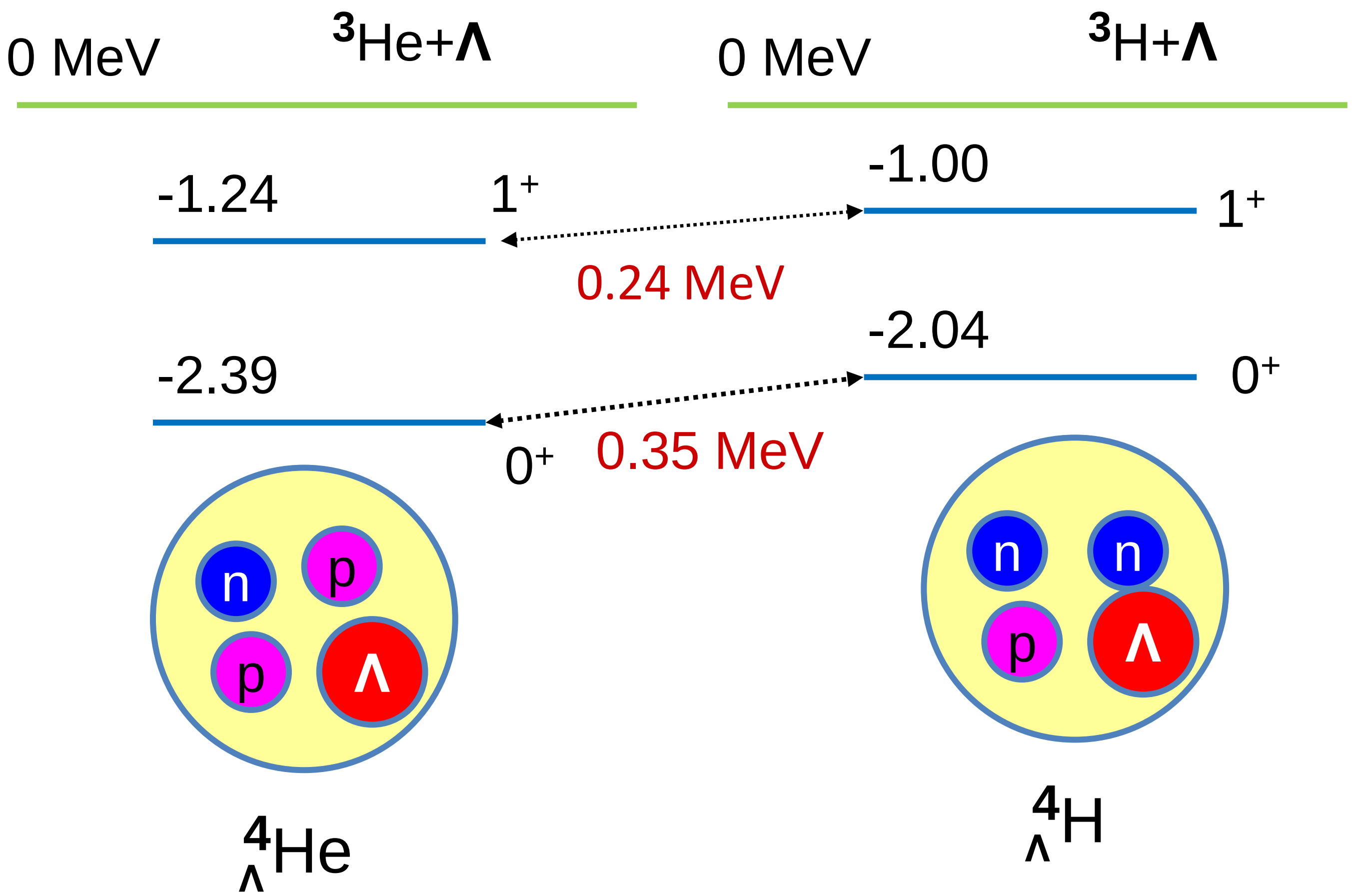


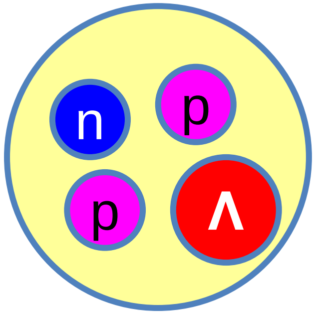
Energy difference comes from dominantly Coulomb force between 2 protons.

Charge symmetry breaking (n-n,p-p) effect is small.

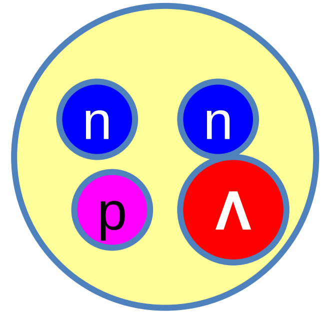
In S= -1 sector

Exp.





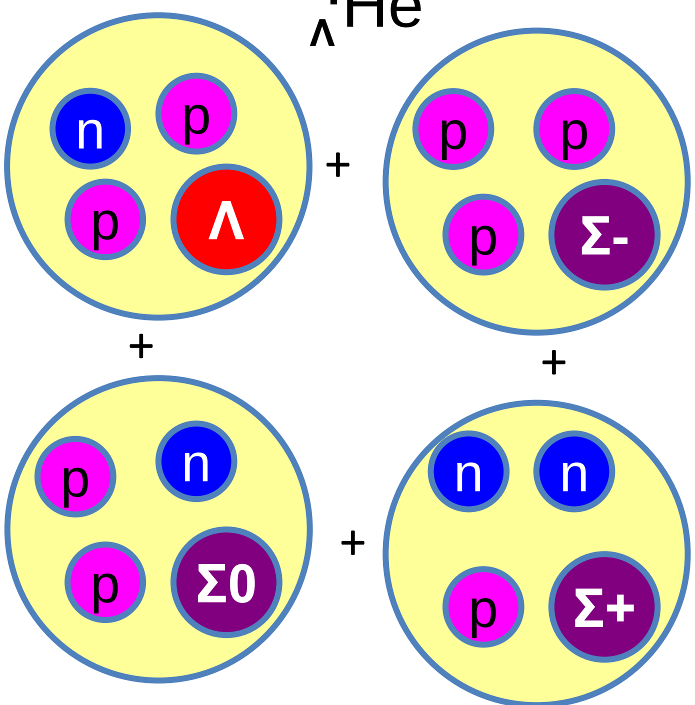
$^{4}_{\Lambda}$He



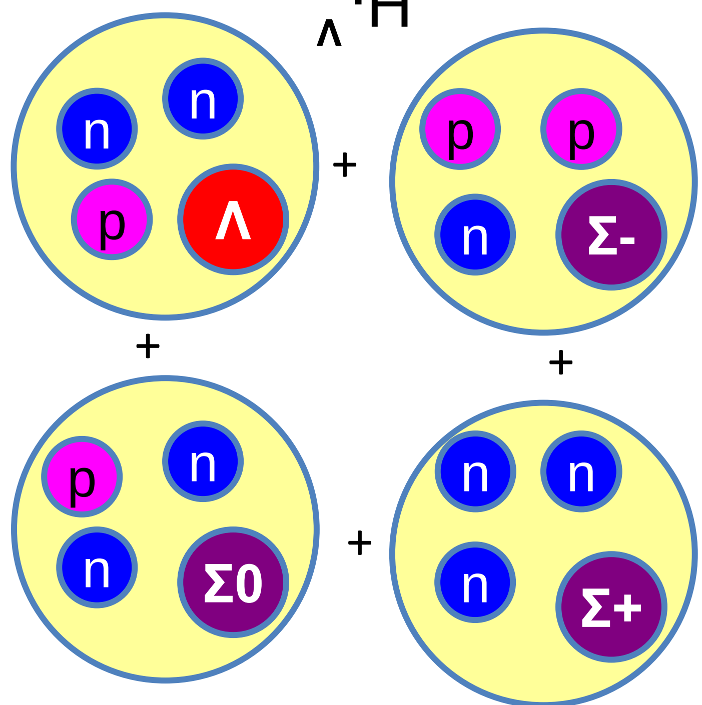
$^{4}_{\Lambda}$H

However, Λ particle has no charge.

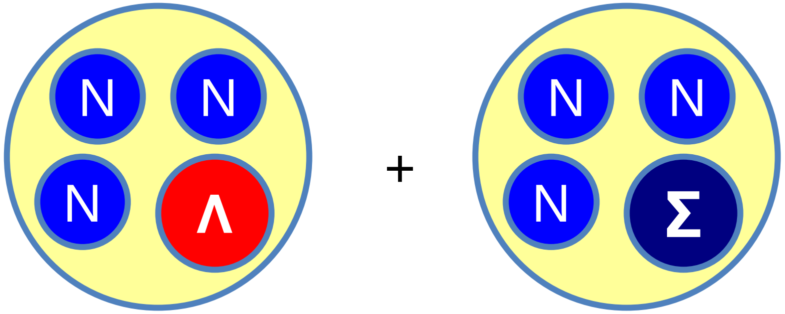
$^{4}_{\Lambda}$He



$^{4}_{\Lambda}$H



In order to explain the energy difference, 0.35 MeV,



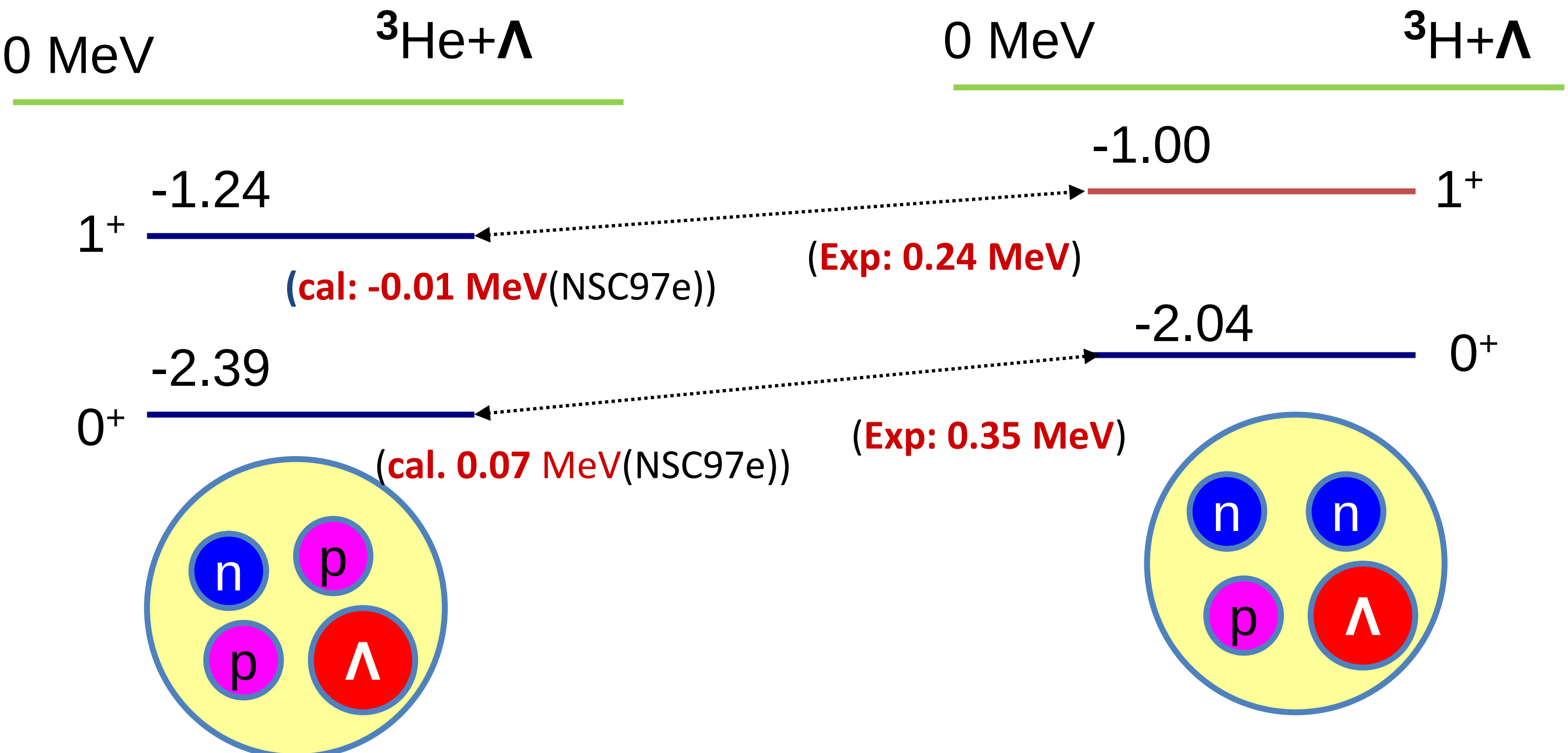
(3N+**Λ**)　　　　(3N+**Σ**)

- E. Hiyama, M. Kamimura, T. Motoba, T. Yamada and Y. Yamamoto,
  Phys. Rev. C65, 011301(R) (2001).

- A. Nogga, H. Kamada and W. Gloeckle,
  Phys. Rev. Lett. 88, 172501 (2002)

- H. Nemura. Y. Akaishi and Y. Suzuki,
  Phys. Rev. Lett.89, 142504 (2002).

Coulomb potentials between charged particles (p, $\Sigma^{\pm}$) are included.



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

- A. Nogga, H. Kamada and W. Gloeckle, Phys. Rev. Lett. 88, 172501 (2002)

$^{4}_{\Lambda}$H

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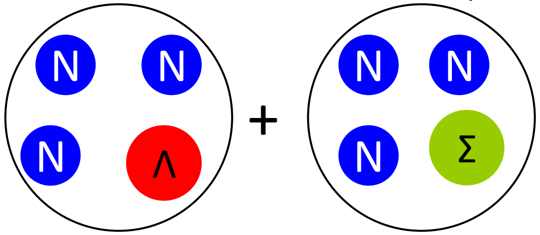
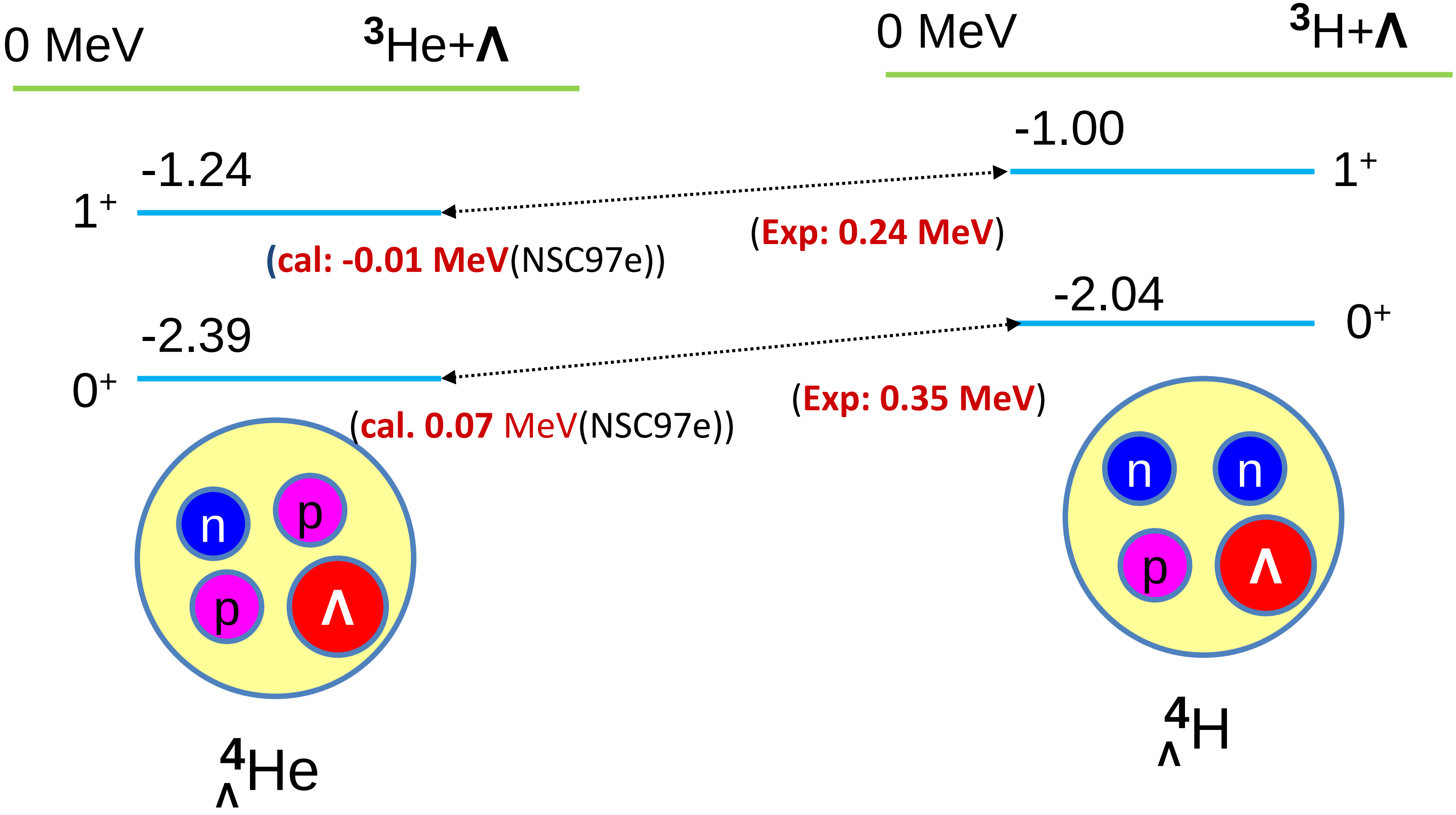
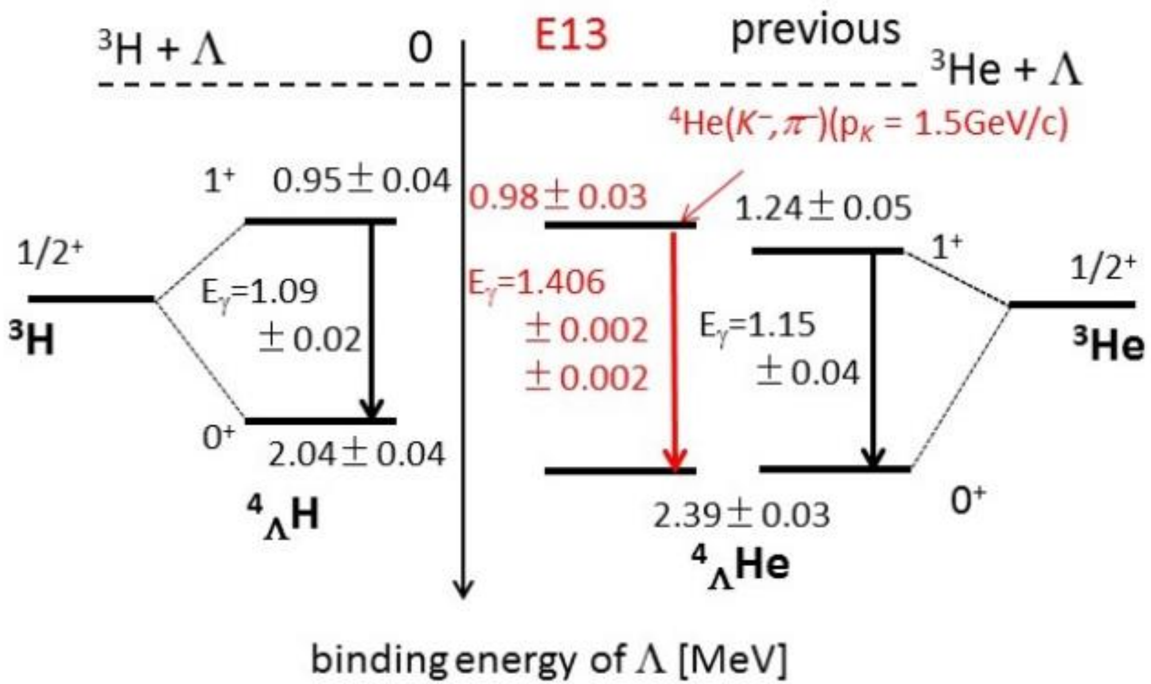




There has been exist NO YN interaction to reproduce the data.



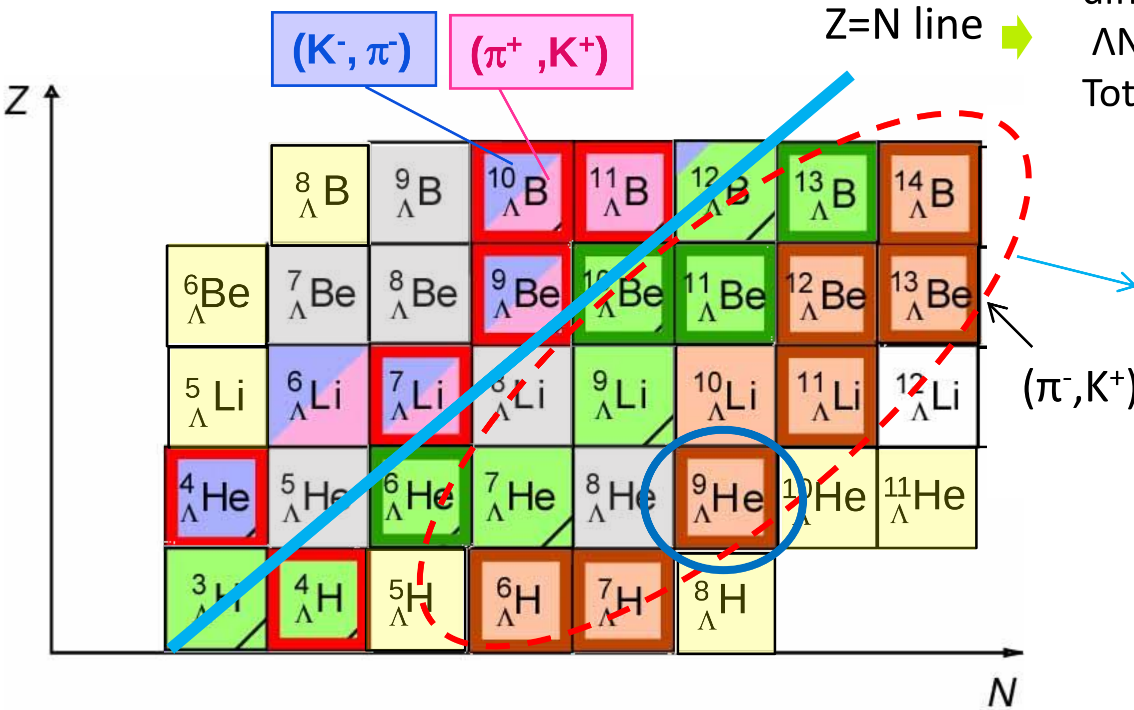
T. O. Yamamoto, Phys. Rev. Lett.115, 2225 (2015).

