Recent progress in hypernuclear physics

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. Chiral, Nijmegen, Kyoto-Niigata) have large ambiguity.

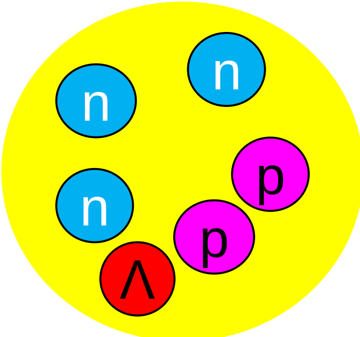
Therefore, for the study of YN and YY interactions, the systematic investigation of the structure of light hypernuclei is one of the important way.

(Some YN scattering experiments have been done and further experiment is planned at J-PARC.)

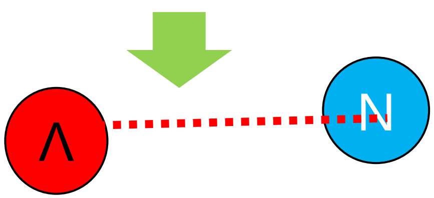
Once YN and YY interactions are determined, we can predict interesting phenomena which cannot be imagined so far. In addition, we could study inner part of neutron stars which have been observed.

Hypernuclear γ-ray data (2019)

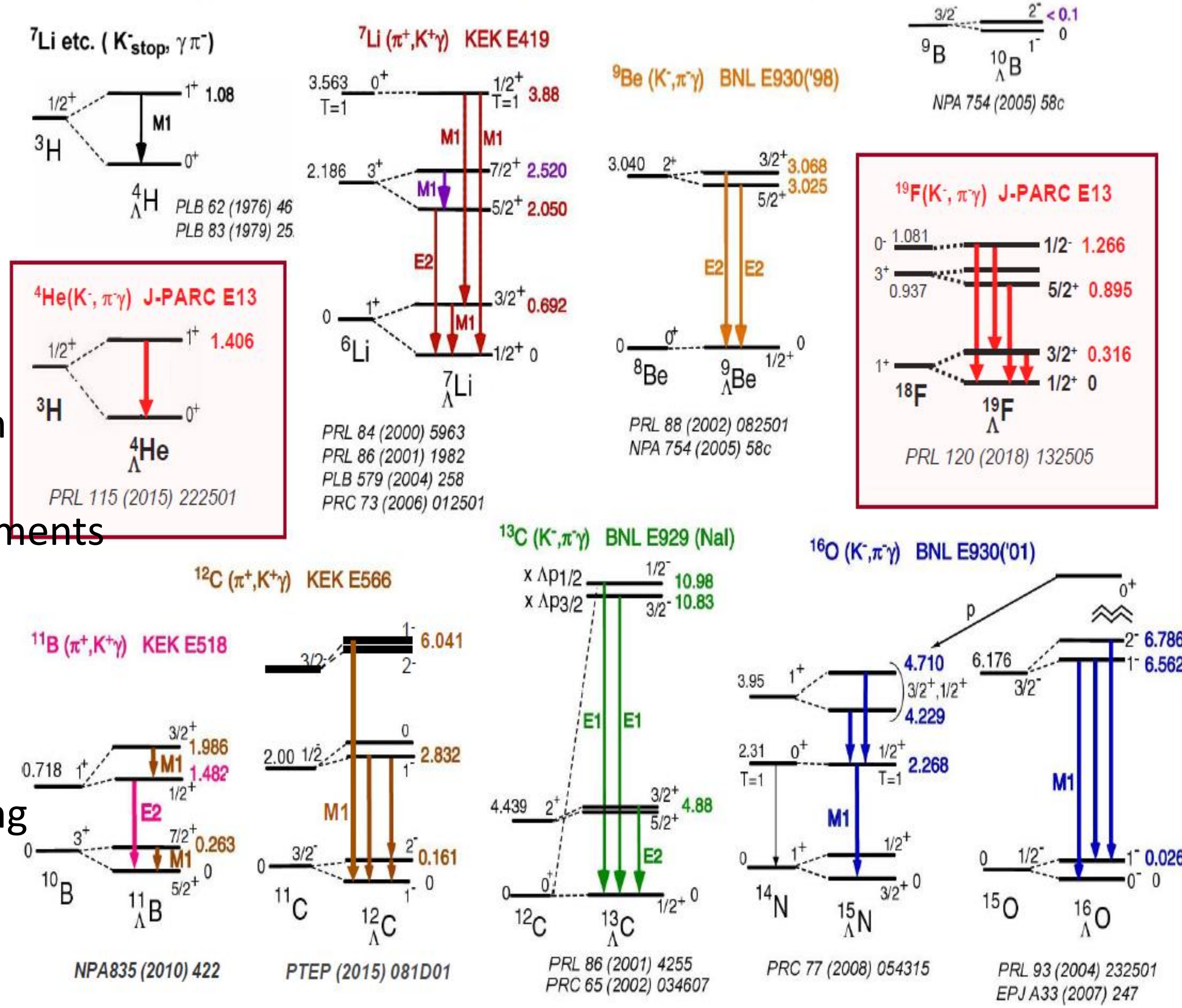
Since 1998



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



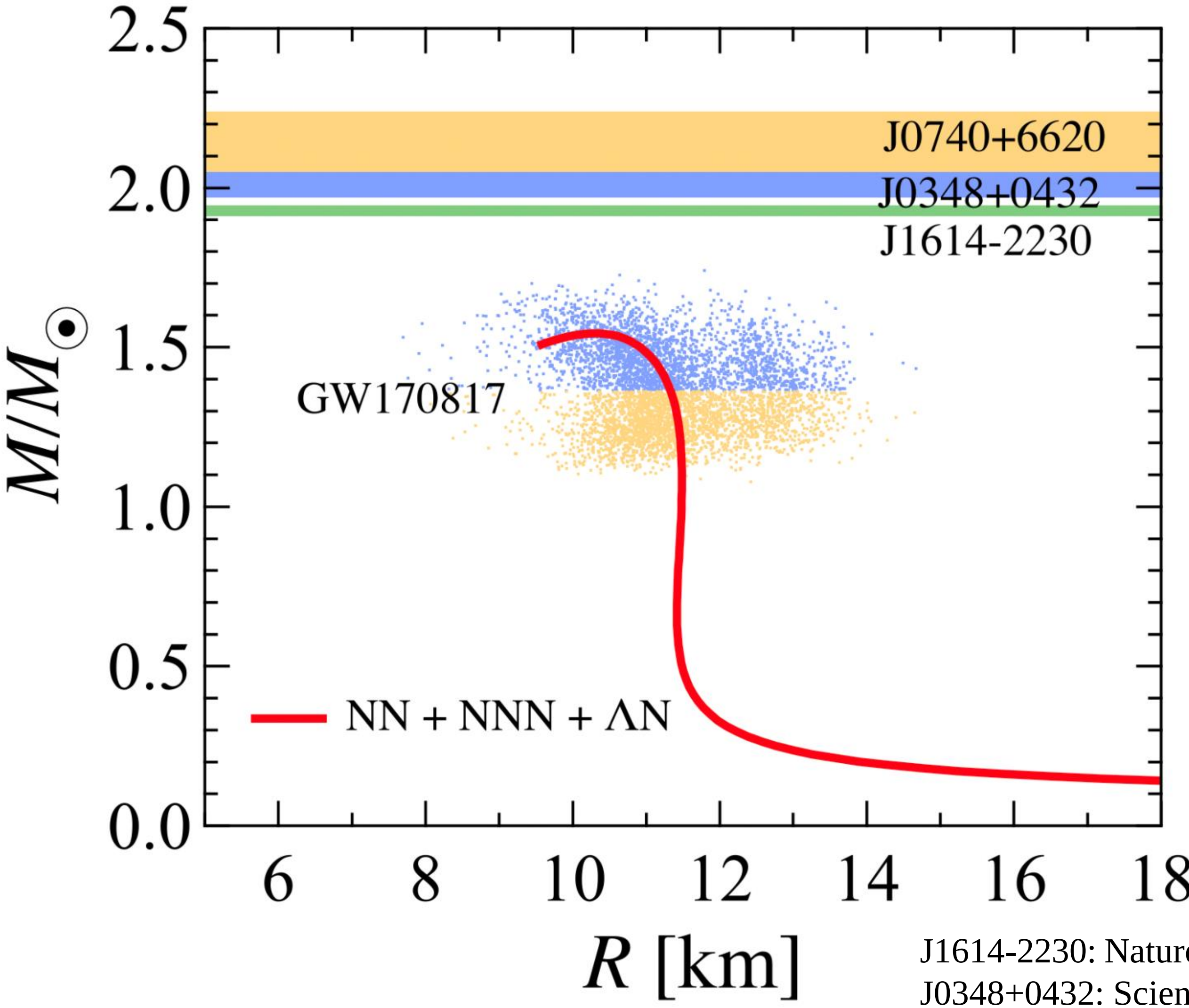
We have been obtaining information on ΛN two-body interaction.