Still it is difficult to reproduce the data for the study of ΛN-ΣN coupling.
We need more data related to ΛN-ΣN coupling.

How do we obtain information on ΛN-ΣN coupling?

(1)YN scattering experiment at K1.1

(2) To study neutron-rich Λ hypernuclei at HIHR



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

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 ΛN-ΣN coupling.

Structure of neutron-rich He Λ Hypernuclei using the cluster orbital shell model

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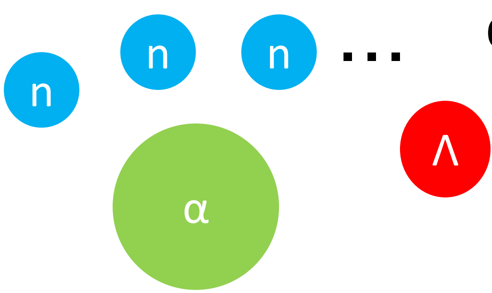
[1] *General Education, Faculty of Engineering, Osaka Institute of Technology, Osaka 535-8585, Japan and*
[2] *Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki 567-0047, Japan*

E. Hiyama[3,4]
[3] *Department of Physics, Tohoku University, Sendai, 980-8578, Japan and*
[3] *RIKEN, Nishina Center, Wako, Saitama, 351-0198,Japan*

We calculated the energy spectra of the neutron-rich He Λ hypernuclei with $A = 6$ to 9 within the framework of an $\alpha + \Lambda + Xn(X = 1 \sim 4)$ cluster model using the cluster orbital shell model. The employed constituent particles reproduce their observed properties. For resonant states of core nuclei such as ^{5}He, ^{6}He and ^{7}He, the complex scaling method is employed to obtain energies and decay widths. The calculated ground states of $^6_\Lambda$He and $^7_\Lambda$He are in good agreement with published data. The energy levels of $^8_\Lambda$He and $^9_\Lambda$He are predicted. In $^9_\Lambda$He, we find one deeply bound state and two excited resonant states, which are proposed to be produced at J-PARC by the double-charge-exchange reaction (π^-, K^+) using a ^{9}Be target.

To be published in Physical Review C



α+xn+Λ model

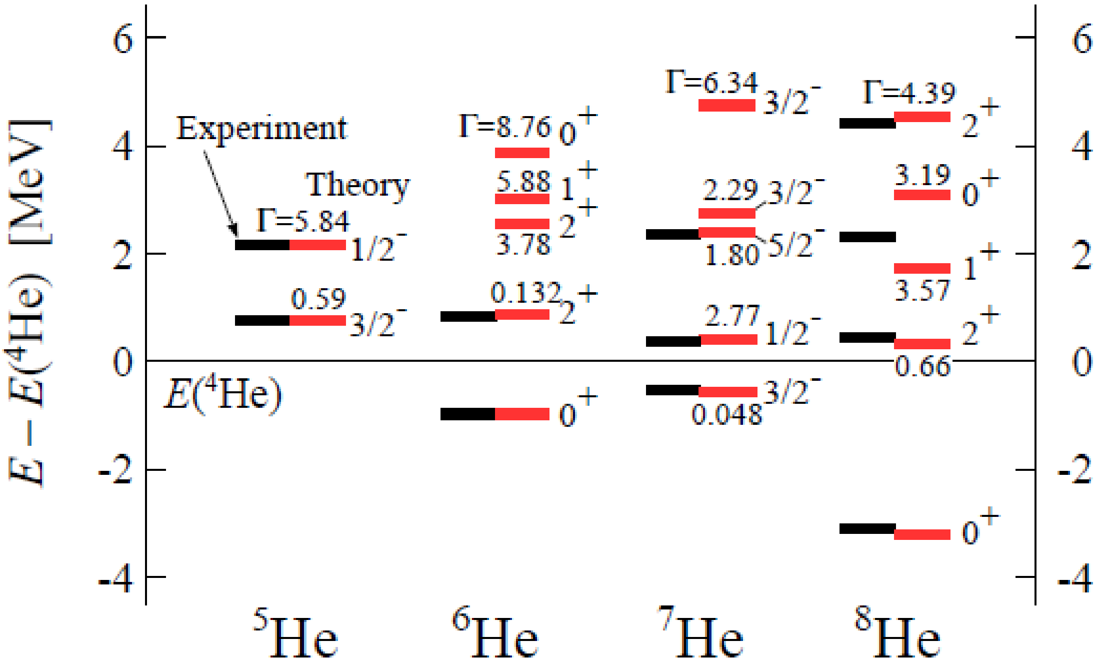
X=1～4

$^6_\Lambda$He, $^7_\Lambda$He, $^8_\Lambda$He, $^9_\Lambda$He

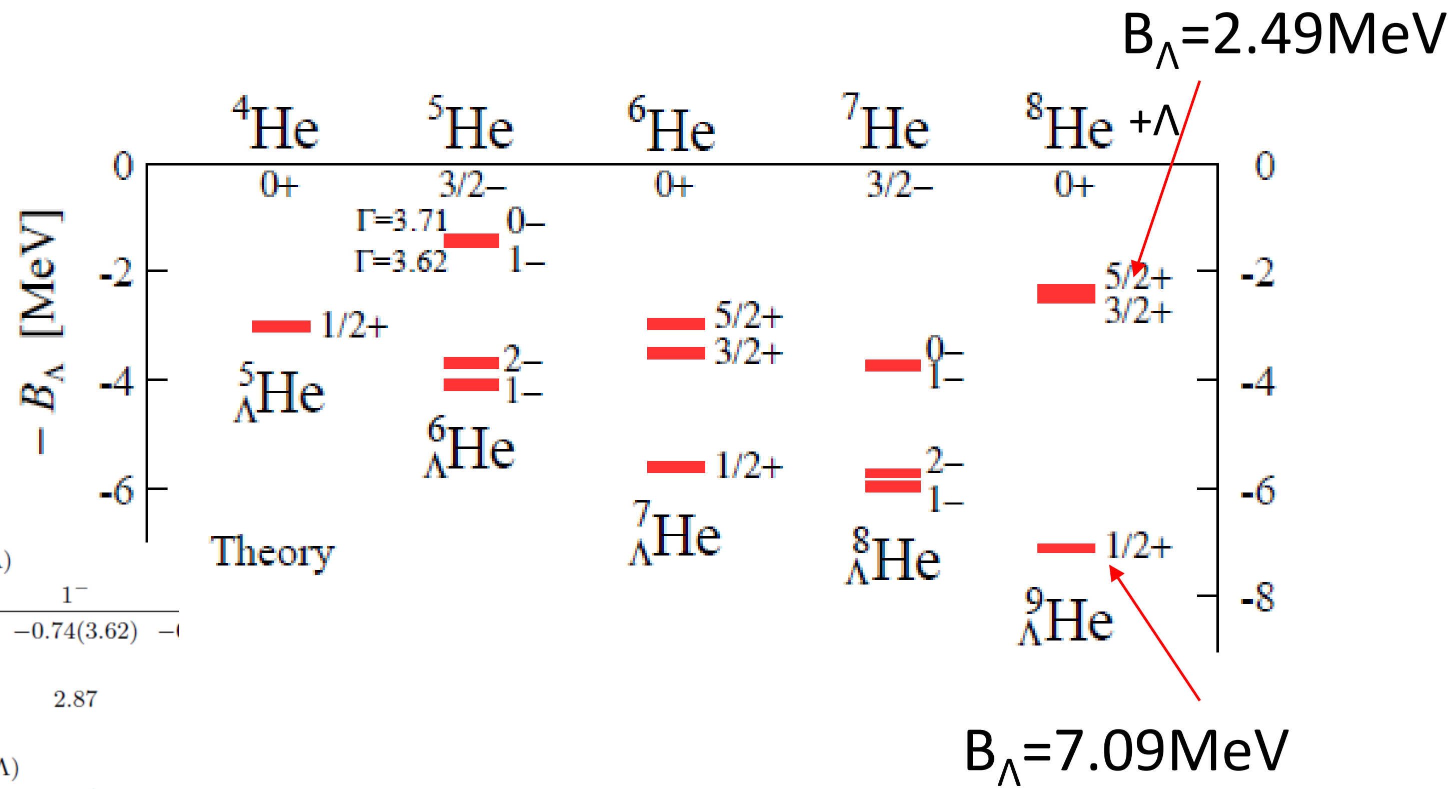
For $^9_\Lambda$He, there have been no observed data.
To predict binding energy of this hypernucleus, it is necessary to reproduce the Energy spectra of core nucleus, ^{8}He.

Currently, ΛN-ΣN coupling potential is renomalized into ΛN interaction.

Energy spectra of He Isotope nuclei:



The theoretical results are in good agreement with data.
Let's add a Λ particle into He isotope nuclei.



$^6_\Lambda$He($\alpha n\Lambda$)

J^π	1^-	2^-	1^-	
E (MeV)	−3.35	−2.94(0.06)	−0.74(3.62)	−[illegible]
$E^{\rm exp}$(MeV)				
B_Λ(MeV)	4.10	3.34	2.87	
$B_\Lambda^{\rm exp}$ (MeV)	4.18			

$^7_\Lambda$He($\alpha nn\Lambda$)

J^π	$1/2^+$	$3/2^+$	$5/2^+$
E (MeV)	−6.48	−4.37	−3.84
$E^{\rm exp}$(MeV)			
B_Λ(MeV)	5.51	3.69	1.42
$B_\Lambda^{\rm exp}$ (MeV)	5.55	3.65	

In $^9_\Lambda$He, three bound states are predicted.
By (π^-,K^+) reaction at J-PARC using ^{9}Be target, it is possible
To produce these hyperucleus.
This would be observation of the
most heavy He isotope Λ hypernucleus .

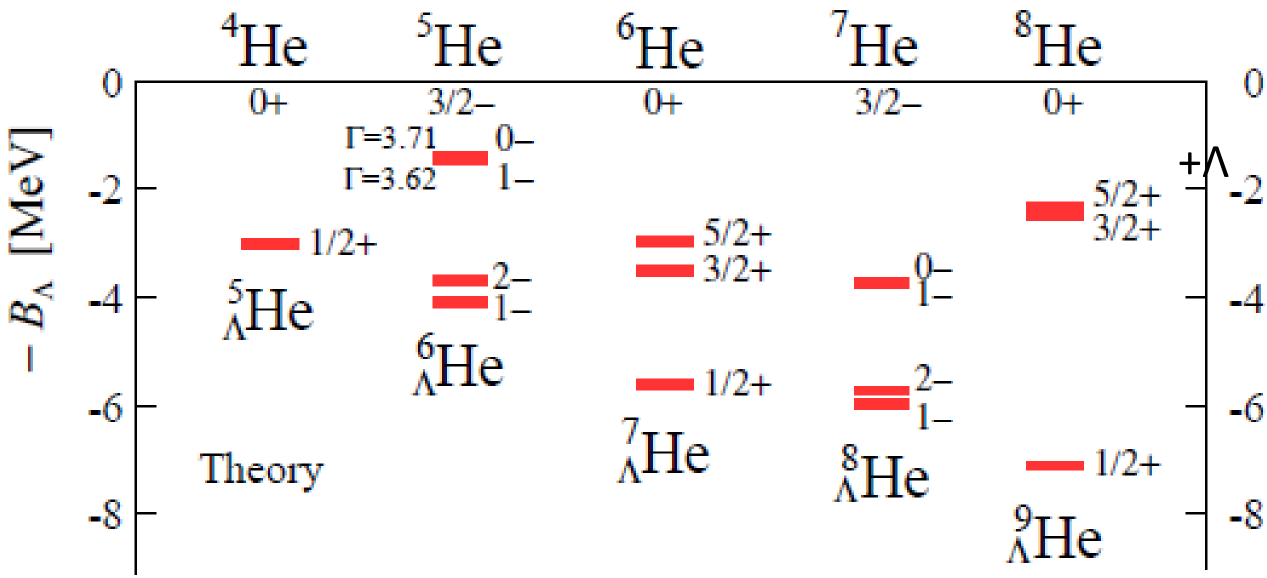
How much Σ probability in He Λ hypernuclei?

A. Umeya, T. Harada, E. Hiyama

Shell model calculation

YN interaction: including ΛN-ΣN coupling

Nijmegen potential model 97f



Umeya adjust YN interaction so as to reproduce the results by Myo.

$^6_\Lambda$He:0.032 %

$^7_\Lambda$He: 0.12%

$^8_\Lambda$He:0.155%

$^9_\Lambda$He: 0.31%

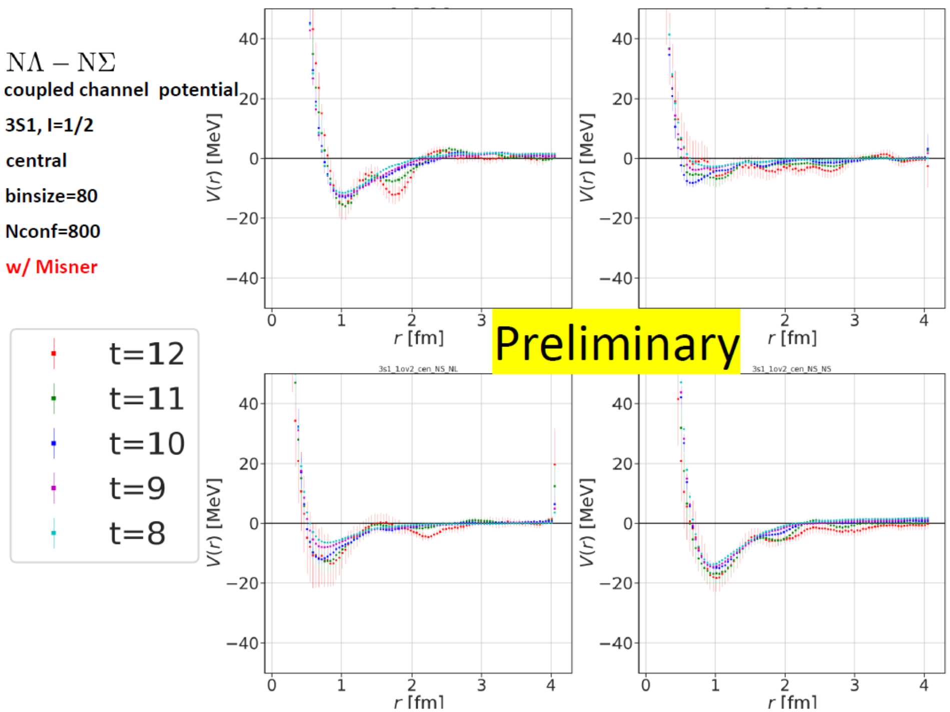
Increasing the number of neutrons, Σ mixing probability becomes larger.

I just used one of several proposed potential models.
ΛN-ΣN coupling has a large number of ambiguity.

・YN scattering experiment
Y. Ichikawa J-PARC-E90

Improvement of potentials
Chiral potential etc.

・YN interaction from view point of Ab-initio calculation such as Lattice QCD



YN interaction by HAL QCD
It will be possible to employ the interaction.

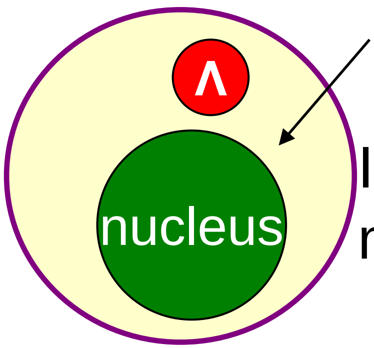
slide by T. Doi

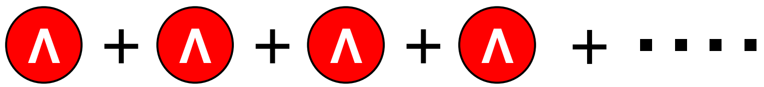
S=-2 hypernuclei

and

YY interaction

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





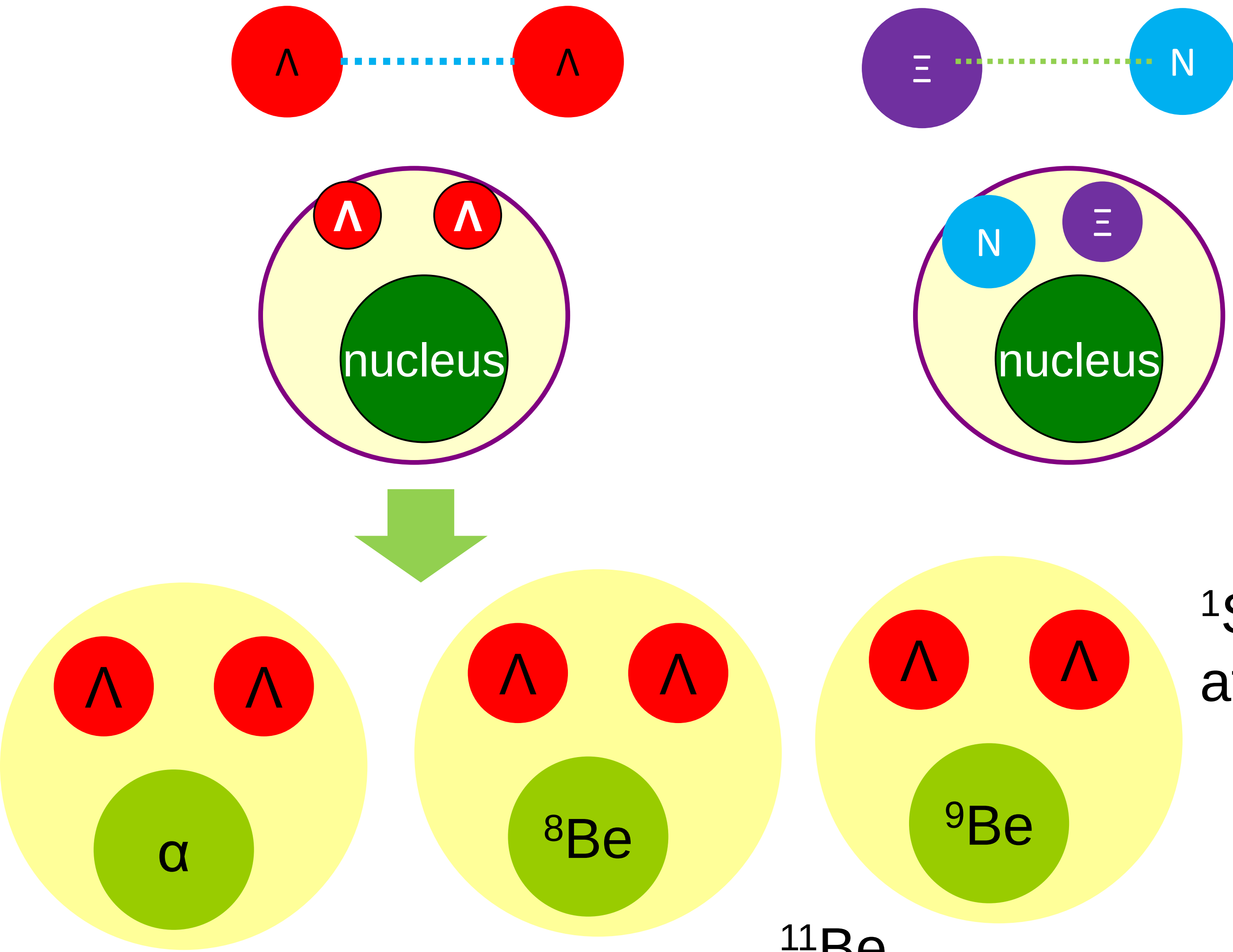
It is conjectured that extreme limit, which includes many Λs in nuclear matter, is the core of a neutron star.

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



$^{1}S_{0}$ of ΛΛ interaction attractive

$_{\Lambda\Lambda}{}^{6}$He $_{\Lambda\Lambda}{}^{10}$Be $_{\Lambda\Lambda}{}^{11}$Be

[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).

· 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

comparison

Emulsion experiment

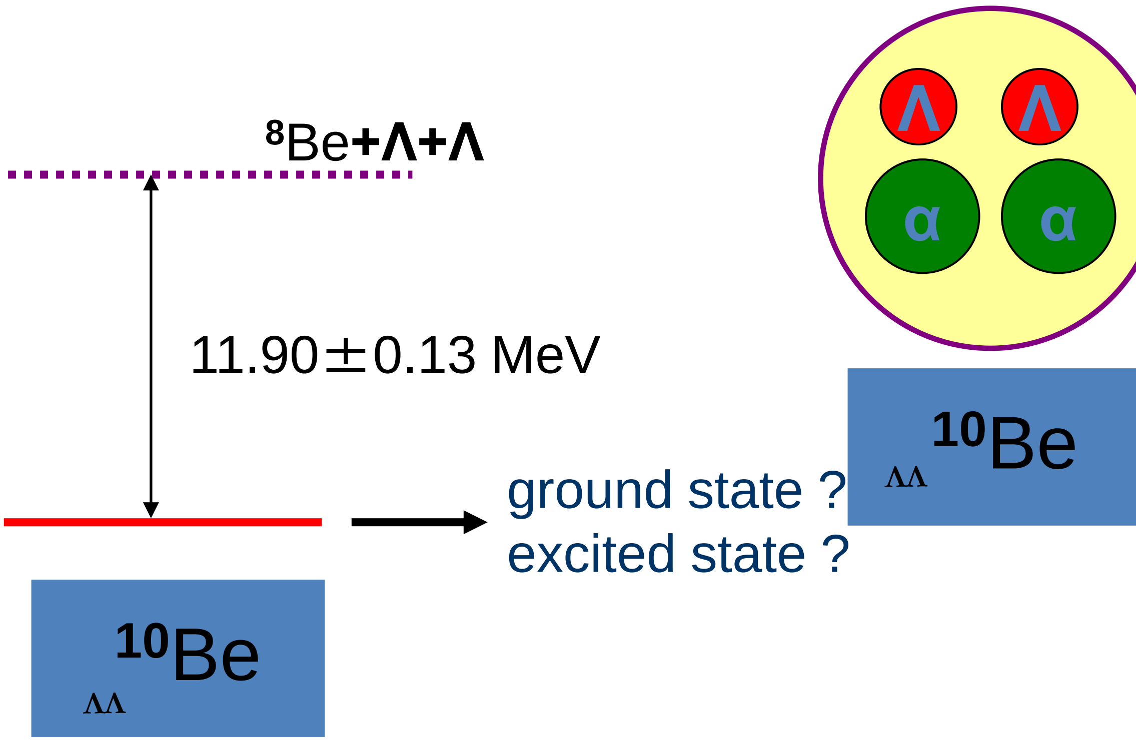
Theoretical calculation

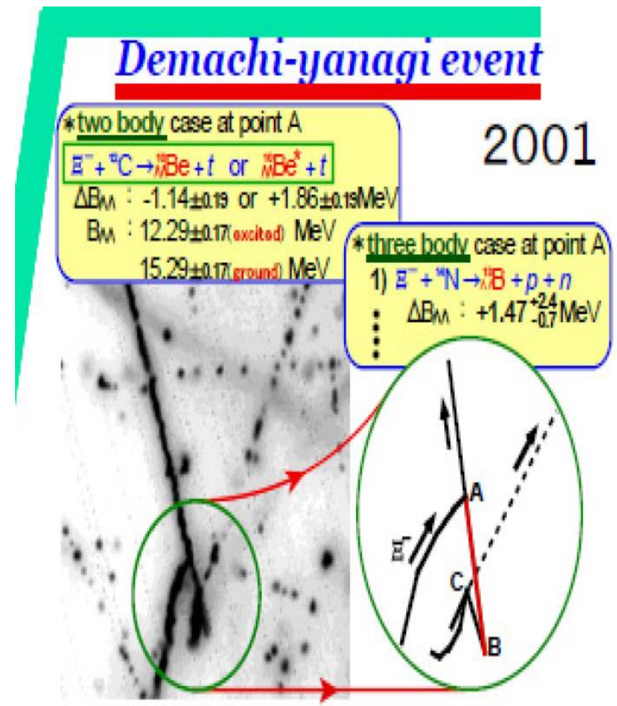
input: ΛΛ interaction to reproduce the observed binding energy of ${}_{\Lambda\Lambda}^{6}He$

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





Demachi-Yanagi event

Our few-body caluclation method

Gaussian Expansion Method (GEM) , since 1987 ,

- A variational method using Gaussian basis functions
- Take all the sets of Jacobi coordinates

Developed by Kyushu Univ. Group, Kamimura and his collaborators.

Review article :
E. Hiyama, M. Kamimura and Y. Kino,
Prog. Part. Nucl. Phys. 51 (2003), 223.

High-precision calculations of various 3- and 4-body systems:

Exotic atoms / molecules , Light hypernuclei,

3- and 4-nucleon systems, 3-quark systems,

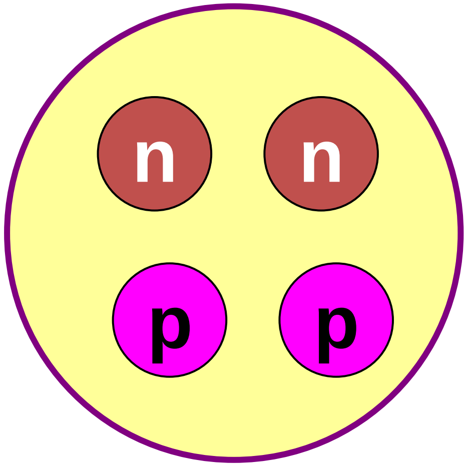
multi-cluster structure of light nuclei, PRC **64**, 044001(2001)

Benchmark-test calculation to solve the 4-nucleon bound state

7 different groups (18 co-authors)

1. Faddeev-Yakubovski (Kamada et al.)
2. Gaussian Expansion Method
   (Hiyama and Kamimura)
3. Stochastic varitional (Varga et al.)
4. Hyperspherical variational (Viviani et al.)
5. Green Function Variational Monte Carlo
   (Carlson at al.)
6. Non-Core shell model (Navratil et al.)
7. Effective Interaction Hypershperical
   HarmonicsEIHH (Barnea et al.)

^{4}He



4-nucleon
bound state
NN**:** AV8'

Benchmark-test calculation of the 4-nucleon bound state

Good agreement among 7different methods

In the binding energy, r.m.s. radius and wavefunction density

H. KAMADA *et al.* PHYSICAL REVIEW C **64** 044001

TABLE I. The expectation values $\langle T \rangle$ and $\langle V \rangle$ of kinetic and potential energies, the binding energies E_b in MeV, and the radius in fm.

Method	$\langle T \rangle$	$\langle V \rangle$	E_b	$\sqrt{\langle r^2 \rangle}$
FY	102.39(5)	−128.33(10)	−25.94(5)	1.485(3)
GEM	102.30	−128.20	−25.90	1.482
SVM	102.35	−128.27	−25.92	1.486
HH	102.44	−128.34	−25.90(1)	1.483
GFMC	102.3(1.0)	−128.25(1.0)	−25.93(2)	1.490(5)
NCSM	103.35	−129.45	−25.80(20)	1.485
EIHH	100.8(9)	−126.7(9)	−25.944(10)	1.486

ours

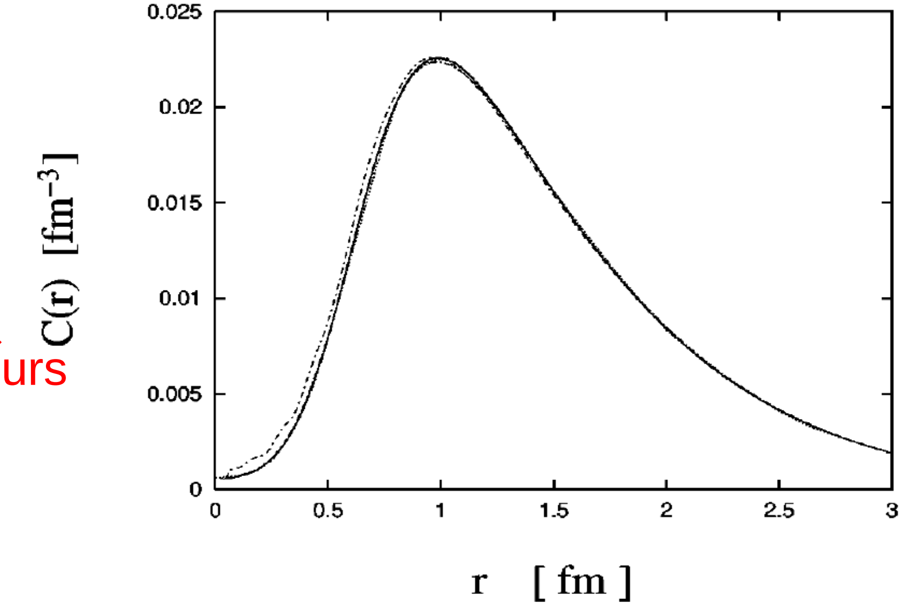
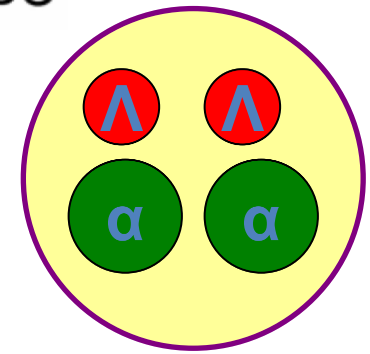


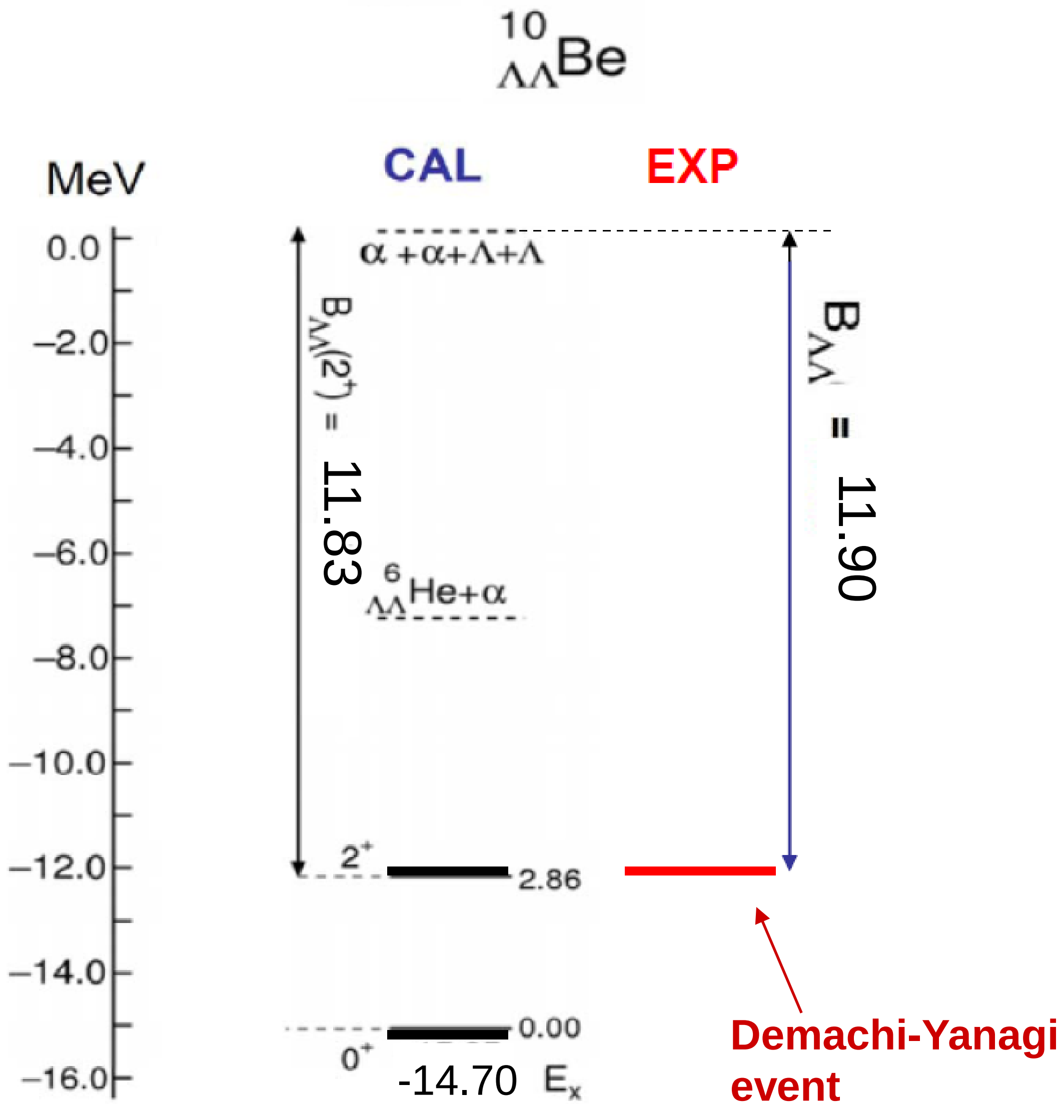
FIG. 1. Correlation functions in the different calculational schemes: EIHH (dashed-dotted curves), FY, CRCGV, SVM, HH, and NCSM (overlapping curves).

very different techniques and the complexity of the nuclear force chosen. Except for NCSM and EIHH, the expectation values of T and V also agree within three digits. The NCSM results are, however, still within 1% and EIHH within 1.5% of the others, but note that the EIHH results for T and V are

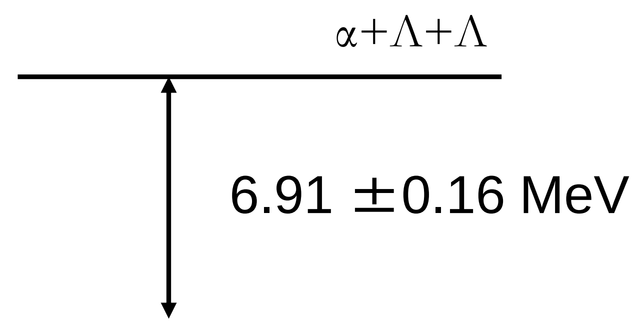
Congratulations!! I was very happy

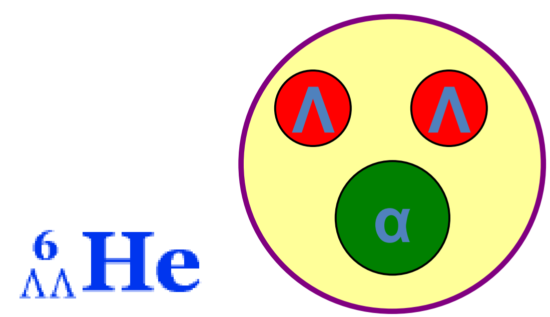
Successful interpretation of spin-parity of ${}^{10}_{\Lambda\Lambda}\mathrm{Be}$





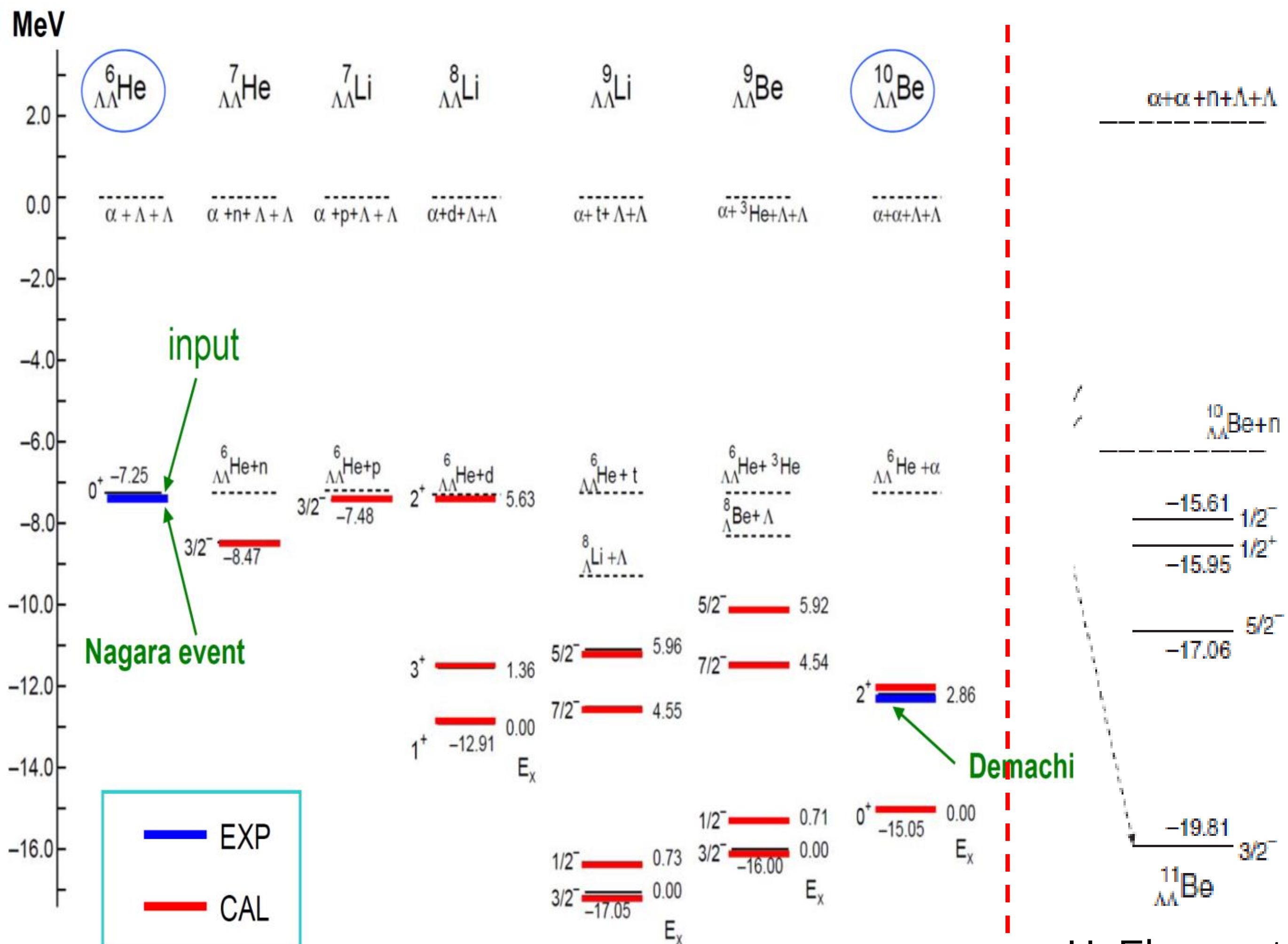
E. Hiyama, M. Kamimura,T.Motoba, T. Yamada and Y. Yamamoto Phys. Rev. 66 (2002) , 024007





Spectroscopy of ΛΛ-hypernuclei

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

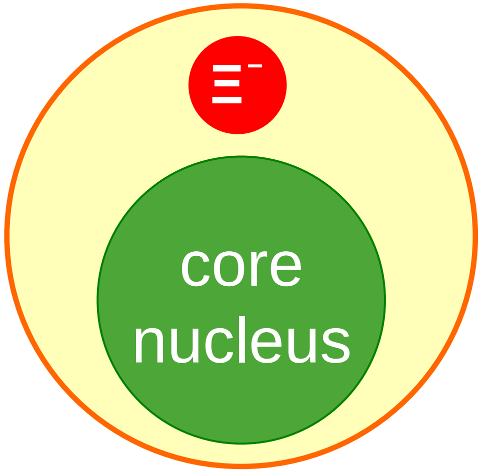


New data: -17.49 MeV

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

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

Ξ hypernuclei

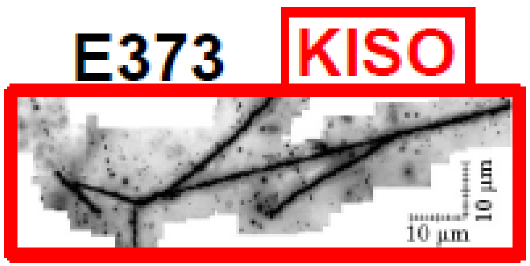


For the study of ΞN interaction, it is important to study the structure of Ξ hypernuclei.

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.



^{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

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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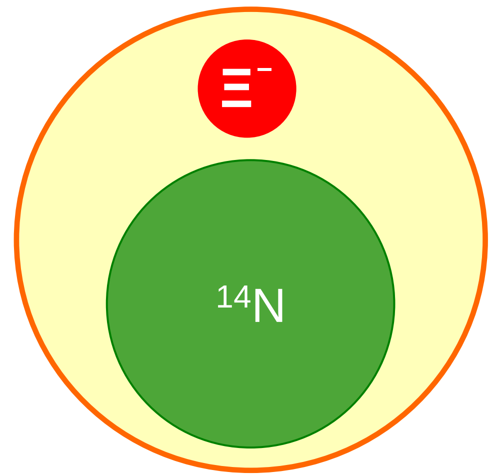
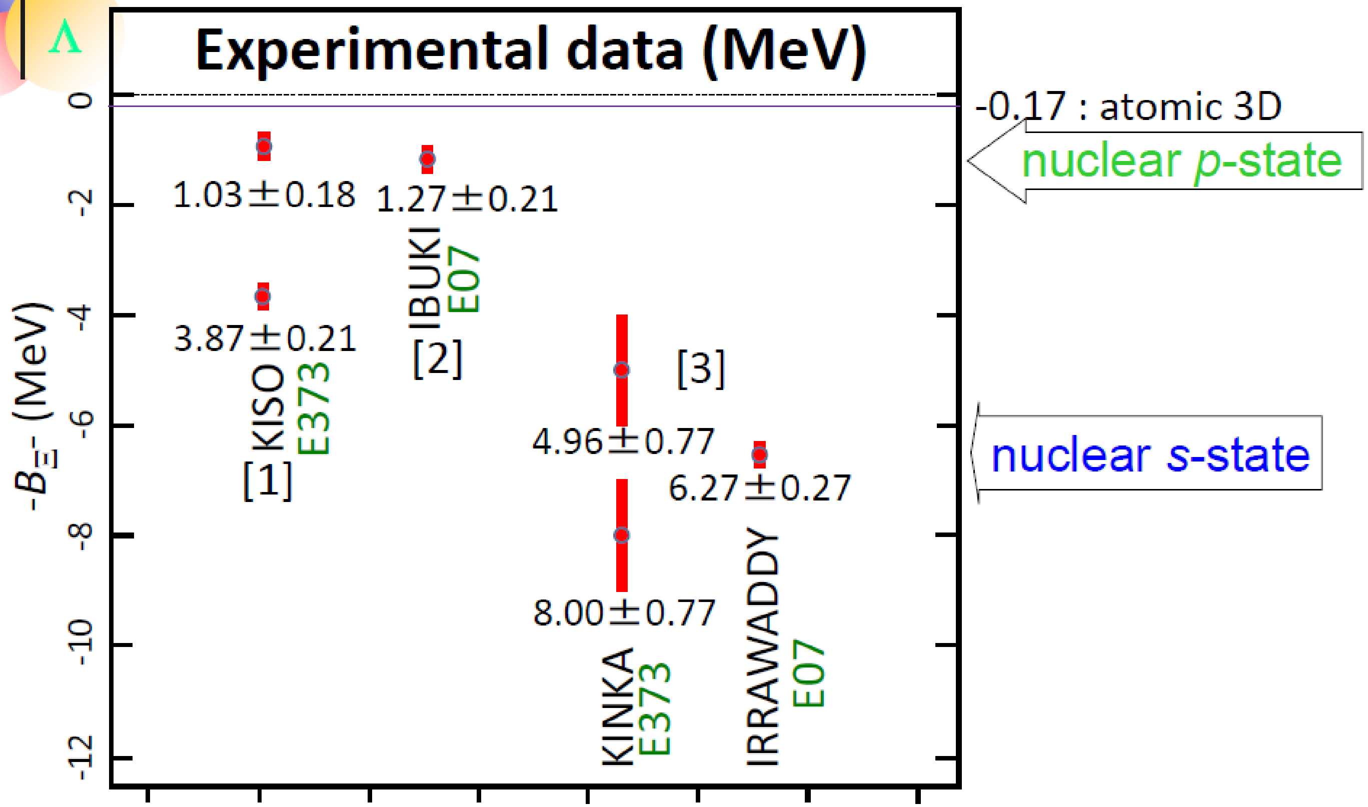
[2] *Department of Physics, Toho University, Funabashi 274-8510, Japan*
[3] *Advanced Science Research Center, JAEA, Tokai 319-1195, Japan*
[4] *Department of Physics, Gyeongsang National University, Jinju 660-701, Korea*
[5] *Institute of Particle and Nuclear Studies, KEK, Tsukuba 305-0801, Japan*
*E-mail: nakazawa@gifu-u.ac.jp

Received October 27, 2014; Revised December 25, 2014; Accepted January 9, 2015; Published March 5, 2015



We understood Ξ-nuclear potential should be attractive.