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

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.

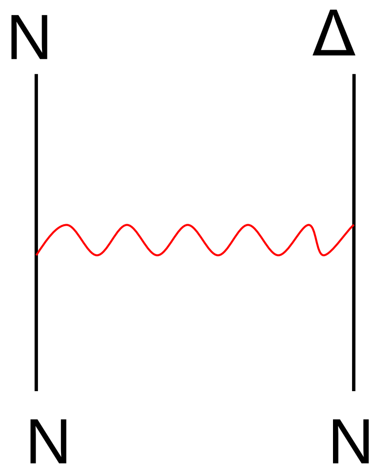
J1614-2230: Nature 467 (2010) 1081, APJ 832 (2016) 167
J0348+0432: Science 340 (2013) 1233232
J0740+6620: Nat. Astron. (2019)
GW170817: PRL 121 (2018) 161101

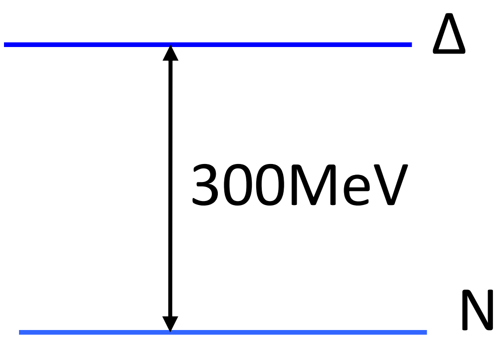
Hyperon puzzle

missing part of YN interaction: ΛN-ΣN coupling

ΛN—ΣN coupling

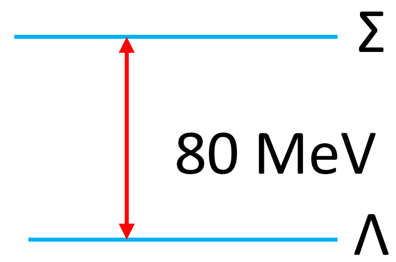
Non-strangeness sector





Probability of Δ in nuclei is not large.

S=-1



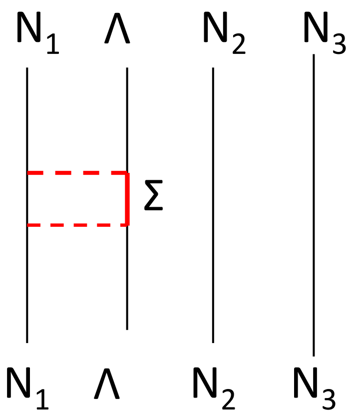
Mass is smaller.
It is expected that Λ-Σ conversion might affect in structure of Λ hypernuclei.

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

Role of the ΛN-ΣN interaction

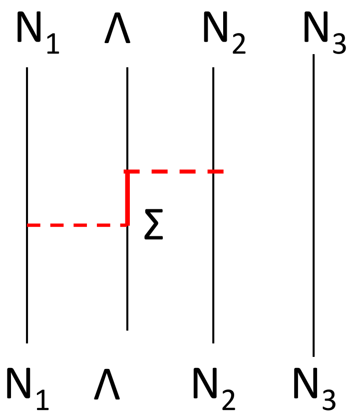
- Three-body effect

①



Effective two-body force

②



Three-body force

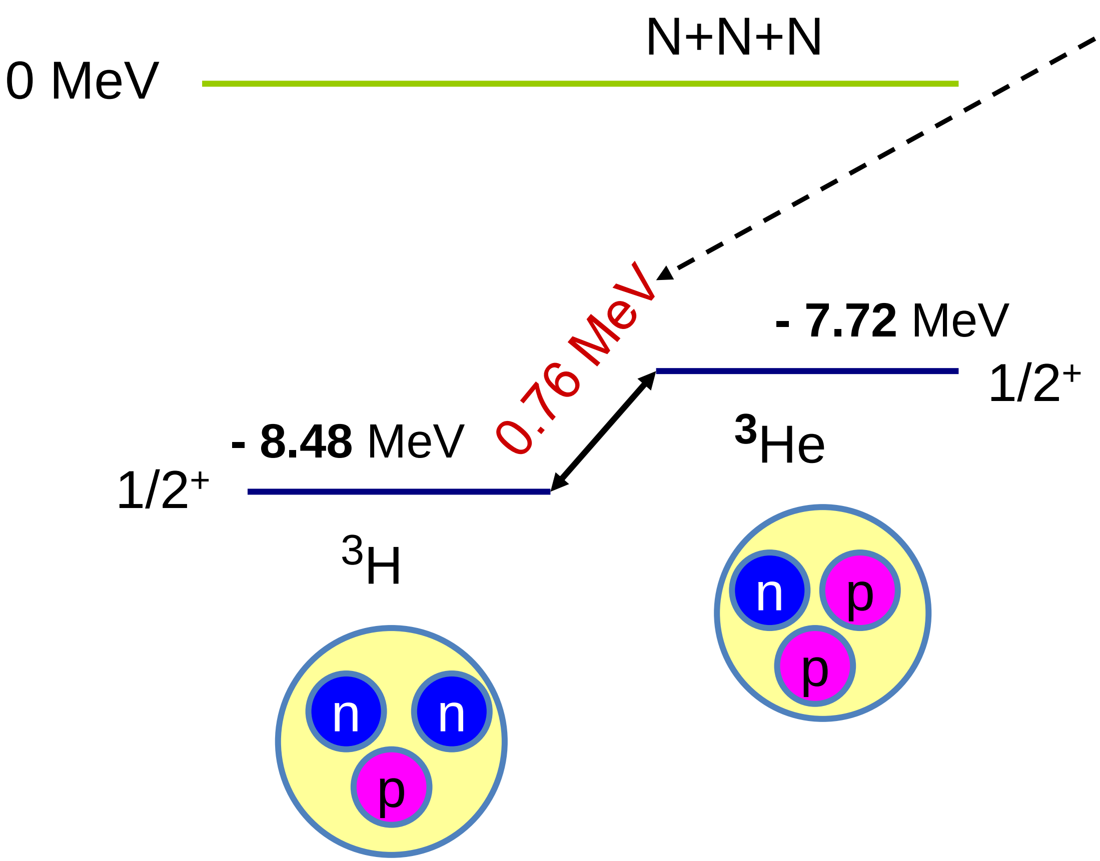
In the neutron matter or neutron star, three-body force might play important role.

- Charge symmetry breaking effect

Charge Symmetry breaking

In S=0 sector

Exp.

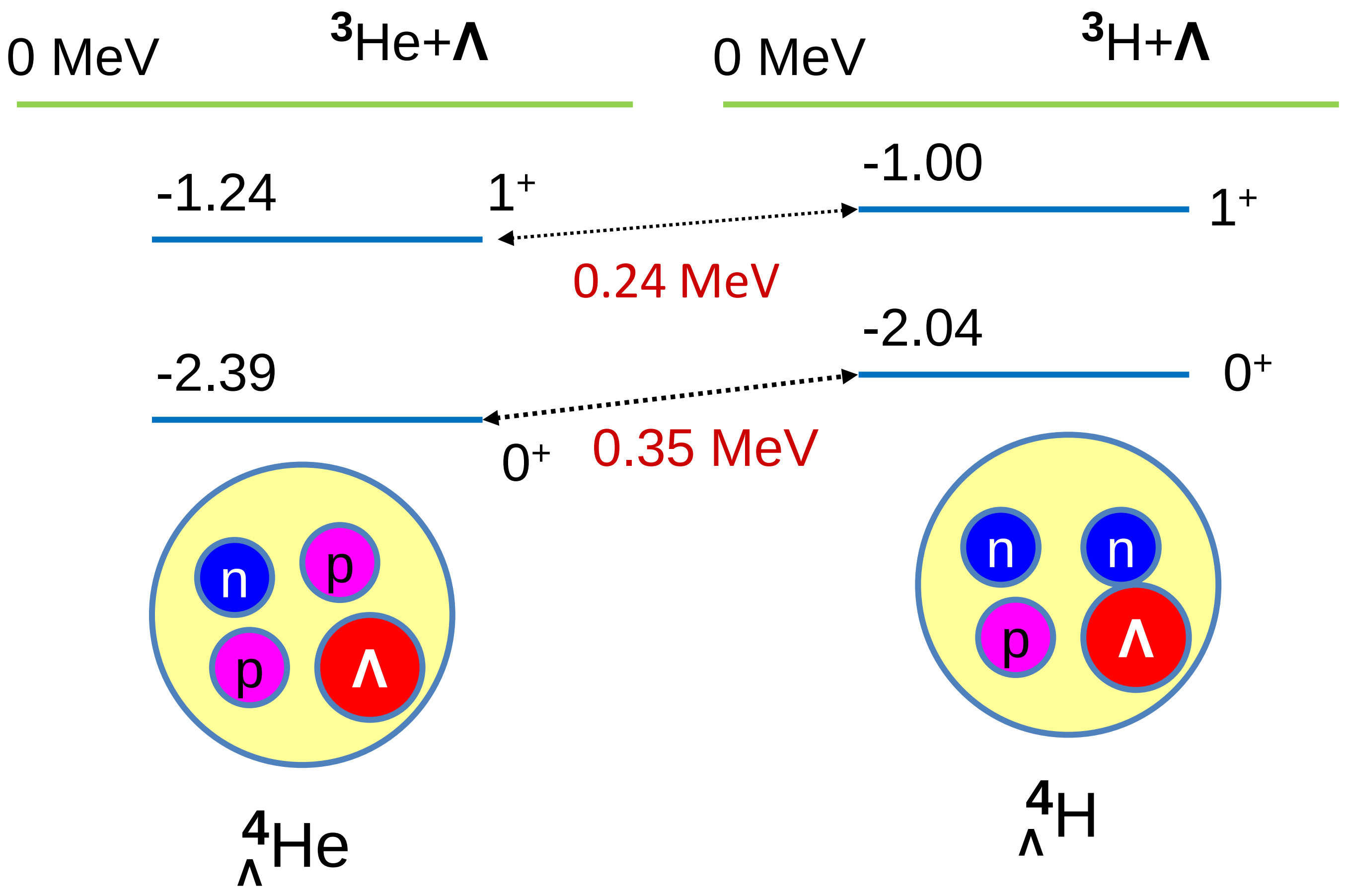


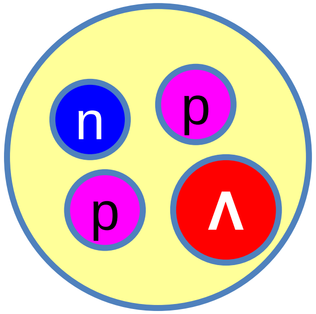
Energy difference comes from dominantly Coulomb force between 2 protons.

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

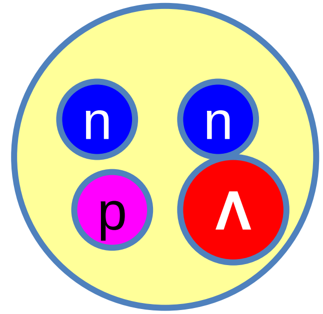
In S= -1 sector

Exp.