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

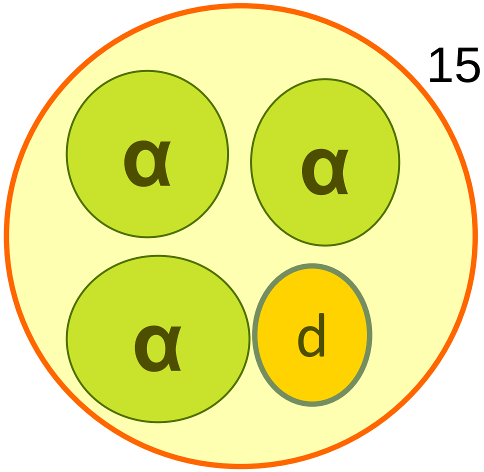


[1] K. Nakazawa, et. al., Prog. Theor. Exp. Phys. **2015**, 033D02 (2015),
E. Hiyama and K. Nakazawa, Ann. Rev. Nucl. Part. Sci. **68**, 131 (2018).
[2] S. Hayakawa, et. al., Phy. Rev. Lett., **126**, 062501 (2021).
[3] M. Yoshimoto, et. al., Prog. Theor. Exp. Phys. **2021**, 073D02 (2021).

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.

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



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

By observation of ${}^{15}_{\Xi}C({}^{14}N\text{-}\Xi)$, we find that $V_{\Xi N}$ itself is attractive.

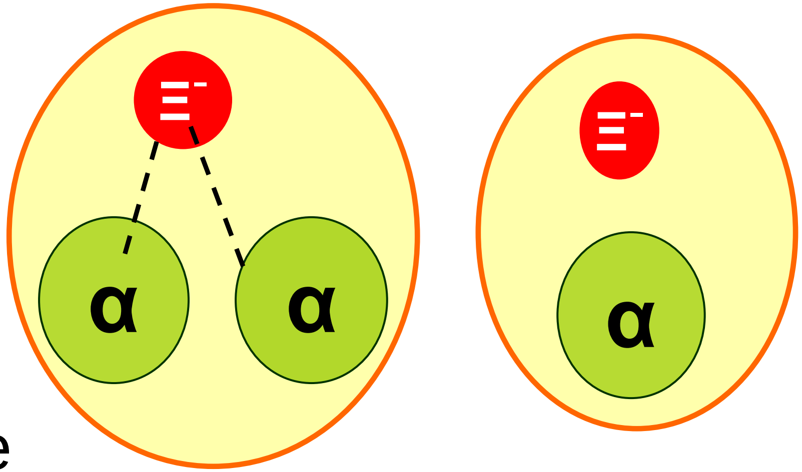
Because,
All of the terms contribute to binding energy of ${}^{15}_{\Xi}C$ (${}^{14}N$ is not spin-, isospin- saturated).

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

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

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

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



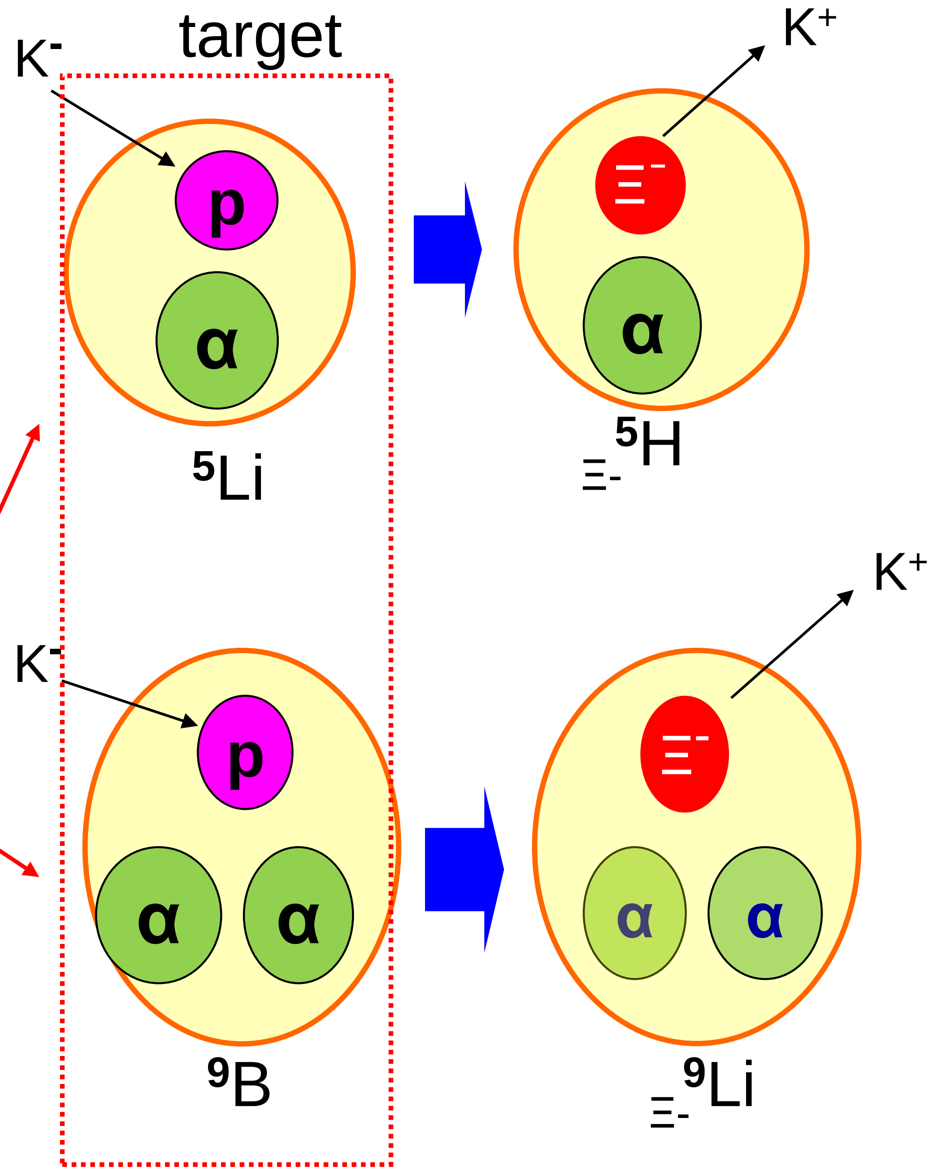
problem : there is NO target to produce them by the (K^-, K^+) experiment .

Because, ・・・

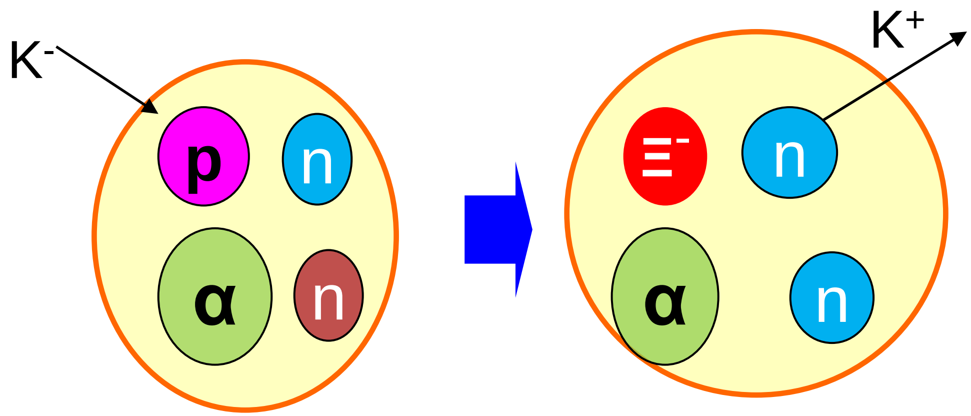
To produce **αΞ$^-$** and **ααΞ$^-$** systems by (K^-, K^+) reaction,

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…

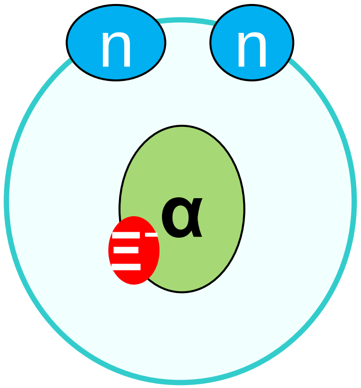


^{7}Li (T=1/2)

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

Why they are suited for investigating V_0?

(more realistic illustration)



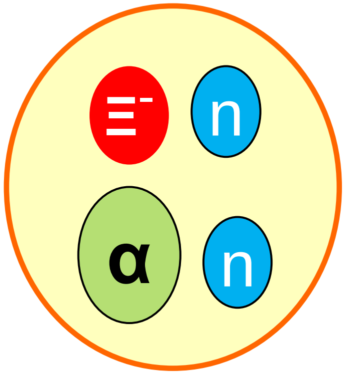
$^{7}_{\Xi^-}H$ (T=3/2)

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**.

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



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

Before the experiments will be done,

we should predict whether this Ξ hypernucleus will be observed as bound states or not.

Namely, we calculate the binding energies of this hypernucleus.

ΞN interaction

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

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.

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),

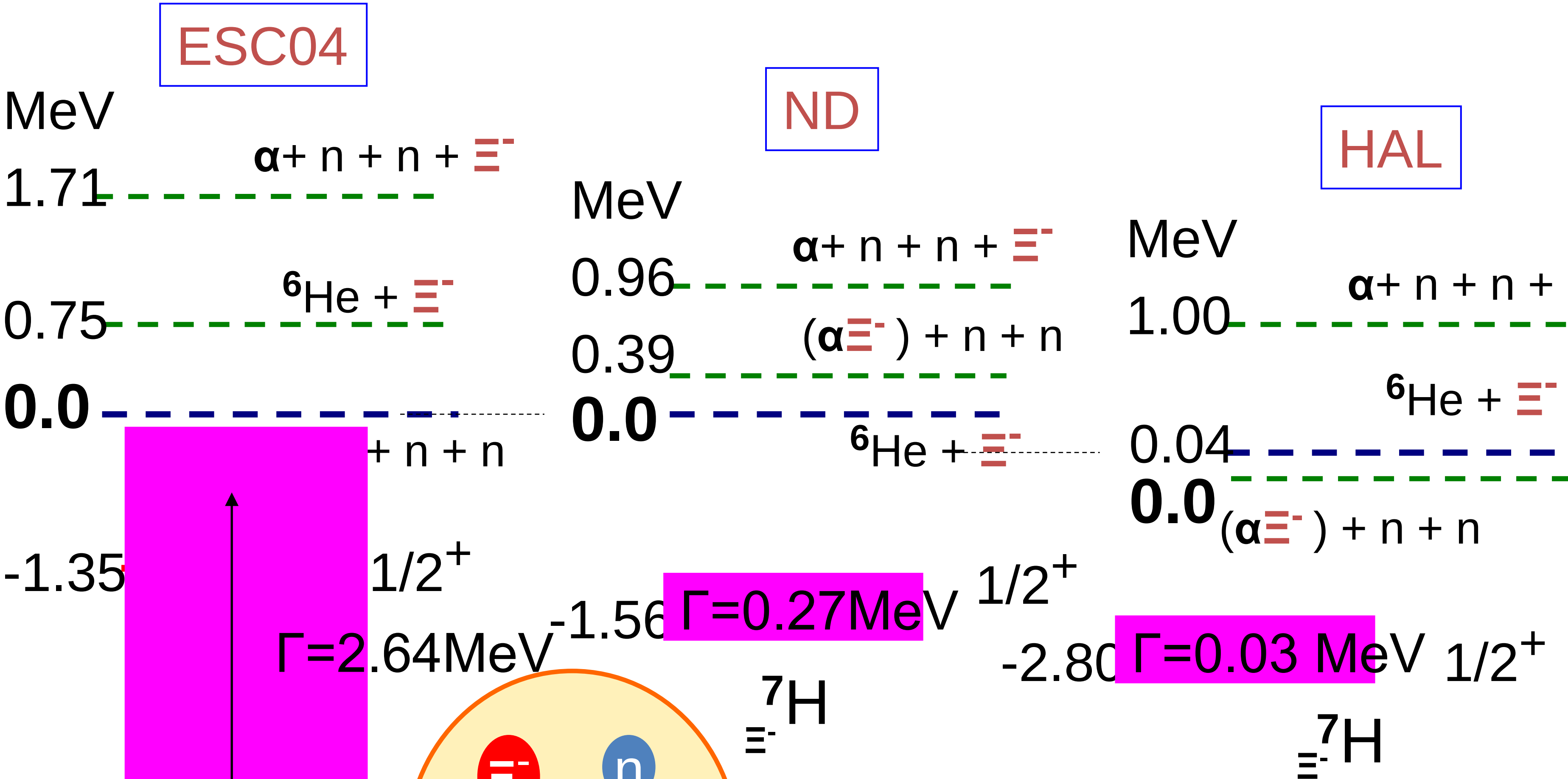
we find that the spin- and isospin-averaged property,

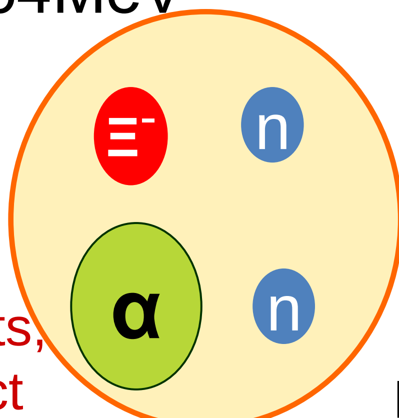
$$V_0 = [\ V(0,0) + 3V(0,1) + 3V(1,0) + 9V(1,1)\ ]\ /\ 16,$$

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

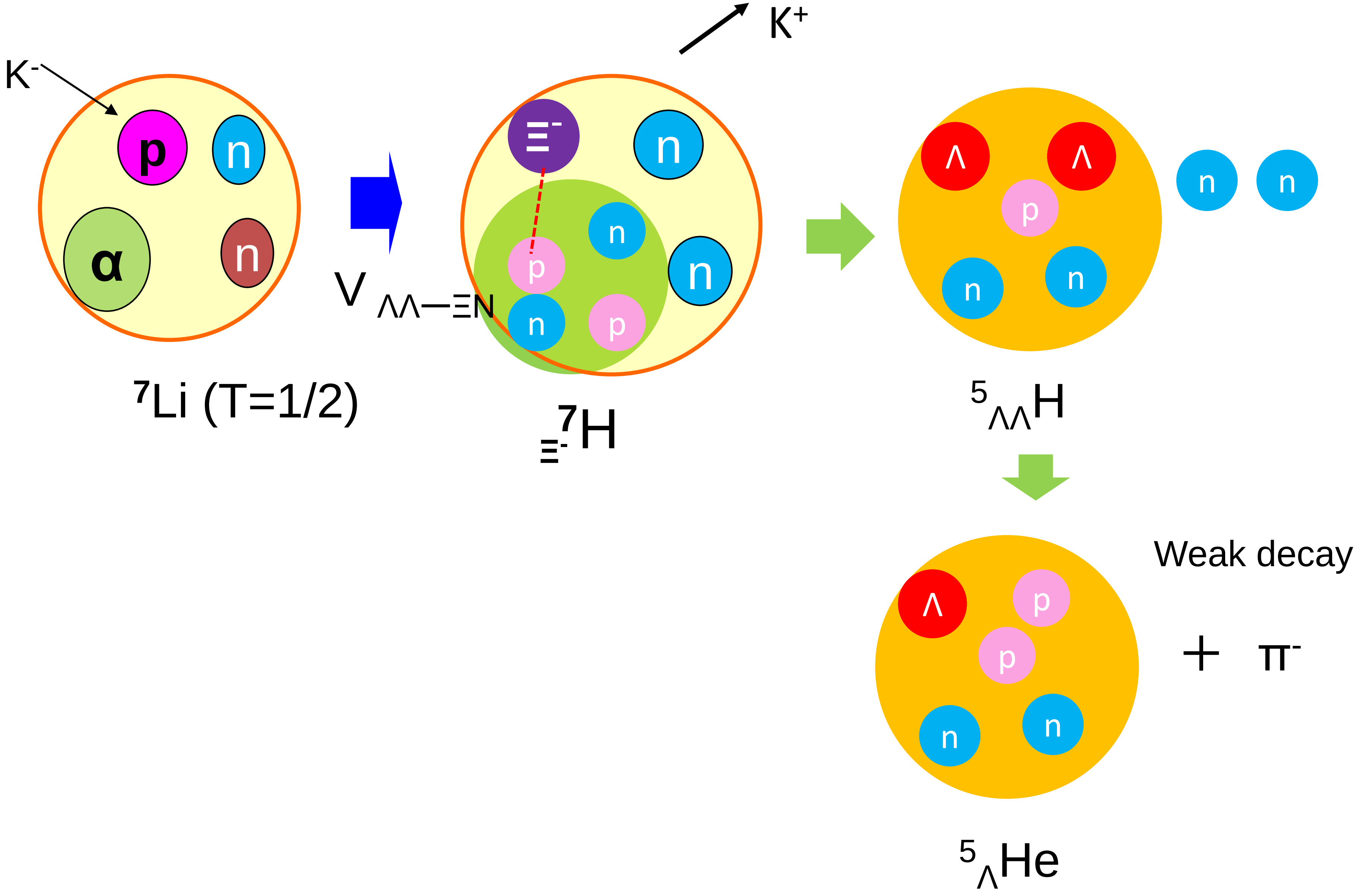




Similar binding energies using ND and ESC04.

In experiments, we can expect a bound state.