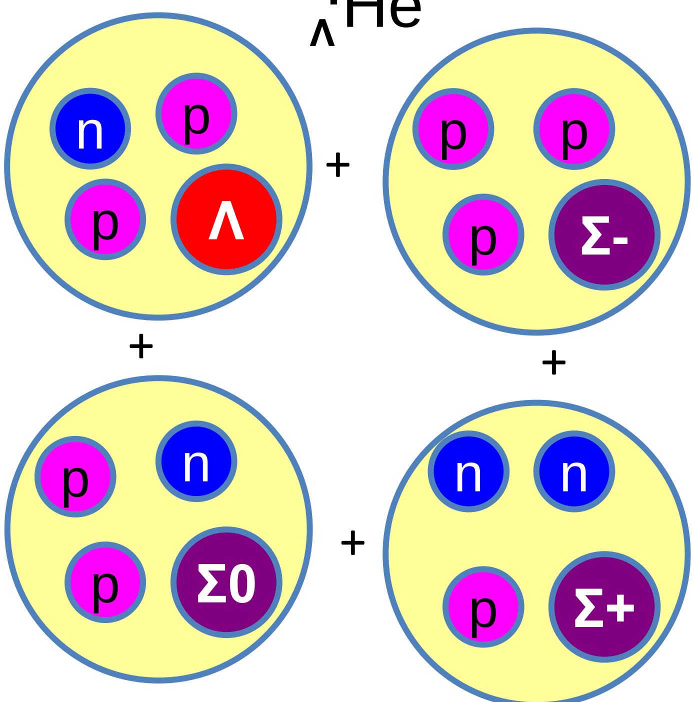
$^{4}_{\Lambda}He$



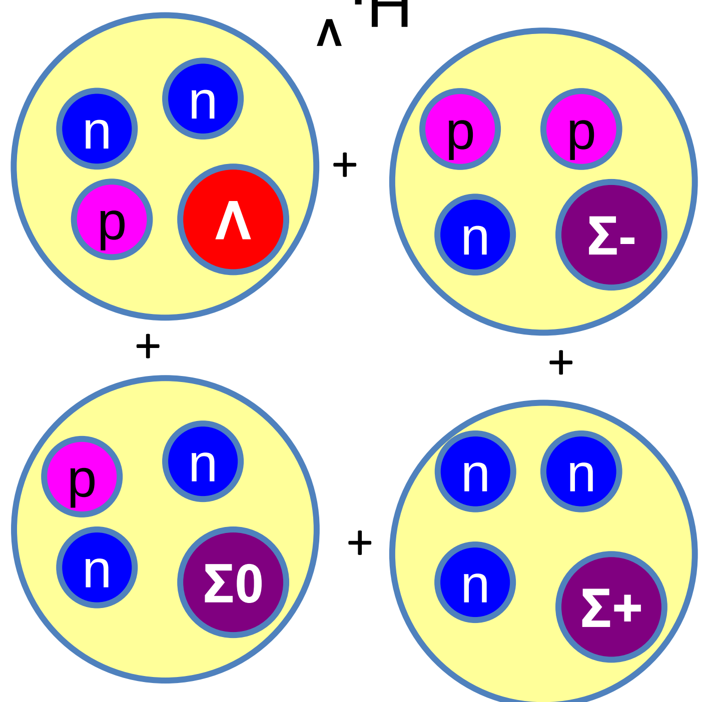
$^{4}_{\Lambda}H$

However, Λ particle has no charge.

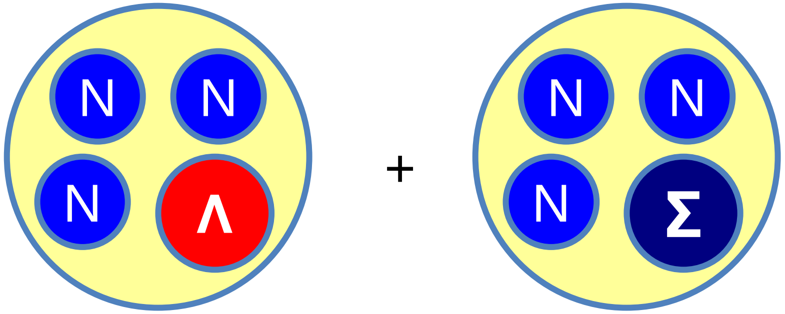
$^{4}_{\Lambda}He$



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



In order to explain the energy difference, 0.35 MeV,



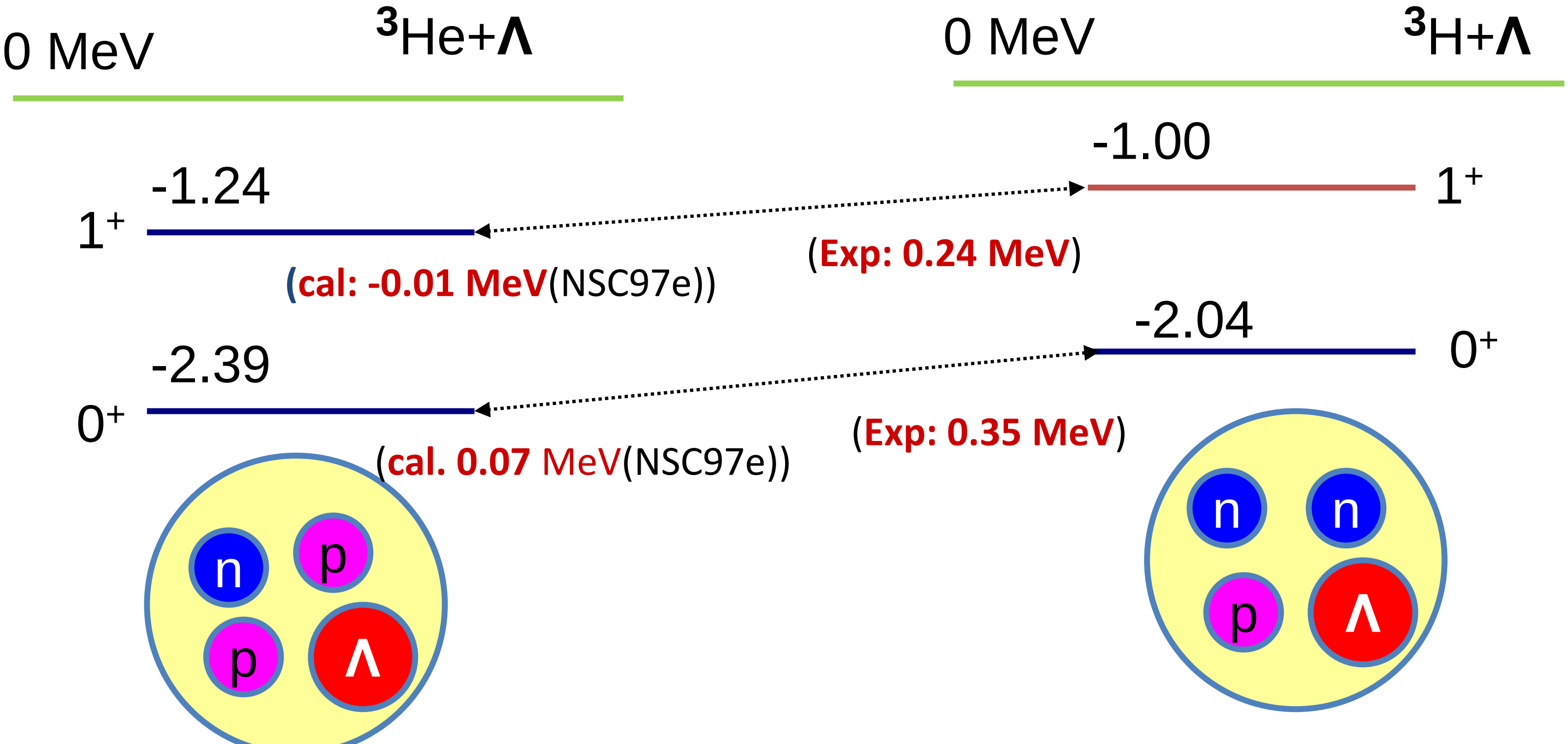
(3N+**Λ**) (3N+**Σ**)

・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.



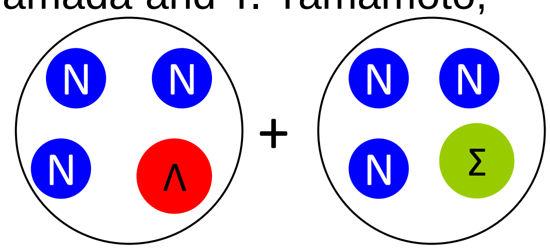
$^4_\Lambda$He

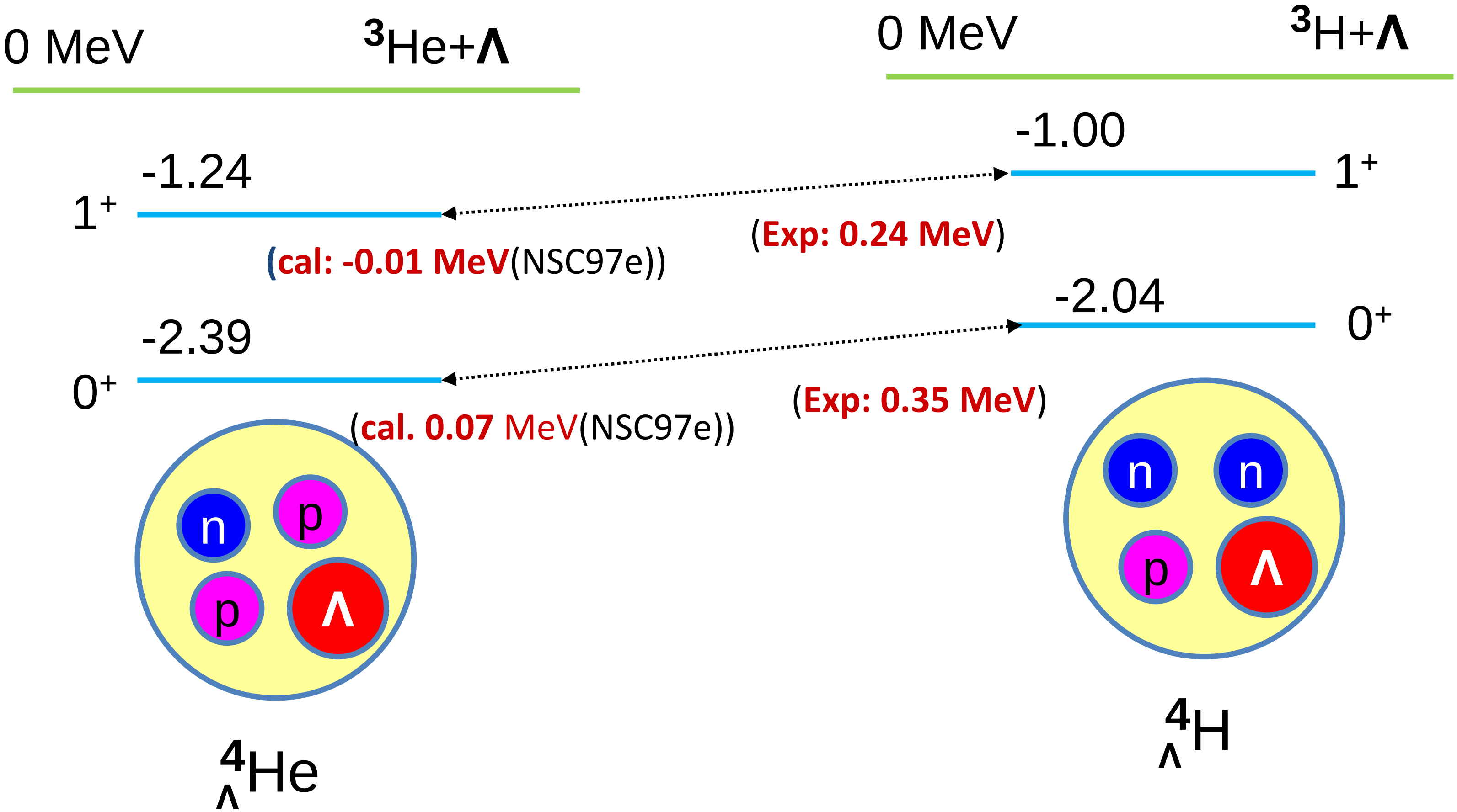
- A. Nogga, H. Kamada and W. Gloeckle, Phys. Rev. Lett. 88, 172501 (2002)

$^4_\Lambda$H

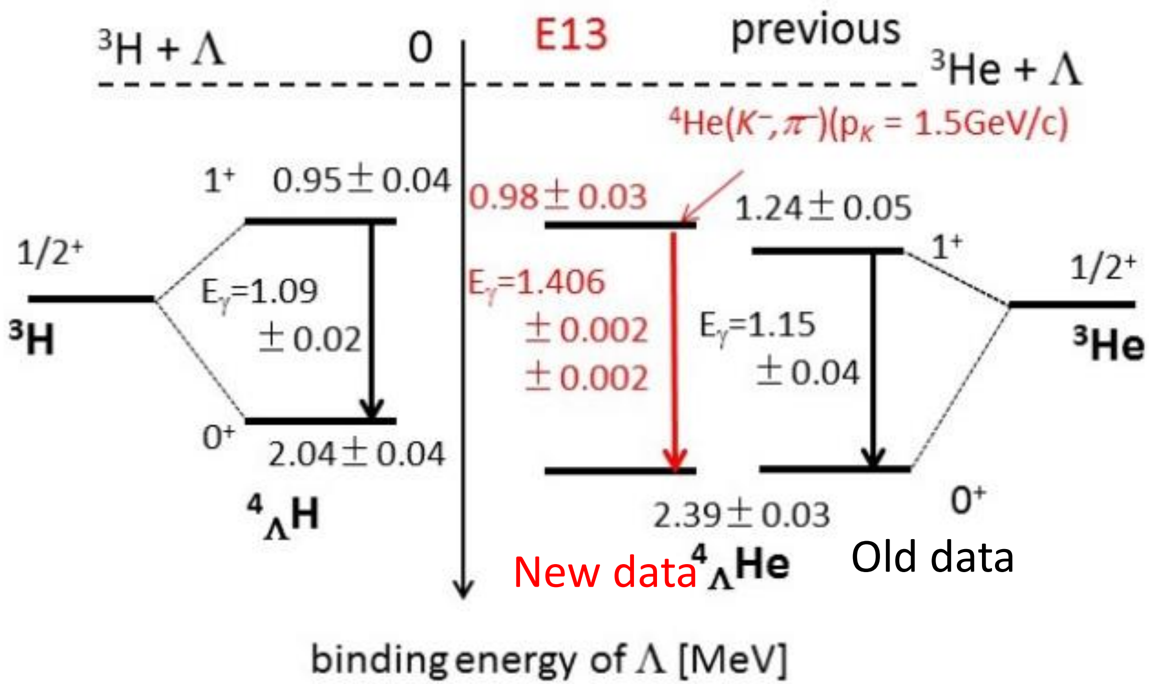
- E. Hiyama, M. Kamimura, T. Motoba, T. Yamada and Y. Yamamoto, Phys. Rev. C65, 011301(R) (2001).