However, decay width is dependent on on employed ΞN potential



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

T S

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

which partial contribution makes attractive for V_0 **?**

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

t=1/2
S=1/2

t=1/2
S=1/2

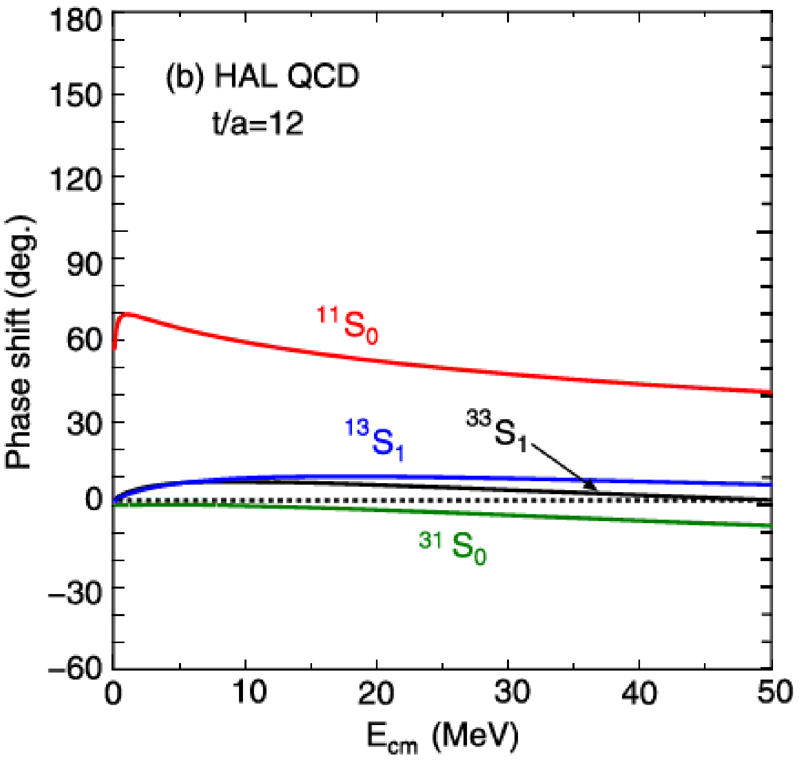
we have a two-body bound state for ΞN system?
No idea

Cf. NN interaction

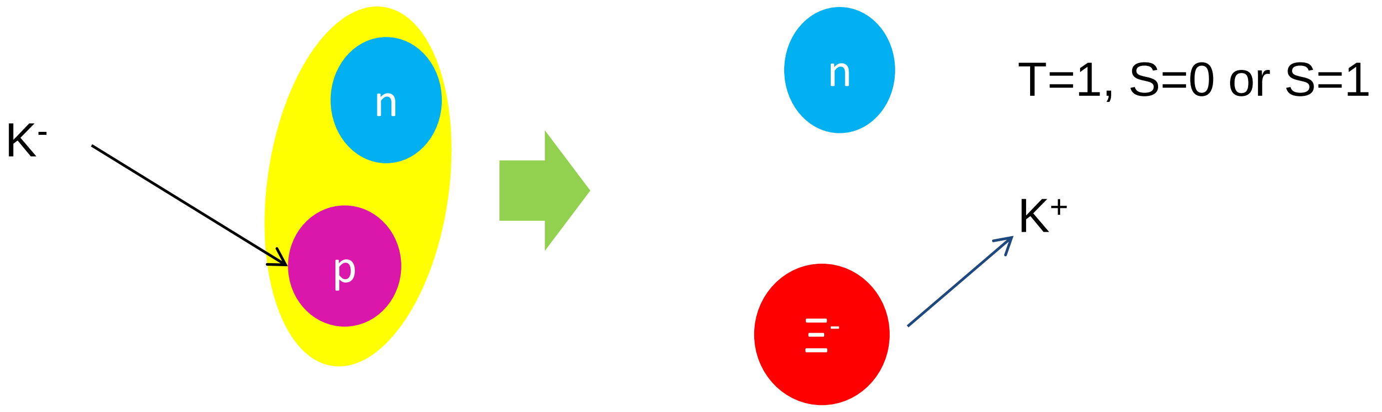
T=0, S=0,l=odd
T=0, S=1 ➡ strong attraction to have a bound state as a deuteron
T=1, S=0
T=1,S=1,l=odd

Property of the spin- and isospin-components of HAL

V(T,S)	HAL
T=0, S=1($^{13}S_1$)	Weakly attractive
T=0, S=0 ($^{11}S_0$)	Strongly attractive
T=1, S=1 ($^{33}S_1$)	Weakly attractive
T=1, S=0($^{31}S_0$)	Weakly repulsive



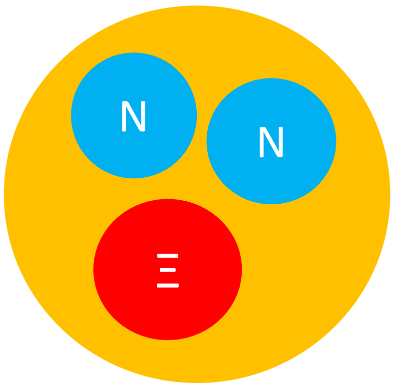
To investigate bound state of ΞN system, it might be possible to perform the following experiment:

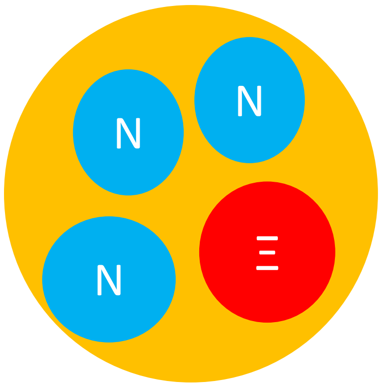


It would be difficult to obtain information on ΞN interaction (T=1,S=0 or 1). Because, there might be no bound state for this system.

To obtain ΞN two-body interaction,
the suited systems to study are s-shell Ξ hypernuclei such as NNΞ and NNNΞ systems.

E. Hiyama et al., PRL124, 092501 (2020)





I show my new results of these light systems.

NN interaction: AV8 potential

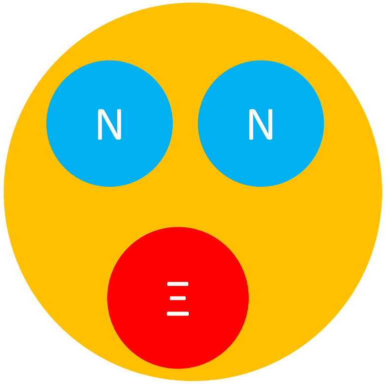
ΞN interaction :

Nijimegen extended soft core potential (ESC08c)

Realistic potential (only ΞN channel)

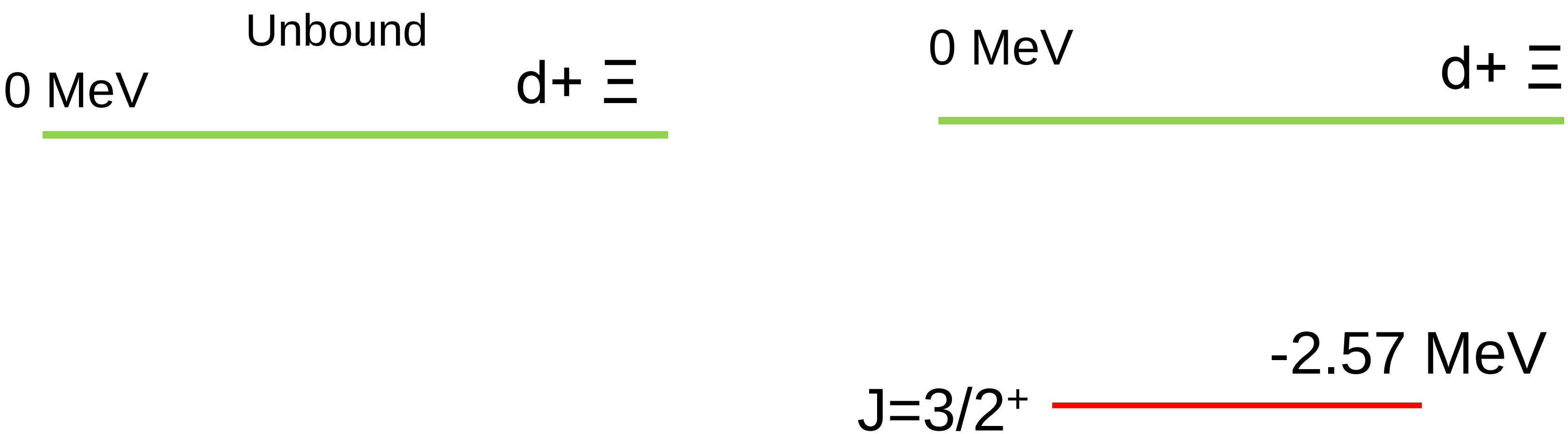
ΞN interaction by HAL collaboration (Lattice QCD calculation)

The potential was made by K. Sasaki, Miyamoto, Hatsuda and Aoki.

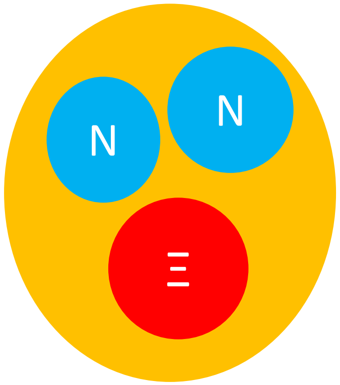


T=1/2, J=1/2$^+$ and J=3/2$^+$

ESC08c



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

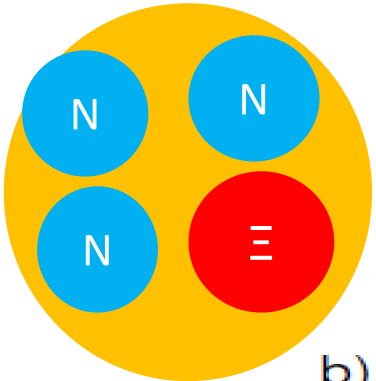
0 MeV

d+ Ξ

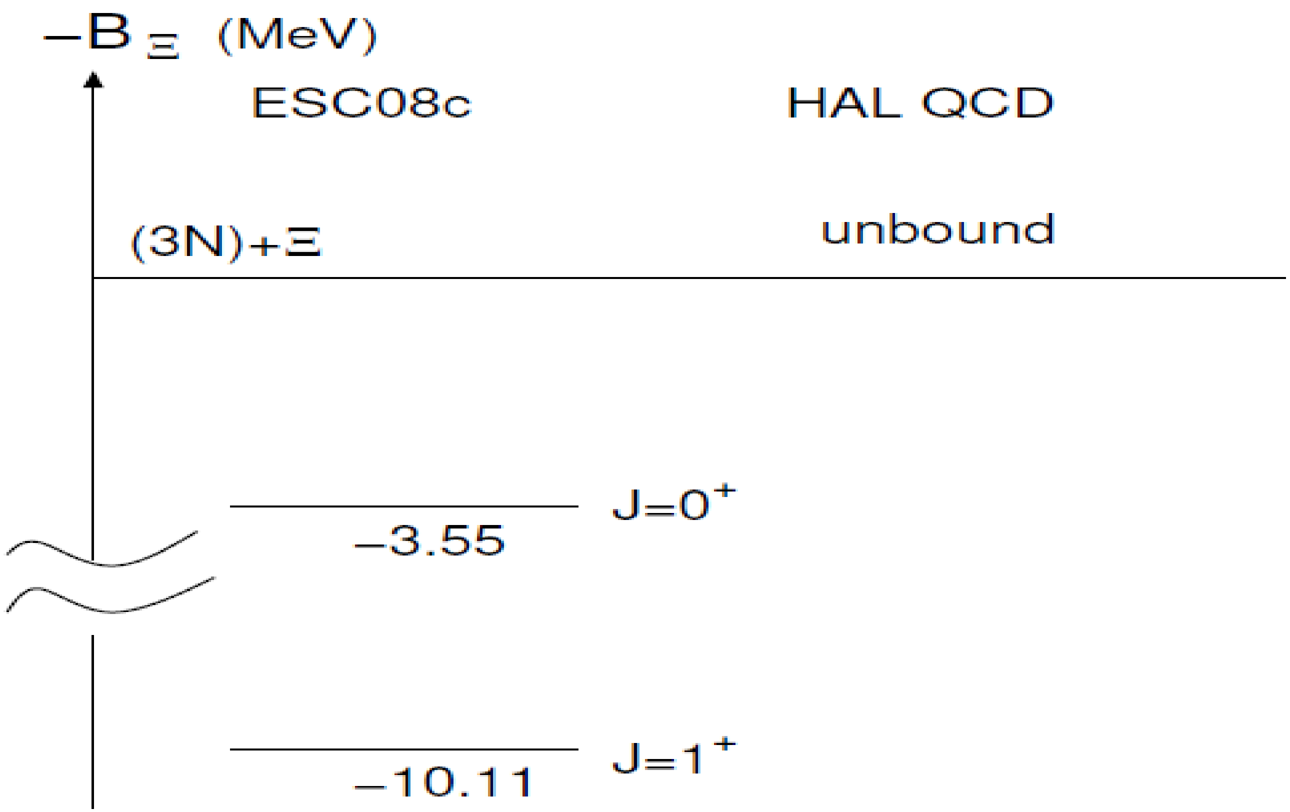
No bound state

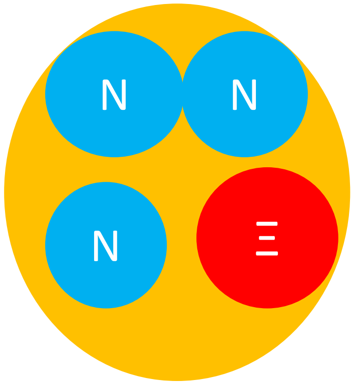
J=3/2$^+$

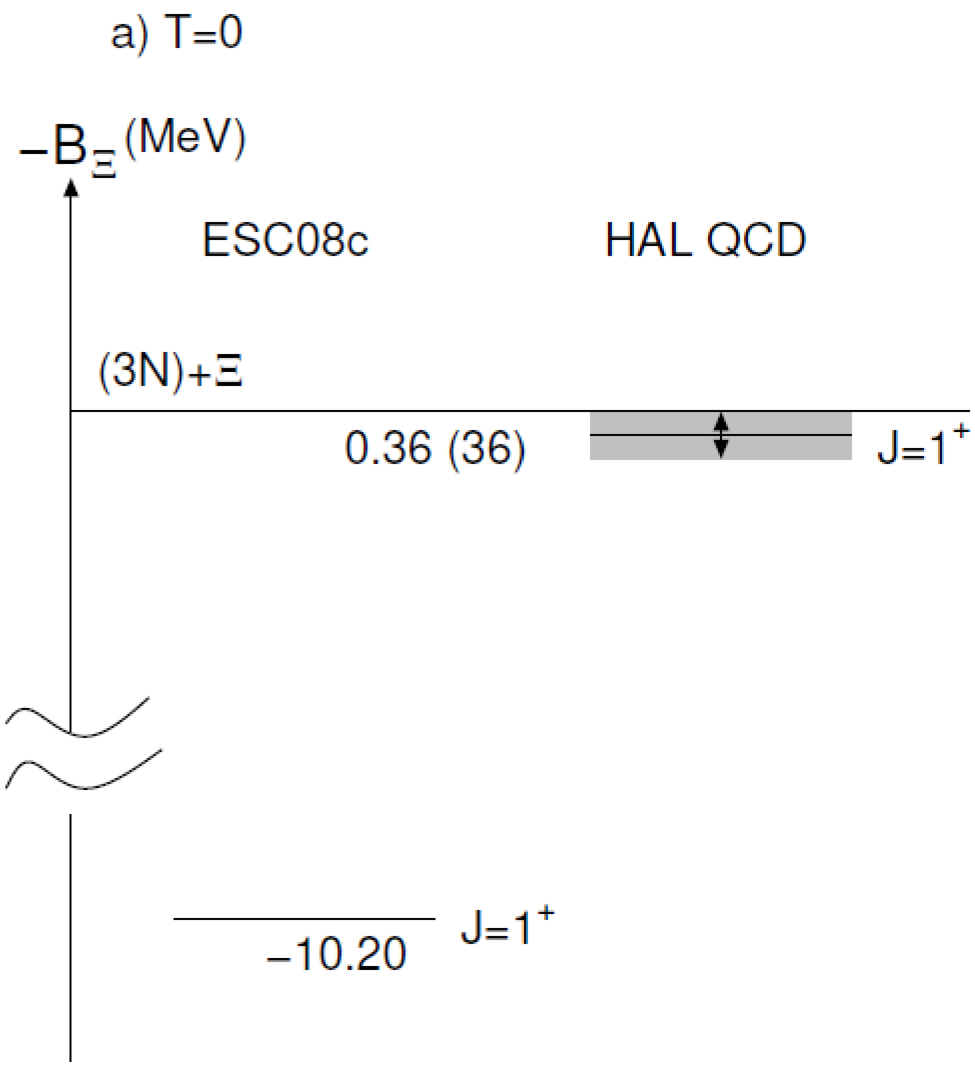
J=1/2+

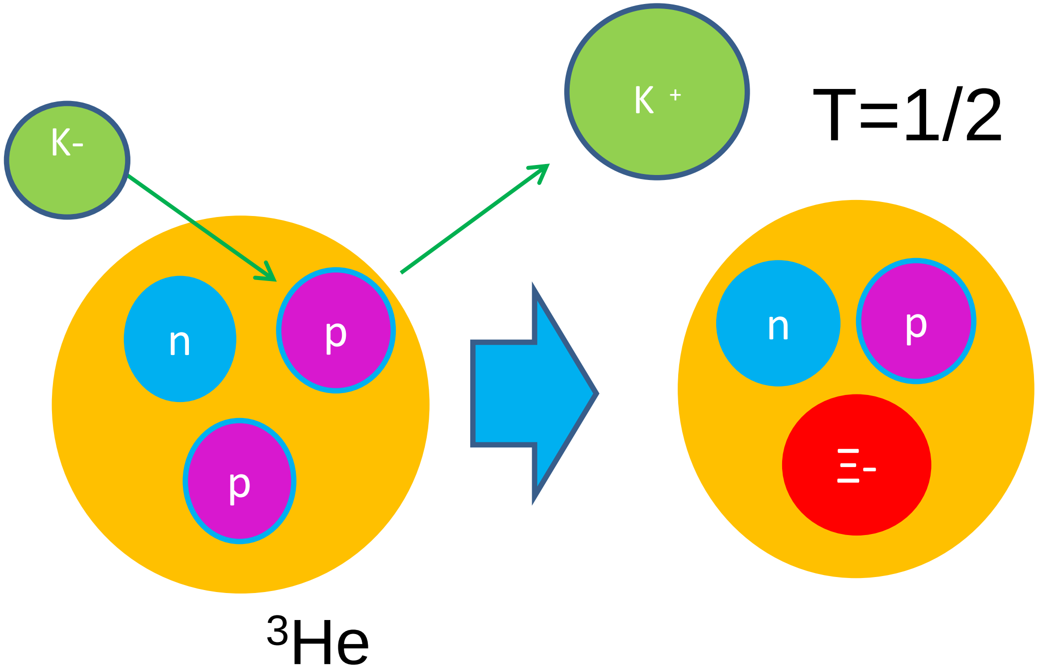


b) T=1



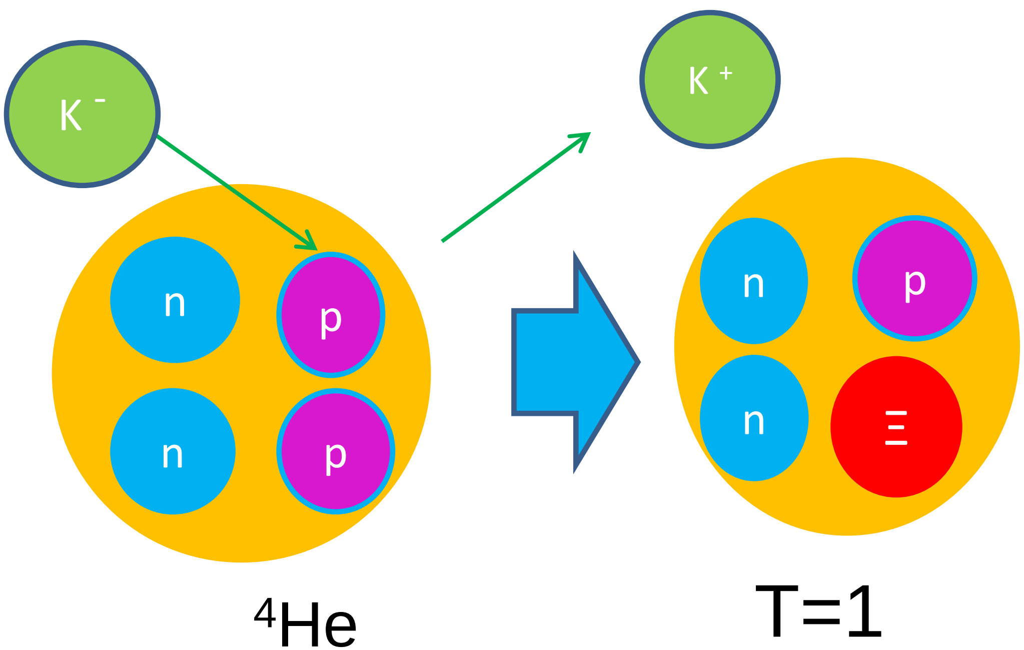

N
N
N
Ξ


a) T=0
$-B_{\Xi}$ (MeV)
ESC08c
HAL QCD
(3N)+Ξ
0.36 (36)
$J=1^+$
−10.20
$J=1^+$



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

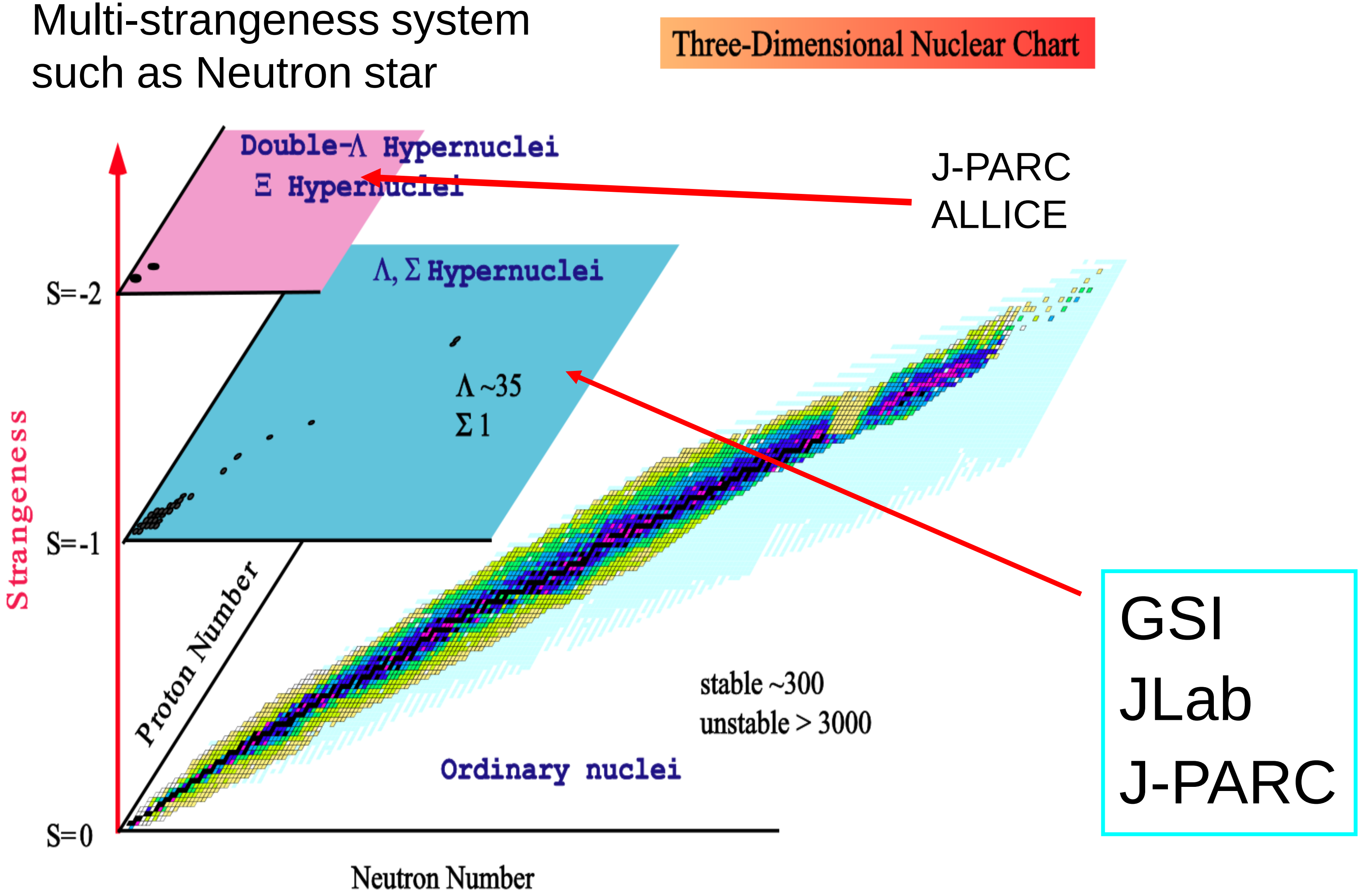
Another tool is to use
Heavy ion collision.