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





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



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

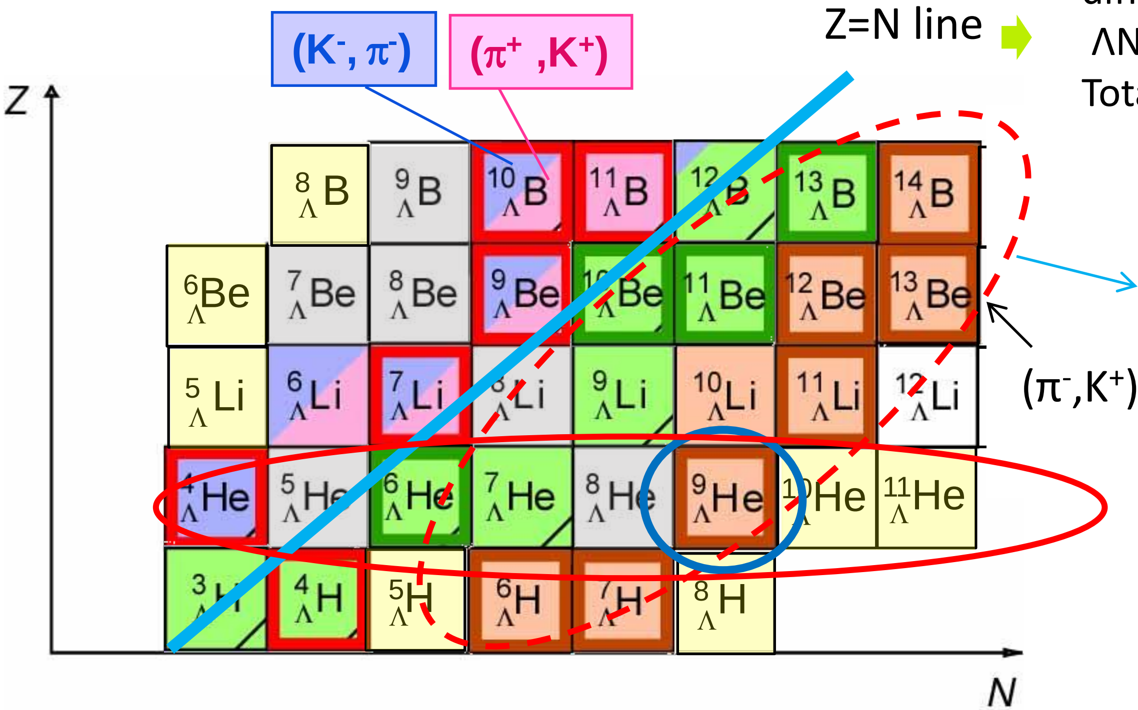
M. Schafer et al., PRC106, L031001(2022)

Still it is difficult to reproduce the data for the study of CSB which is related to 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 J-PARC

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



difficult to obtain information on ΛN-ΣN coupling

Total isosopin of core nuclei is small.

Total isospin is larger.

ΛN-ΣN coupling give a great contribution to binding energies of neutron-rich Λ hypernuclei.

These neutron-rich Λ hypernuclei are important.

Especially, He isotope is important to obtain information on ΛN-ΣN coupling, Because He isotope Λ hypernuclei have been observed. Among these Λ hypernuclei, $_{\Lambda}^{9}$He is planned to produce in the future.

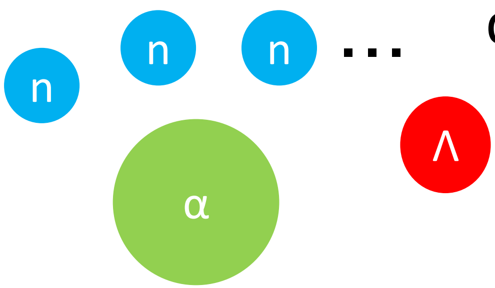
Structure of neutron-rich He Λ Hypernuclei using the cluster orbital shell model

T. Myo[1,2]
[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.

T. Myo and E. Hiyama,
Phys. Rev. C107, 054302(2023)



α+xn+Λ model

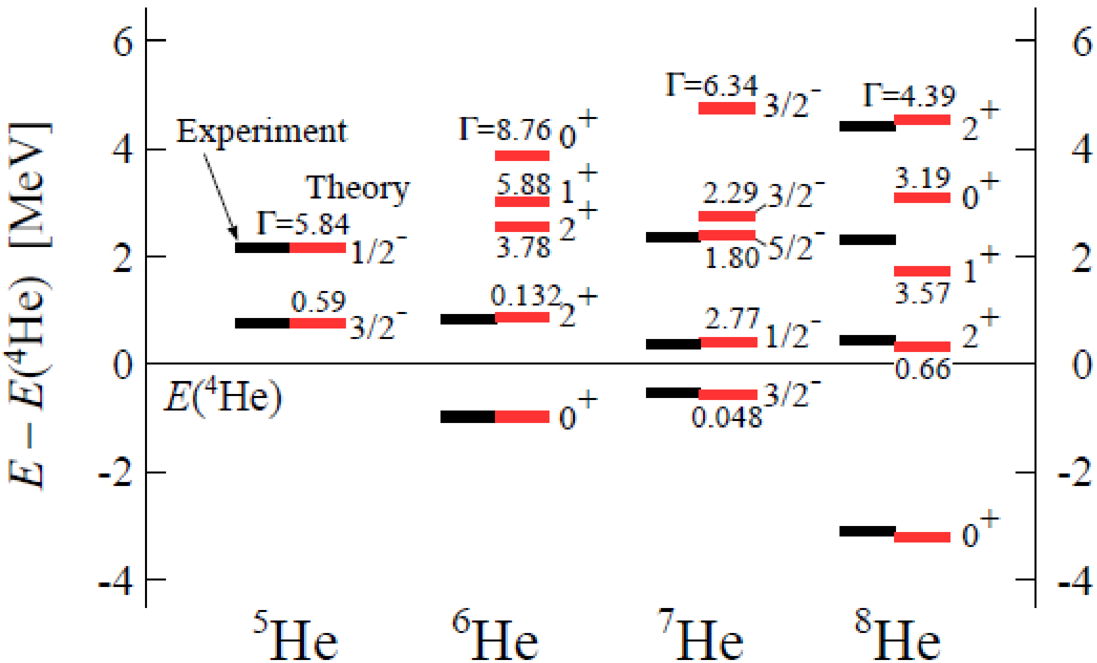
X=1〜4

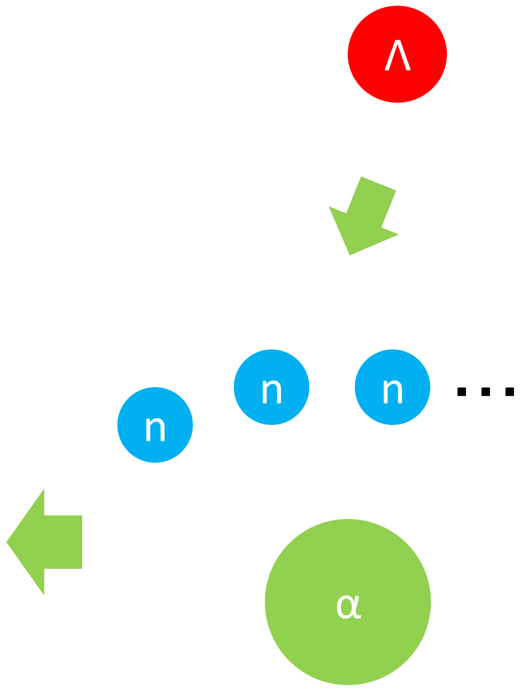
$^6_\Lambda$He, $^7_\Lambda$He, $^8_\Lambda$He, $^9_\Lambda$He

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.

Cf. R. Wirth and R. Roth, Phys. Lett. B779, 336 (2019).: Non-core shell model+NN+NNN+YN
Since they did not focus on reproducing observed binding energies of hypernuclei and core nuclei, it was difficult to predict the energy spectra of $^9_\Lambda$He.