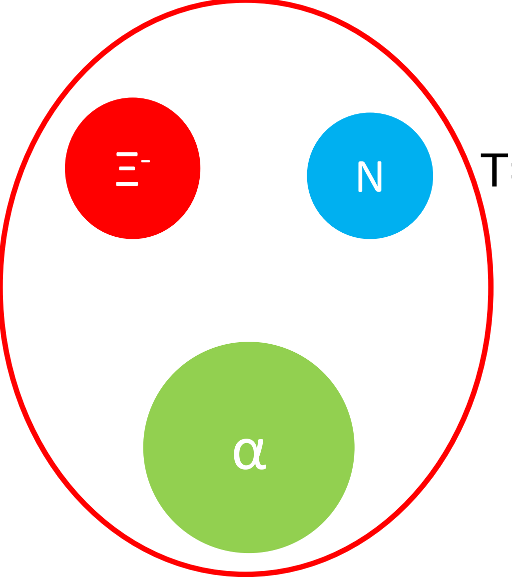
In the future,
we hope to observe
these light Ξ hypernuclei.

Concluding remark

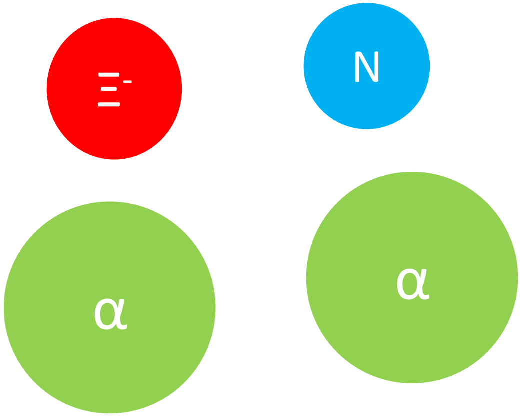
Multi-strangeness system
such as Neutron star



Thank you



T=1, S=0 or S=1



We can add a α or two $α_s$.
Due to the attraction of αΞ and αN interactions,
ΞN system might have bound system.

PHYSICAL REVIEW C **106**, 064318 (2022)

Probing the ΞN interaction through inversion of spin-doublets in $\Xi N\alpha\alpha$ nuclei

E. Hiyama,[1,2] M. Isaka,[3] T. Doi,[4] and T. Hatsuda[4]
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[2]*Nishina Center for Accelerator-Based Science, RIKEN, Wako, 351-0198, Japan*
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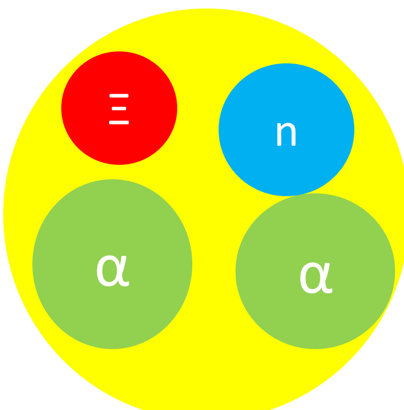
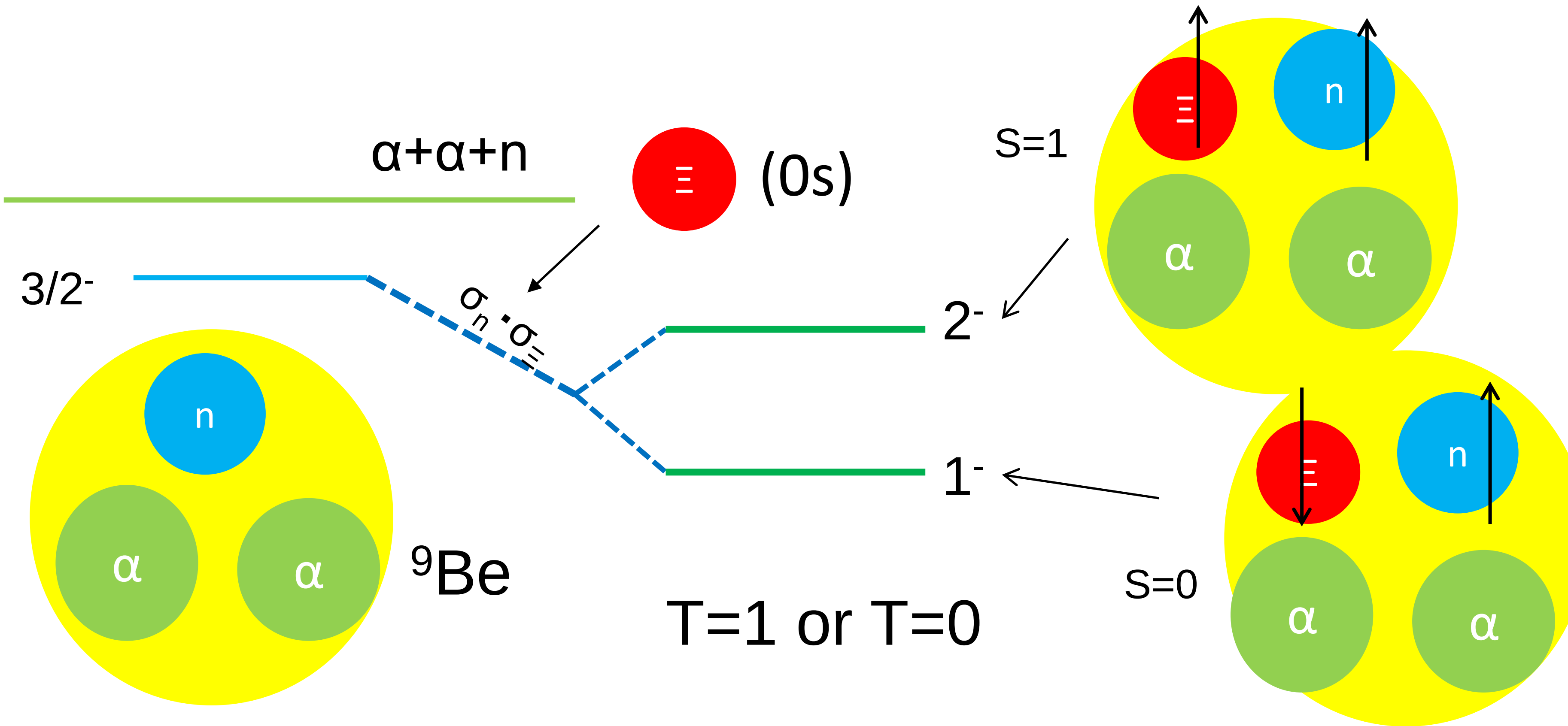
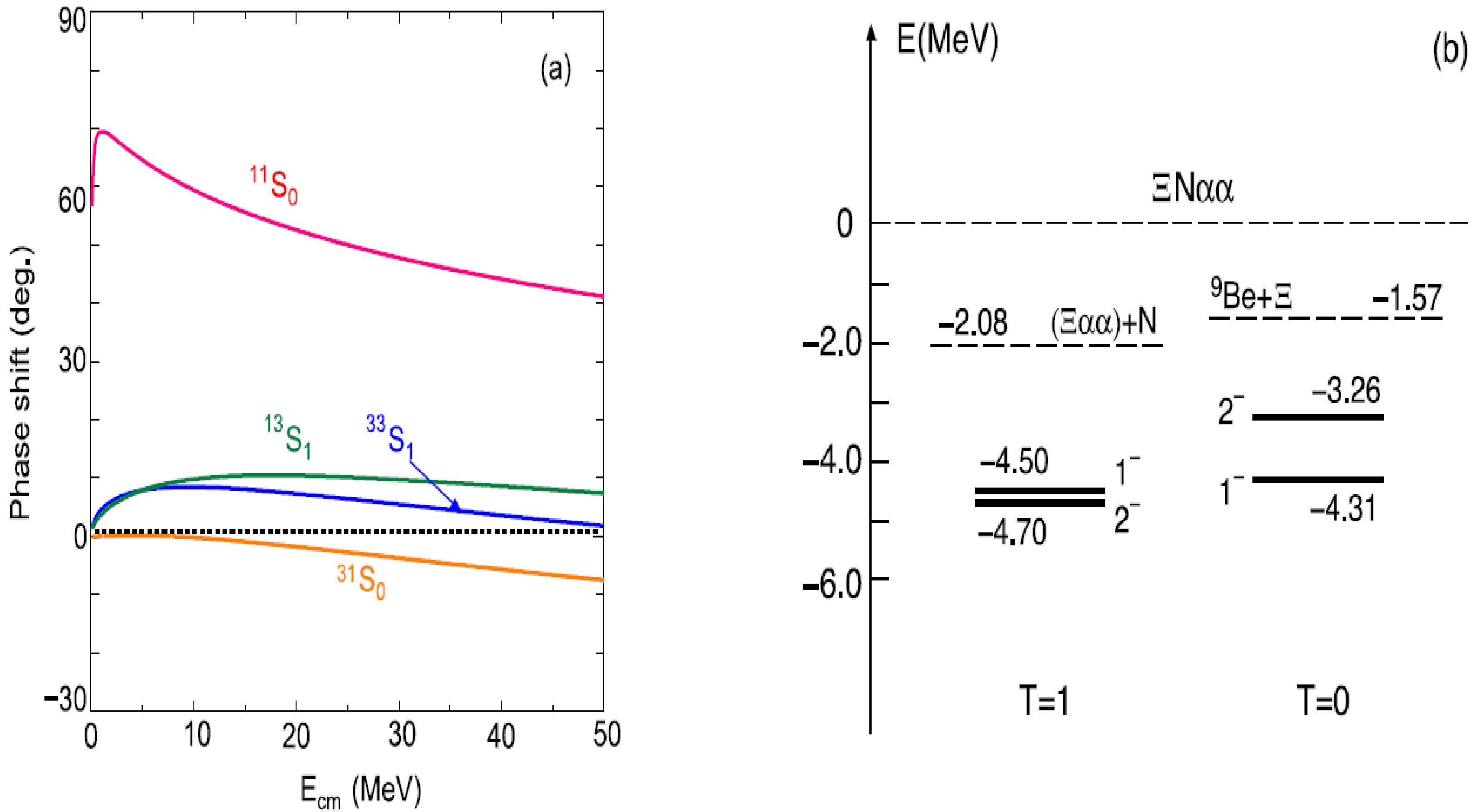
(Received 22 September 2022; accepted 18 November 2022; published 16 December 2022)



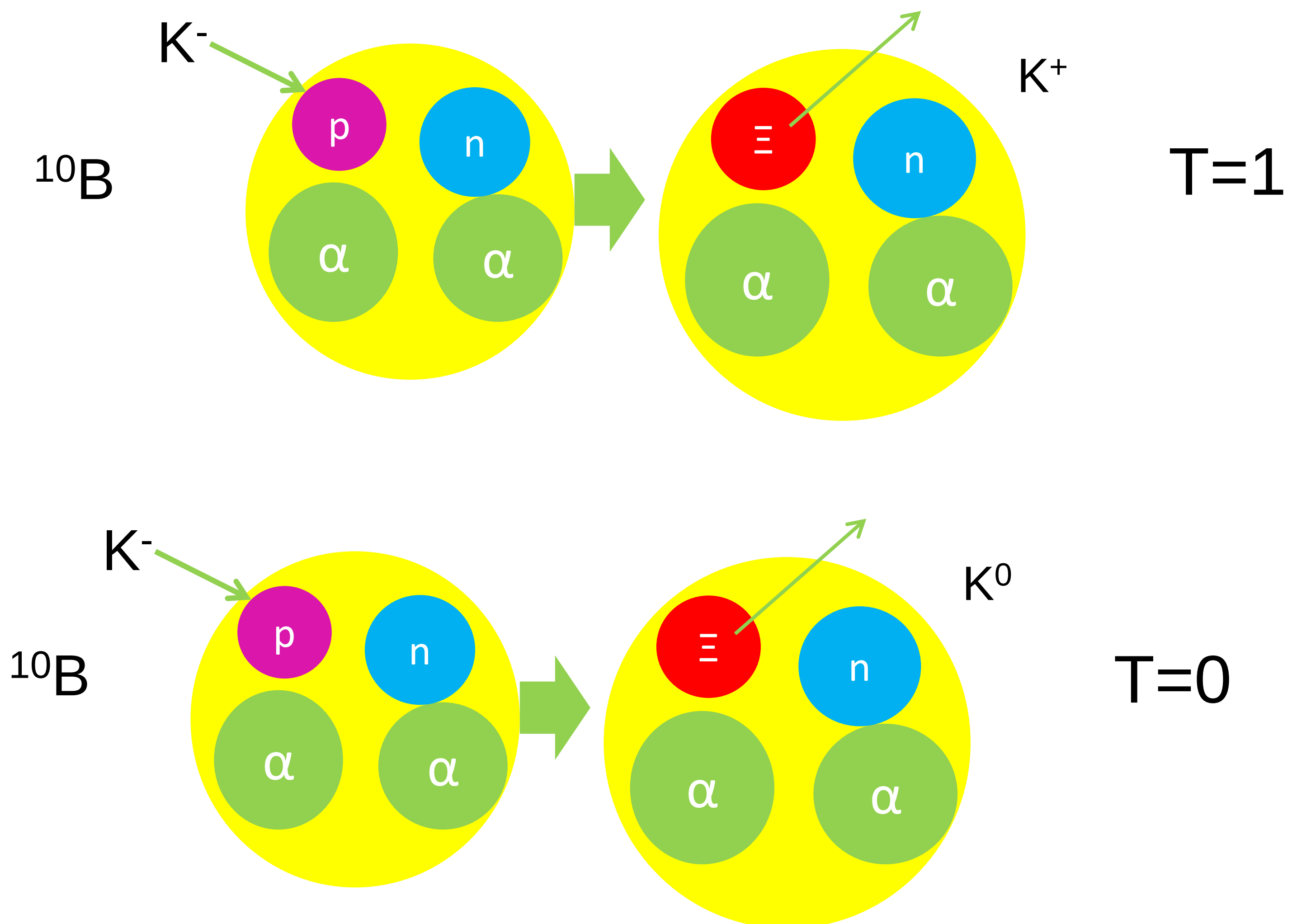
This Ξ hypernucleus
is suited for study of spin-isospin
ΞN interaction.


α+α+n
Ξ
(0s)
3/2-
σn・σΞ
2-
1-
S=1
Ξ
n
α
α
S=0
Ξ
n
α
α
n
α
α
9Be
T=1 or T=0



From the level structure of A=10 Ξ hypernuclei, we obtain information on spin- isospin parts of ΞN interaction.
Level ordering is important.

To obtain information on two-body partial wave contribution, it is useful to employ ^{10}B target.



Strategy of how to solve ‘hyperon puzzle’ together with Theory and experiment using K1.1 and HIHR

International network is important.

My collaborators

Brazil: M. Yamashita(Sao Paulo)

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T. Doi(RIKEN), T. Hatsuda(RIKEN), T. Myo(Osaka),
M. Oka(JAEA), K. Sasaki(Kyoto),
Y. Tanimura(Tohoku), T. Motoba(Osaka),
Y. Yamamoto(Tsuru),
T. Yamada(Kanto), Y. Funaki(Kanto),
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R. Lazauskas(Strasburg)

Netherland: Th. Rijken(Nijmegen)

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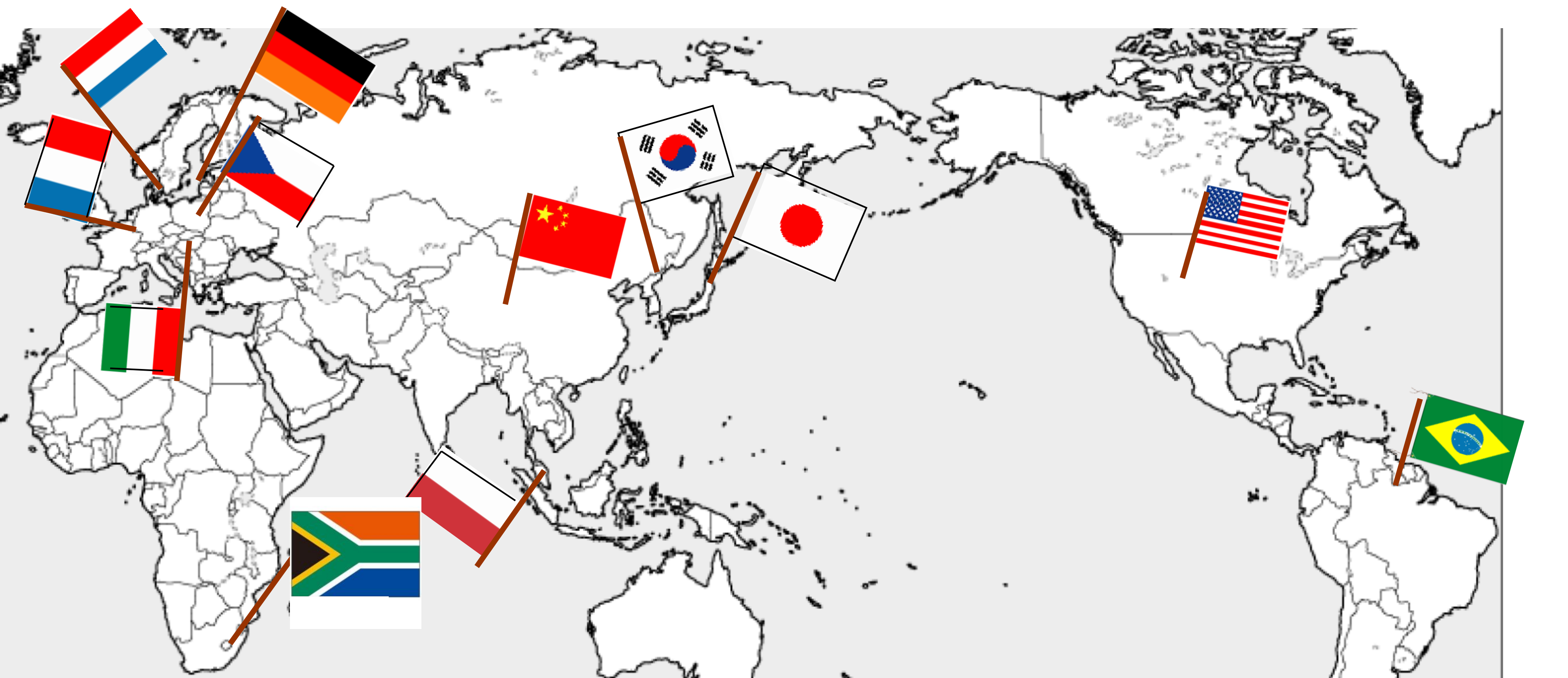


YN scattering experiment (K1.1)

Femtoscopic experiment

Realistic YN interaction

Chiral effective field theory (J. Haidenbauer, L. Geng),

Nijmegen:meson-exchange potential (Th.A. Rijken)

Lattice QCD (T. Doi, K. Sasaki etc.)

+

Ab- initio calculation: No-core shell model calculation(R. Worth etc.)

Self-consistent Green's function method(C. Barbieri)

Gaussian Expansion Method(E. Hiyama)

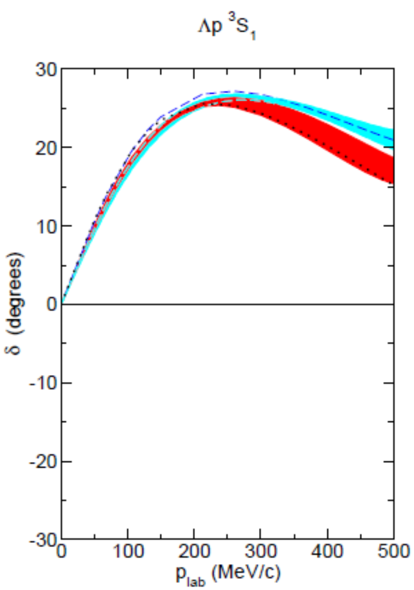
comparison

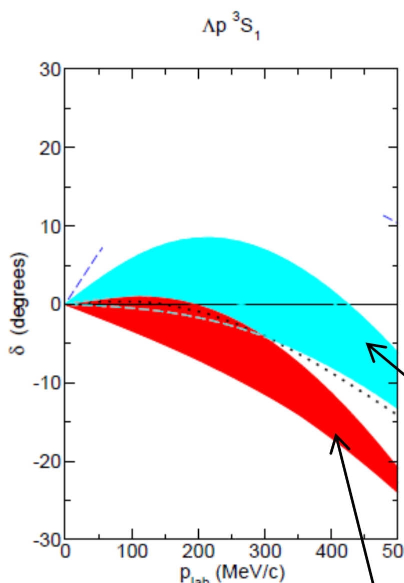
Data on s-shell Λ hypernuclei
and light neutron-rich Λ hypernuclei
at HIHR (better than 100 keV accuracy)

Determination of YN interaction

Current situation

Two-body interaction





Phase shift with ΛN-ΣN coupling

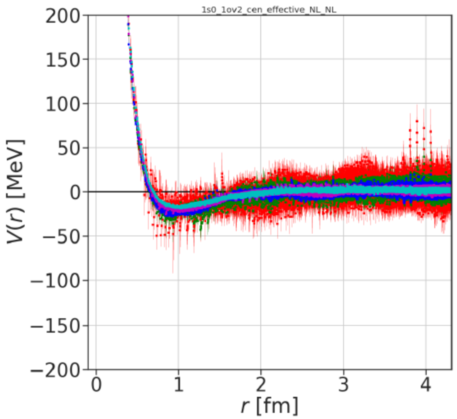
Phase shift without ΛN-ΣN couping

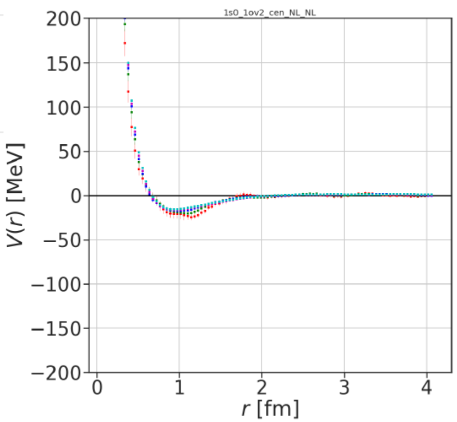
Chiral YN interaction (2013,2019):
still, we have a large degree of ambiguity for ΛN-ΣN coupling.