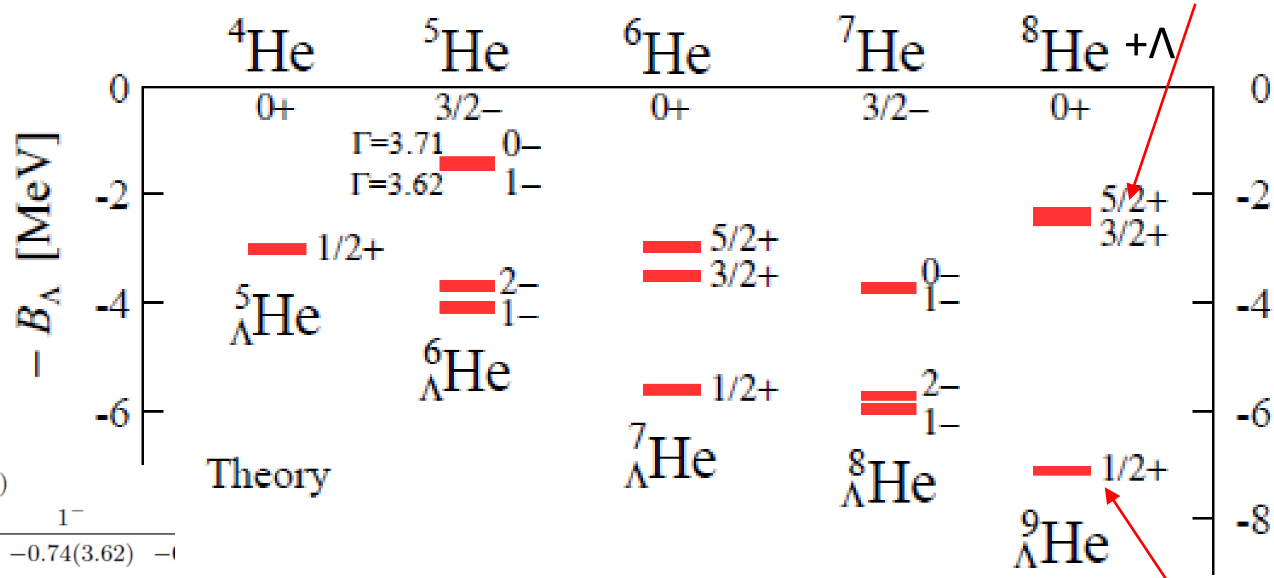
Energy spectra of He Isotope core nuclei:





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

B_Λ=2.49MeV



B_Λ=7.09MeV

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

J^π	1^-	2^-	1^-	
E (MeV)	−3.35	−2.94(0.06)	−0.74(3.62)	−(
E^{exp}(MeV)				
B_Λ(MeV)	4.10	3.34	2.87	
B_Λ^{exp} (MeV)	4.18			

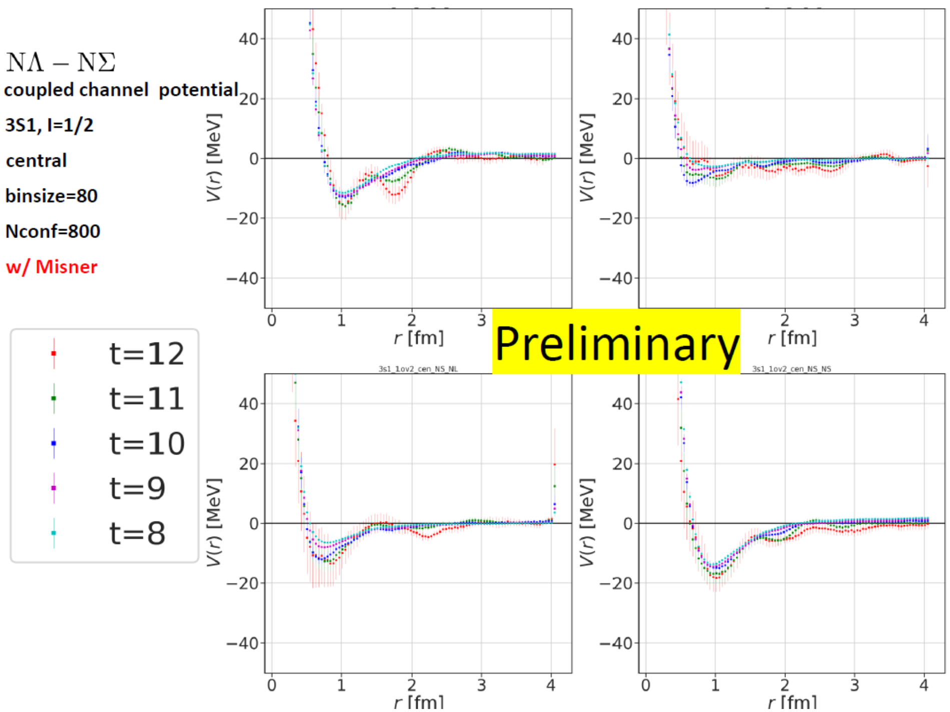
$^7_\Lambda$He($\alpha nn\Lambda$)

J^π	$1/2^+$	$3/2^+$	$5/2^+$
E (MeV)	−6.48	−4.37	−3.84
E^{exp}(MeV)			
B_Λ(MeV)	5.51	3.69	1.42
B_Λ^{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 thise hyperucleus.
This would be observation of the most heavy He isotope Λ hypernucleus .

- YN scattering experiment proposal: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.

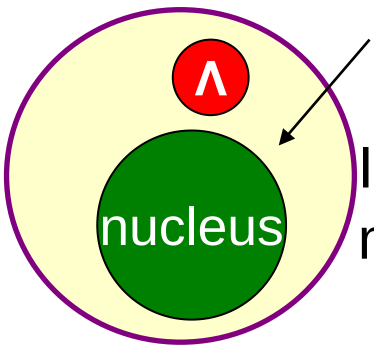
slide by T. Doi

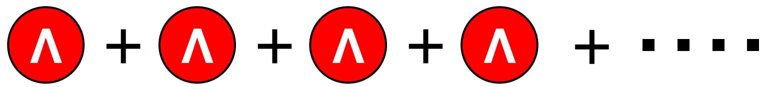
S=-2 hypernuclei

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.

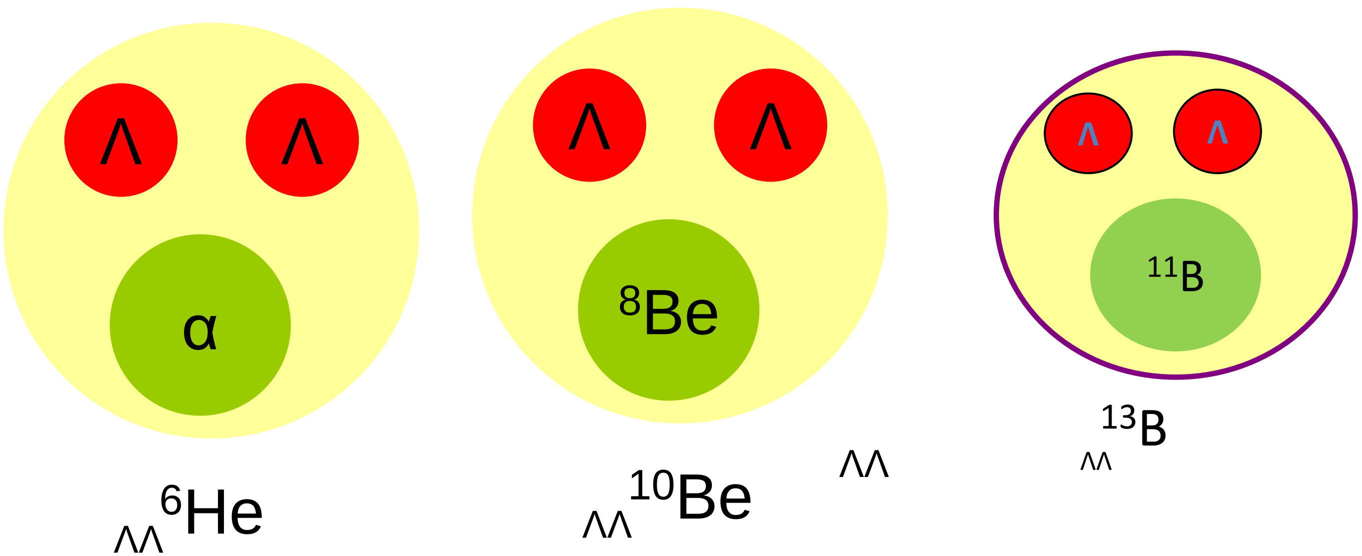
In this meaning, the sector of S=-2 nuclei , double Λ hypernuclei and Ξ hypernuclei is just the entrance to the multi-strangeness world.