HAL potential (based on Lattice QCD)

ΛN effective potential

$^1S_0$ m_π=146MeV





given by Takahiro Doi at Lattice21 symposium

YN scattering experiment (K1.1)

Femtoscopic experiment

Realistic YN interaction

Chiral effective field theory (J. Haidenbauer, L. Geng),

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Ab- initio calculation: No-core shell model calculation(R. Worth etc.)

Faddeev method(A. Nogga, R. Lazauskas etc)

Gaussian Expansion Method(E. Hiyama)

comparison

Data on s-shell Λ hypernuclei and light neutron-rich Λ hypernuclei at HIHR (better than 100 keV accuracy)

Determination of YN interaction

Current situation

Ab-initio calculation

Faddeev method: up to 4-body calculation
Gaussian Expansion method: up to 5-body calculation
Non-core shell model calculation: up to 13-body calculation

By development of
Supercomputer,
It is possible to
extend the method
to more than
10-body calculation.

Heavy Λ hyperclei (Pb, Sn, Zr, La, Y ・・・) at HIHR

Relativistic mean field theory(J. Hu, Y. Zhang, S-G. Zhou, T. Sun, H. Sagawa etc.)
Skyme Hartree Fock theory(X-R. Zhou)
Brueckner-Hartree-Fock(H-J. Schulze, I. Vidana)
AMD calculation (M. Isaka)

+

Effective YN interaction +ΛNN three-body interaction

Provide energy spectra with better than 100 keV accuracy at HIHR

Determination of short-range part of ΛNN interaction

Realistic two-body interaction +ΛNN three-body interaction

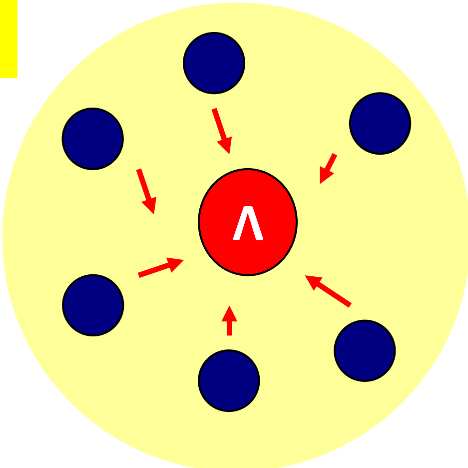
Coupled-cluster calculation (Togashi)
Brueckner-Hartree-Fock (Schlze,Vidina)

Reliable EOS

At the same time, another important issue is to explore interesting phenomena in Λ hypernuclei.

No Pauli principle
Between N and Λ

Hypernucleus



Λ particle can reach deep inside, and attract the surrounding nucleons towards the interior of the nucleus.

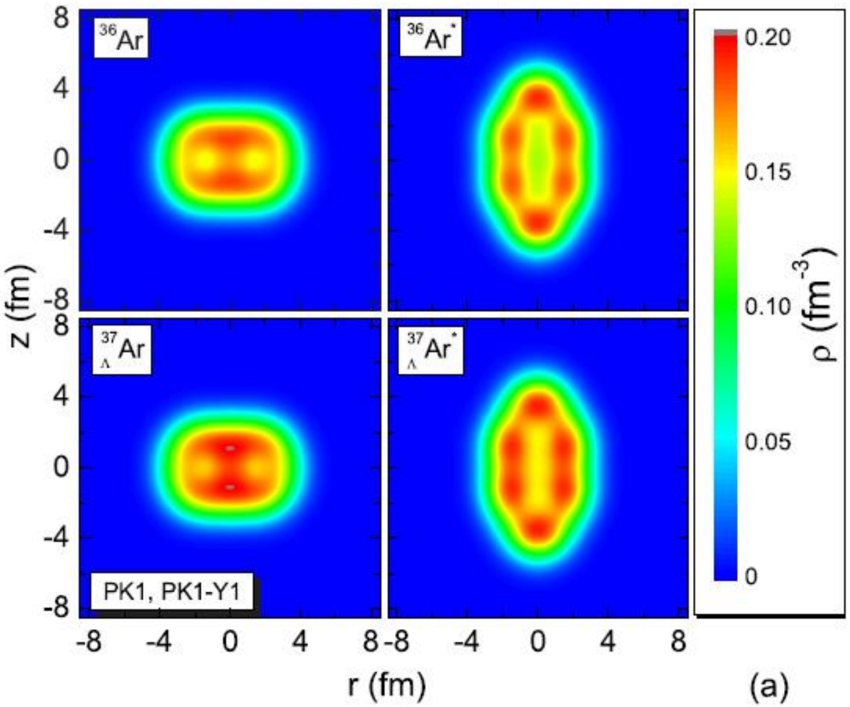
Λ particle behaves as 'impurity' in nuclei.

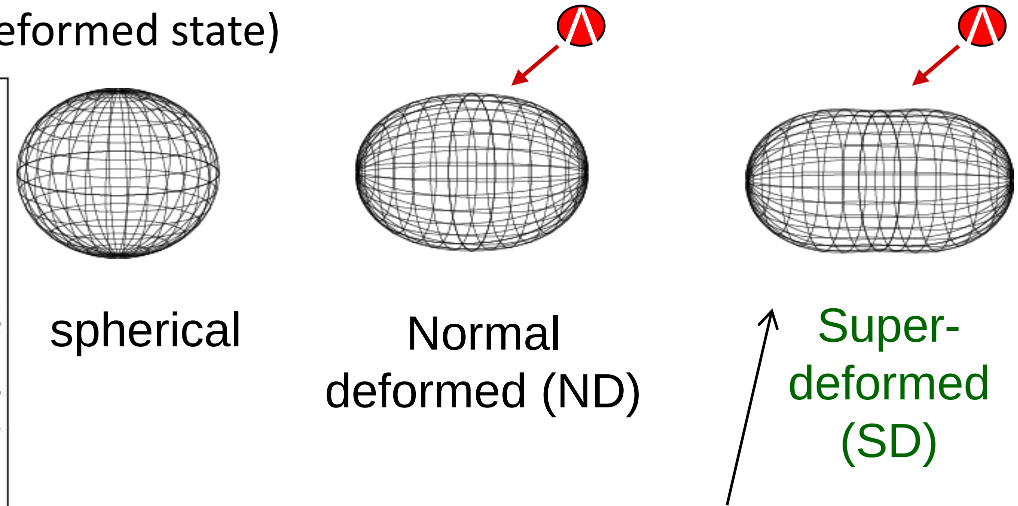
Especially, in heavy Λ hypernuclei, it is expected that there are many interesting phenomena .

- nuclear density is different in states.
- clustering, shell structure
- linear chain state in high excited state
- super-deformed states

For example:

ground state excited state(super-deformed state)





Super-deformed shape is related to the appearance of a large shell gap at a 2:1 axis ratio of the nuclear deformation for Specific numbers.

B-N. Lu, E. Hiyama, H. Sagawa, S-G. Zhou, PRC89, 044307(2014).

We can see ring-shape structure more clearly by the addition of Λ particle.

Once we have a lot of data on heavy Λ hypernuclei, we can explore interesting phenomena in Λ hypernuclei.

Wait for many data of heavy Λ hypernuclei at HIHR

Chinese theorists are quite interested in hypernuclear physics from view point of mean field theory.

To stimulate the Chinese researchers furthermore, I organized strangeness nuclear physics workshop in China and Japan.

(1) SNP workshop, Osaka, Japan, 2017
(2) SNP workshop, Changsha,China, 2014
(3) SNP workshop, Xiamen, China, 2013

SNP workshop, Xiamen, China, 2013

SNP workshop, Osaka, 2017

Next SNP workshop (online)

・International workshop on Strangeness nuclear physics
--- future prospect using K1.1 and HIHR new beam line at J-PARC
Dec. 18,19, 2021
Chair: J. Hu (Nankai, China), E. Hiyama(Tohoku/RIKEN)

To encourage PhD students:
・Domestic workshop on Strangeness nuclear physics
Sep. 21-23, 2021 : Hybrid-style(Online+onsite) at Aobayama science hall

International network is important.

My collaborators

Japan: M. Isaka (Hosei), H. Sagawa (Aizu), M. Kimura (Hokkaido)
T. Doi (RIKEN), T. Hatsuda (RIKEN), T. Myo (Osaka),
M. Oka (JAEA), K. Sasaki (Kyoto),
Y. Tanimura (Tohoku), T. Motoba (Osaka),
Y. Yamamoto (Tsuru),
T. Yamada (Kanto), Y. Funaki (Kanto),
A. Umeya (Nihon)

USA: B. F. Gibson (LANL), J. Stone (ONL)

Italy: H-J. Schulze, I. Vidana (Catania)
C. Barbieri (Milano)

France: J. Carbonell (Saclay),
R. Lazauskas (Strasburg)

Brazil: M. Yamashita (Sao Paulo)

Korea: H-C. Kim (Inha), Y. Oh (Kyunpook)
M. Choeun (Soongsil), C. Ho (Daegu)

China: S-G Zhou (CAS), L. Geng (Beihang), X-R. Zhou (Shaighai)
Q. Meng (Nanjing), J. Hu (Nankai), Y. Zhang (Tenjing),
T. Sun (Zhenzhou)

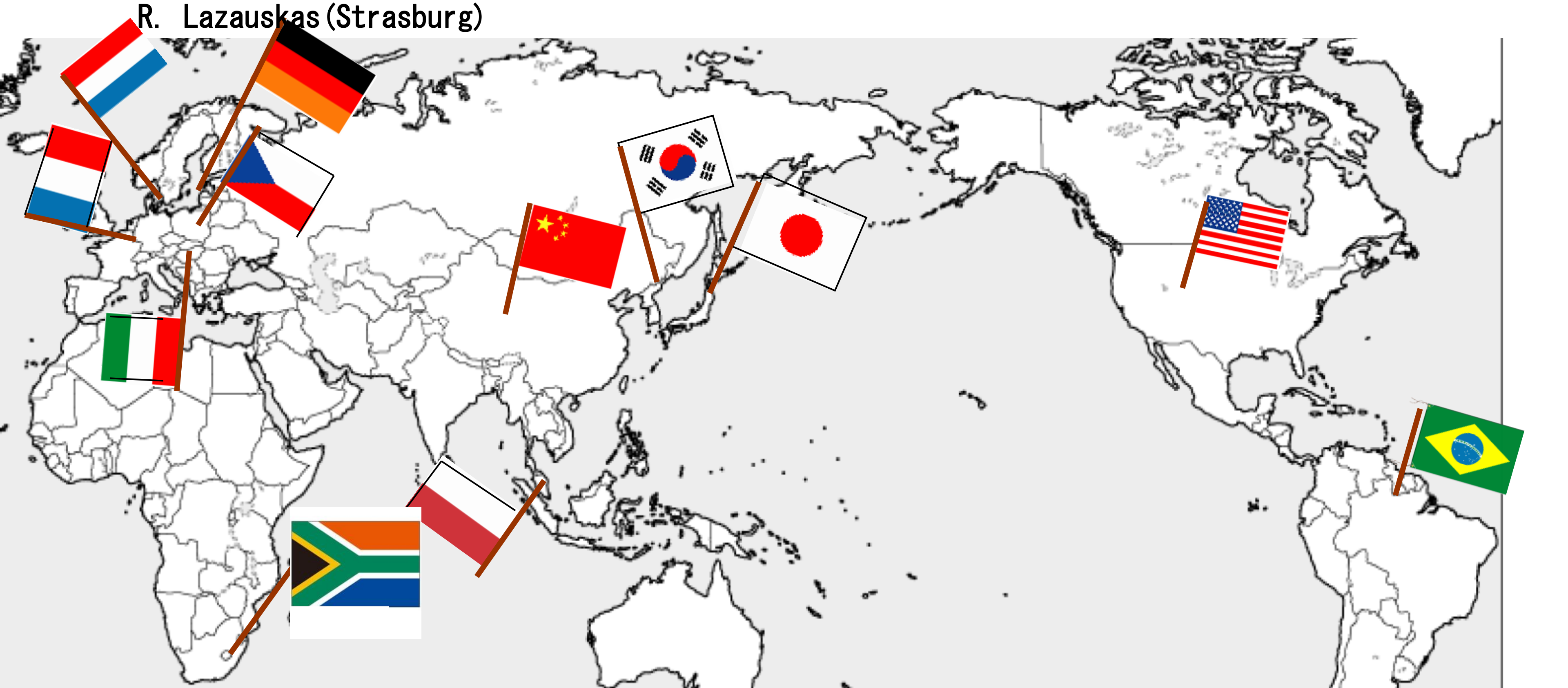
South Africa: E. F. Meoto (Univ. of South Africa)

Indonessia : T. Mart (Indonessia)

Germany: W. Weise (TUM), J. Haidenbauer (Juelich)

Netherland: Th. Rijken (Nijmegen)

Czech: P. Byzovsky (CAS)



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（$\mathbf{V_0}$）.

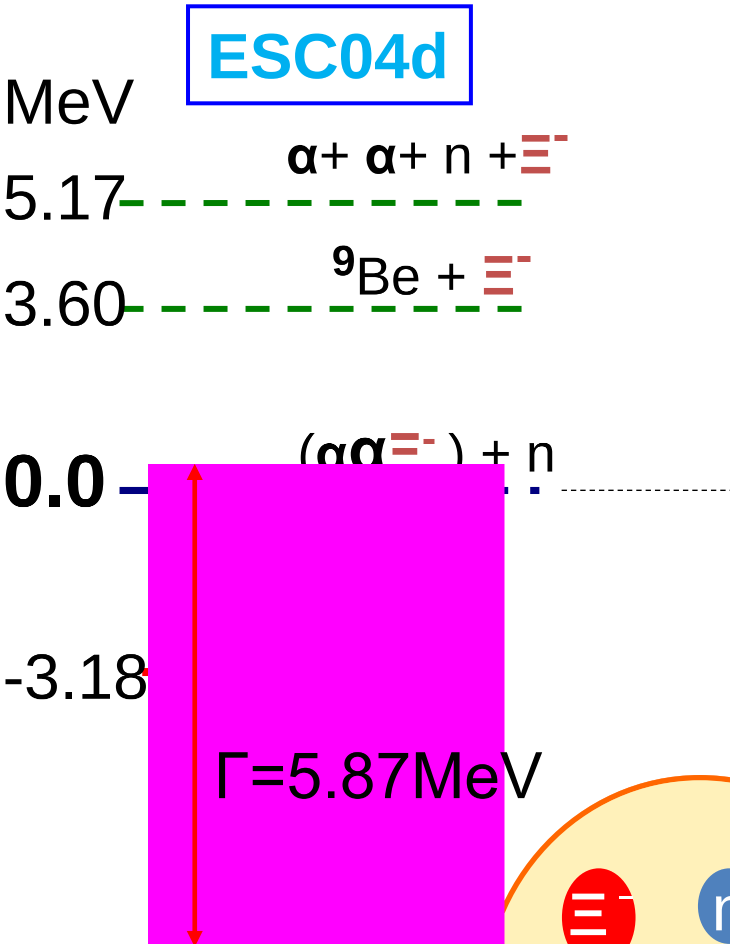
Then, to get information about this part, we propose to perform the (K^-,K^+) experiment by using ^{7}Li and ^{10}B targets At J-PARC.

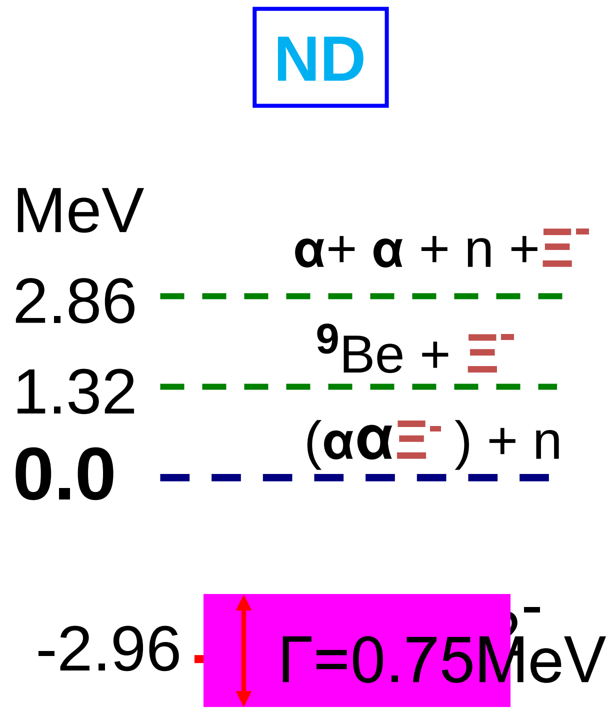
Also next, it is interesting to know

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

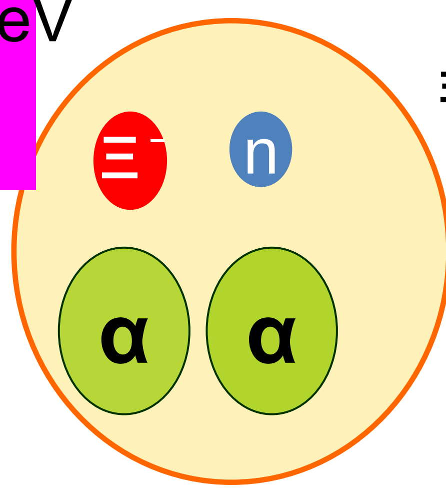
4-body calculation of $^{10}_{\Xi^-}\mathrm{Li}$

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





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

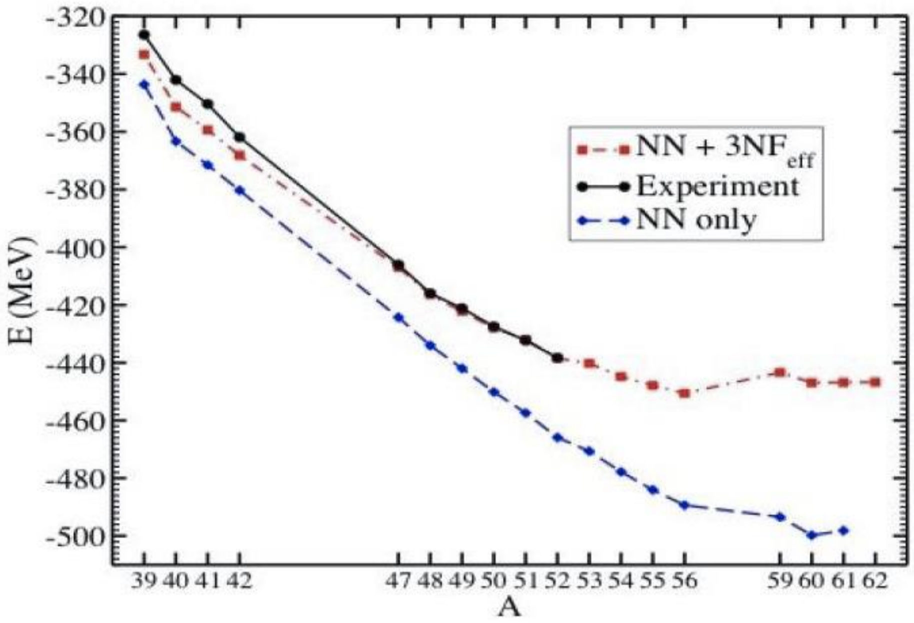


Similar binding energies using ND and ESC04d.

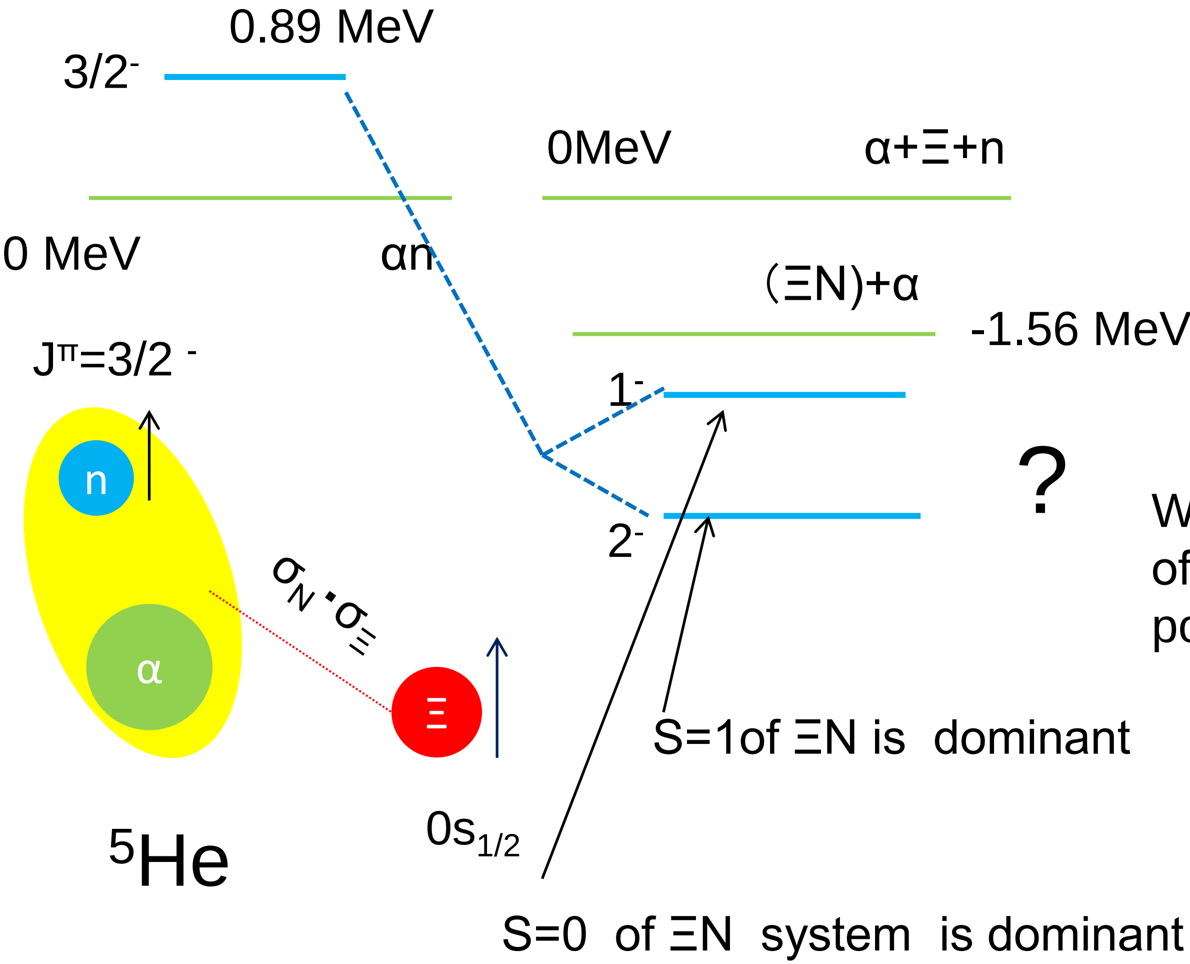
Independent on employed ΞN potential

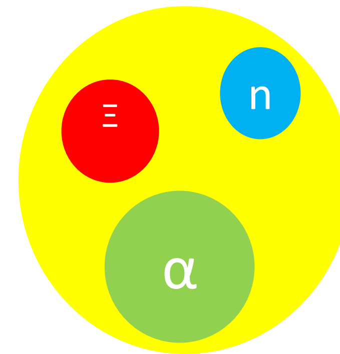
But, decay width is dependent on employed ΞN interaction.

In experiments, we can expect a bound state.



G. Hagen et al., PRL 109 (2012) 032502





What about level structure of αΞN system using HAL potential?

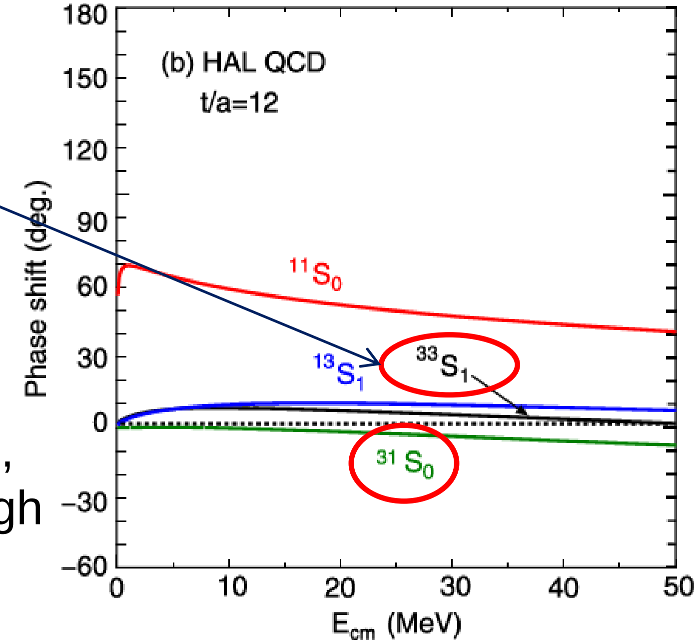
0MeV α+Ξ+n

No bound

-1.22

(αΞ)+n

T=1,S=1



HAL

T=1

Attractions of T=1,S=1, T=1,S=0 are not enough to make bound states.

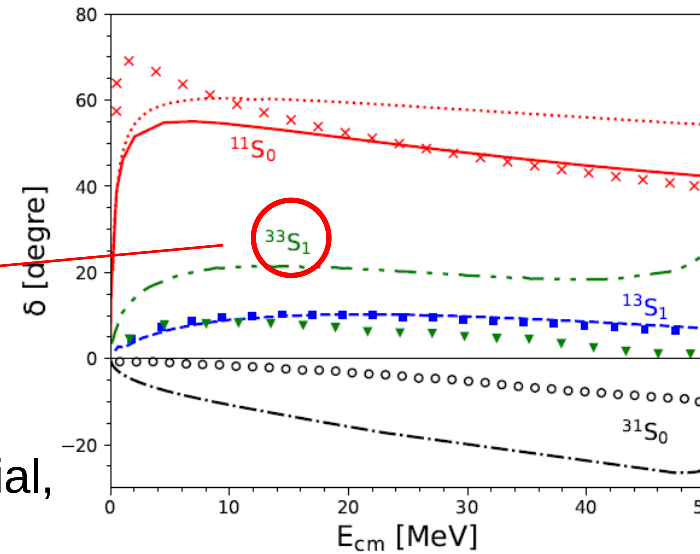
0MeV α+Ξ+n

(αΞ)+n

-1.22

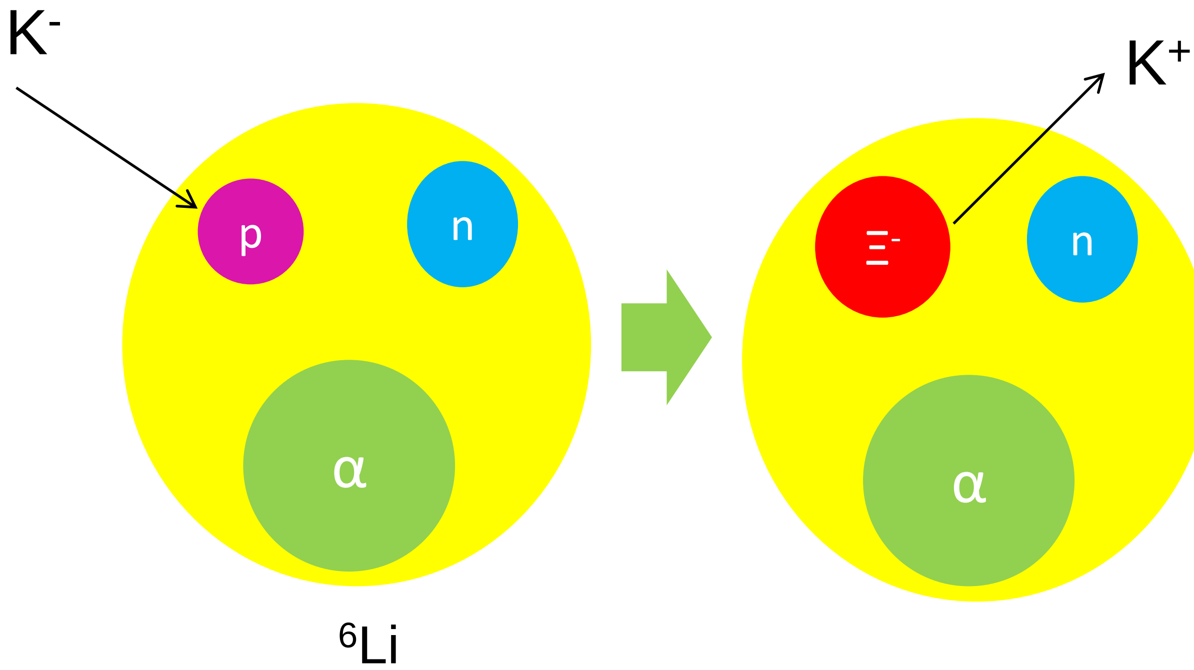
2^-

-1.47 MeV



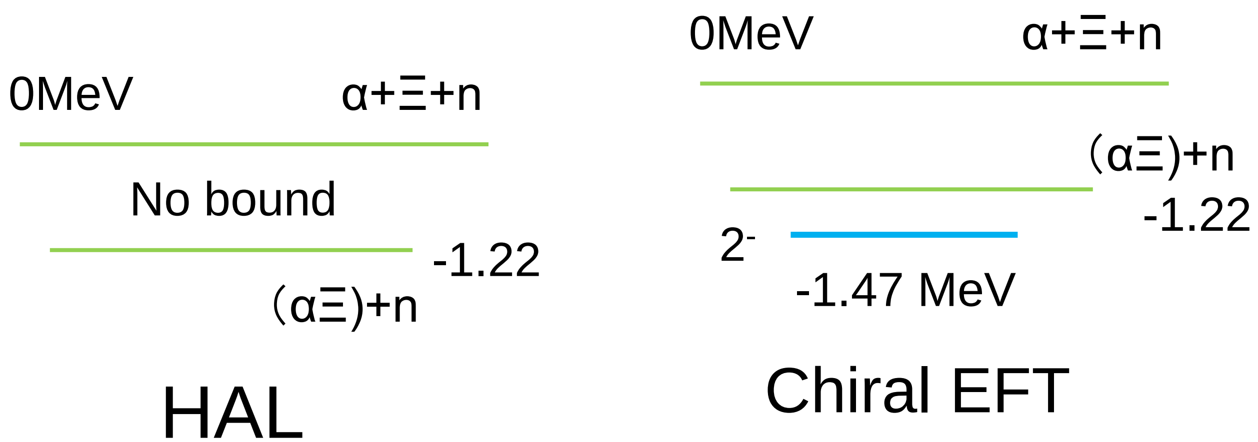
If we use $^{33}S_1$ information based on chiral EFT potential, We have a bound state in 2^-.

H. Le, et al., EPJA57,339(2021)
Chiral EFT ΞN interaction.

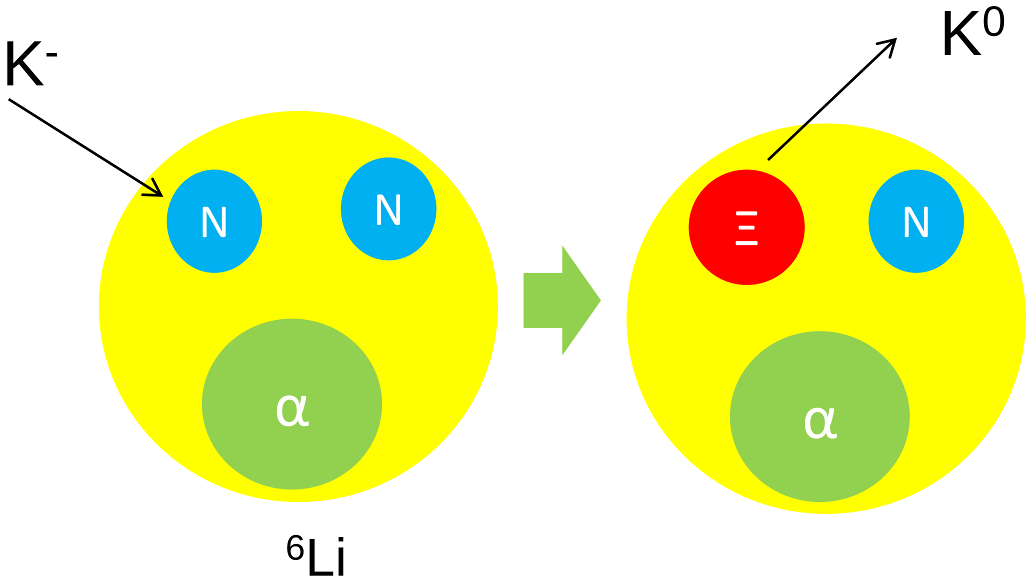


T=1,S=0 or S=1

Experimentally,
It is possible to
produce Ξ hypernucleus.

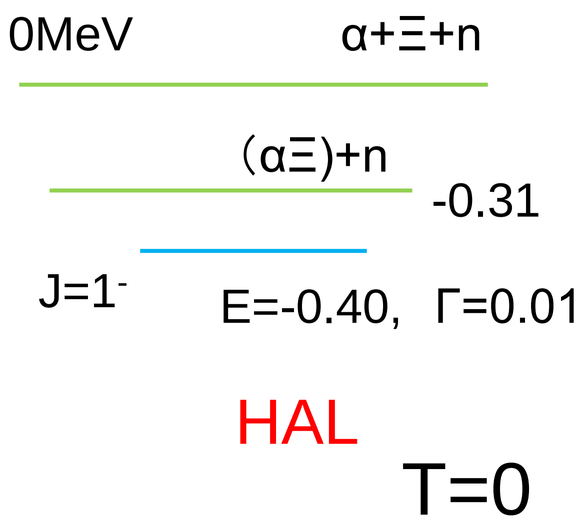


Bound state is dependent on ΞN potential employed. Then, it would be risky to use ^{6}Li target by (K^{-},K^{+}) reaction.



T=0,S=0 or S=1

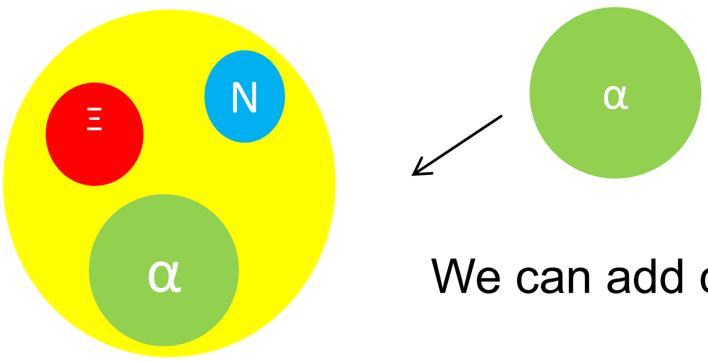
We can obtain information on T=0, S=0 and S=1 ΞN interaction.



T=0,S=0 of ΞN interaction dominant

Currently, (K$^-$,K^0) reaction would be difficult experiment. Then, it might be risky to use ^{6}Li target.

To extract ΞN interaction, we need deeper binding energy.

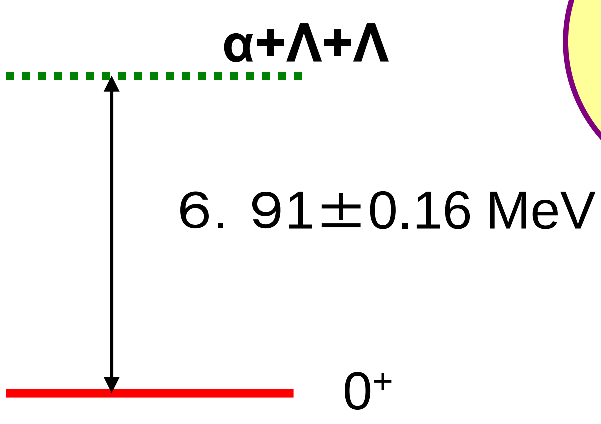


We can add one more α particle.

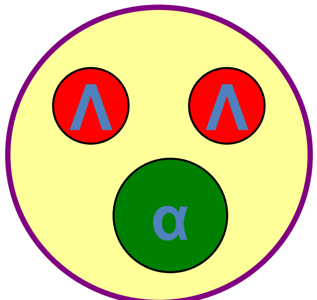
In 2001, the epoch-making data has been reported by the KEK-E373 experiment.

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

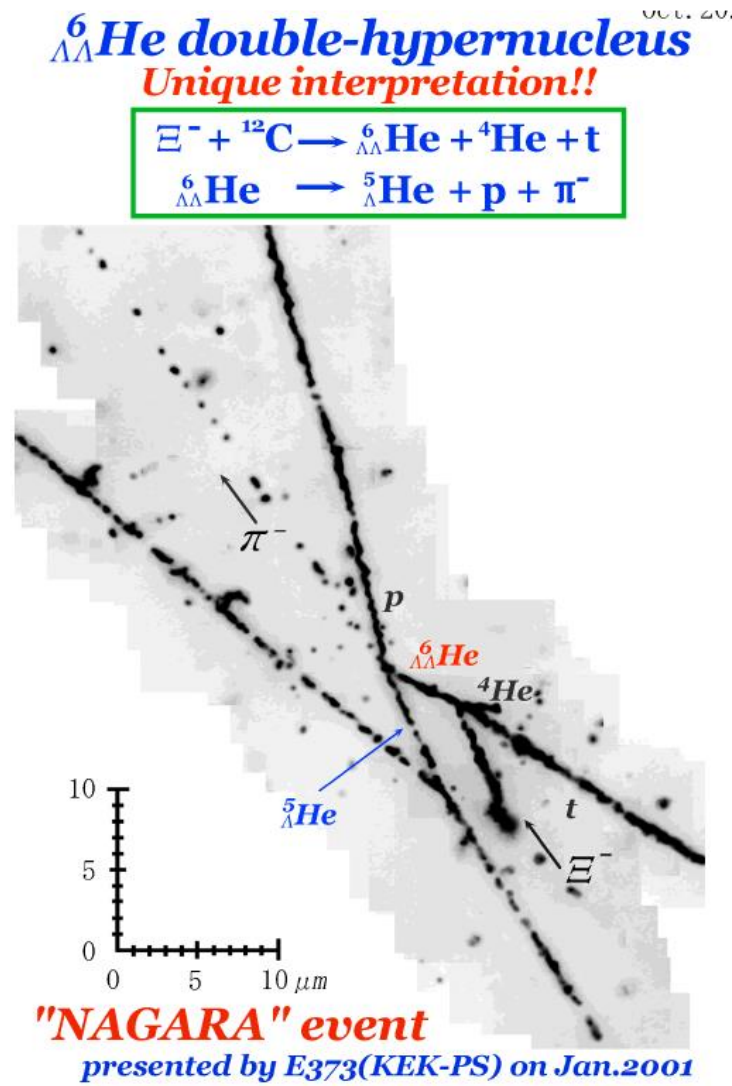
Uniquely identified without ambiguity for the first time



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



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



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

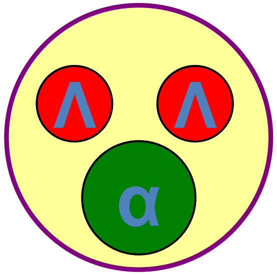
Strategy of how to determine YY interaction from the study of light hypernuclear structure

YY interaction
Nijmegen model D

① **Use**

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

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



Accurate structure calculation

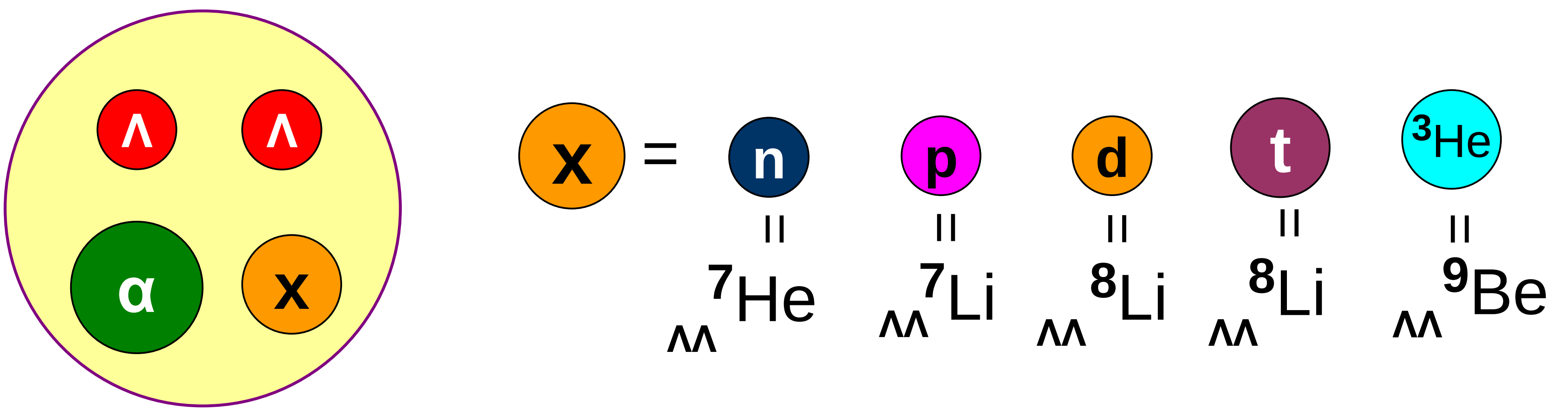
② **compare between the theoretical result and the experimental data of the biding energy of $^{6}_{\Lambda\Lambda}He$**

④ **prediction of new** double Λ hypernuclei

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

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)



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.

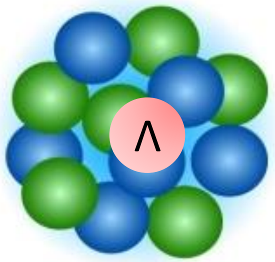
OtherΞN interaction are repulsive or weak attractive.

We employ ESC04 and ND.

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

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

Heavy Λ hypernuclei exp. + theoretical cal.

Determine ΛNN interaction

Reliable EOS

Isotope dependence of ΛNN three-body force

Calc. by Nijmegen ESC16 model