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.

Before 2000

Only three double Λ hypernuclei



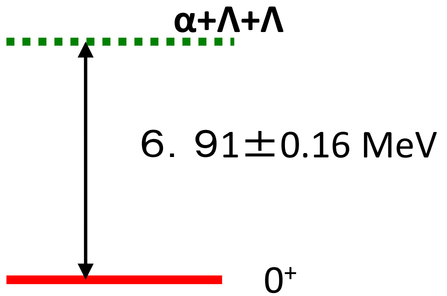
Ambiguity for identifying these double Λ hypernuclei

There was NO observed double Λ hypernuclei without ambiguity.

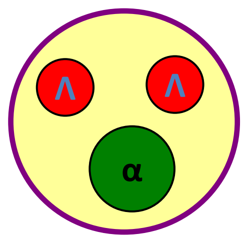
In 2001, the epoch-making data has been reported by the KEK-E373 experiment.

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

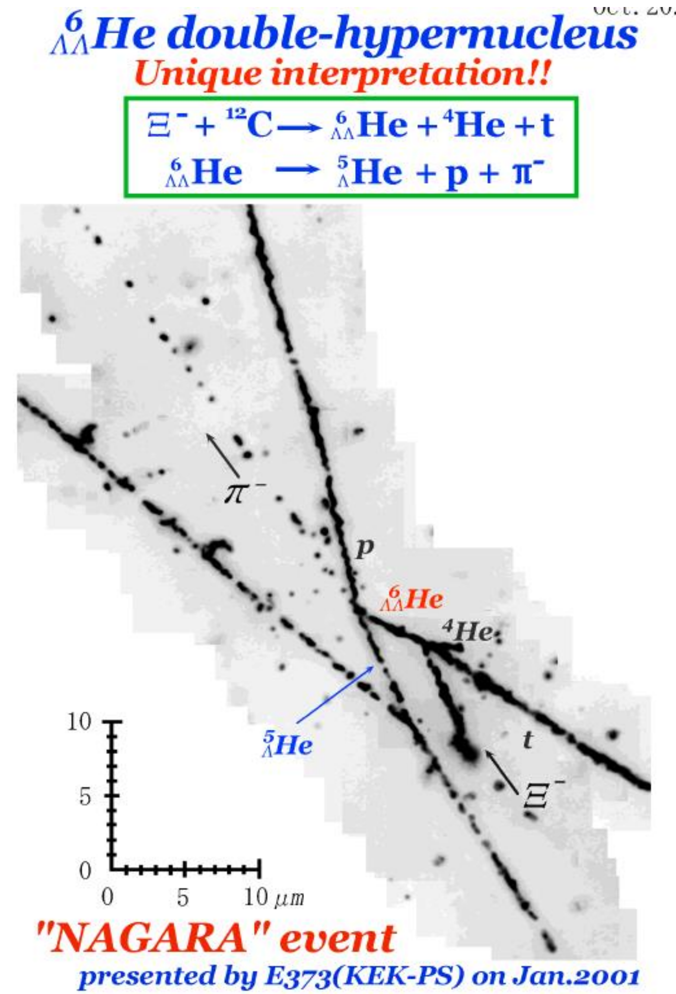
Uniquely identified without ambiguity for the first time



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

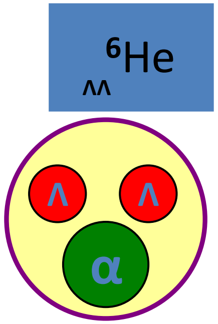
① use

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

Accurate structure calculation

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

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



④ **prediction of new** double Λ hypernuclei

・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

comparison

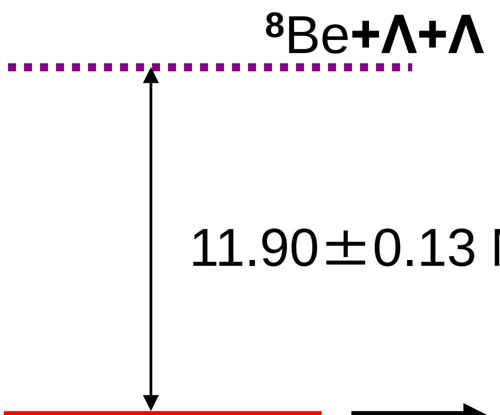
Theoretical calculation

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

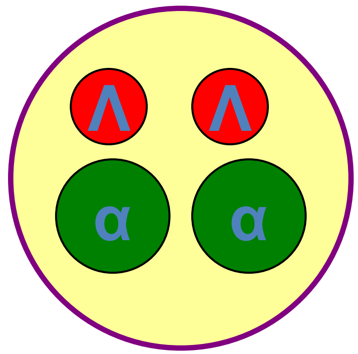
the identification of the state

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

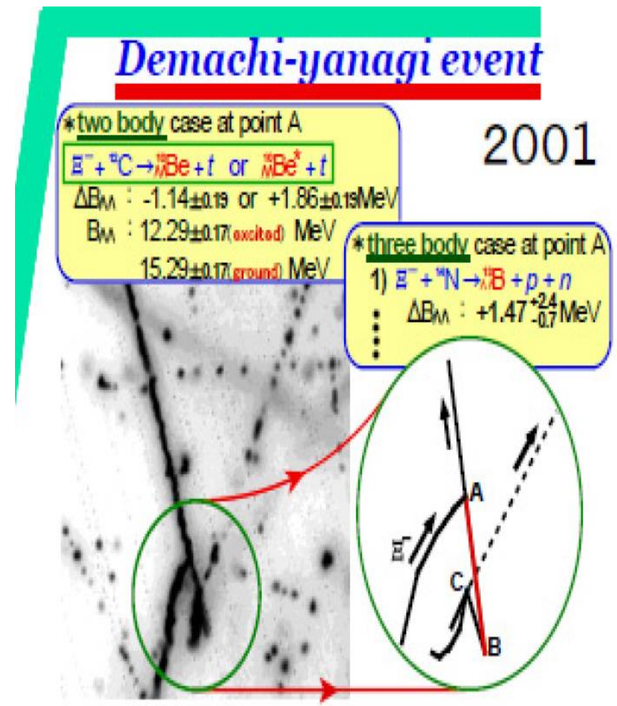
Observation of ${}^{10}_{\Lambda\Lambda}\mathrm{Be}$ --- KEK-E373 experiment



${}^{10}_{\Lambda\Lambda}\mathrm{Be}$ → ground state ? excited state ?

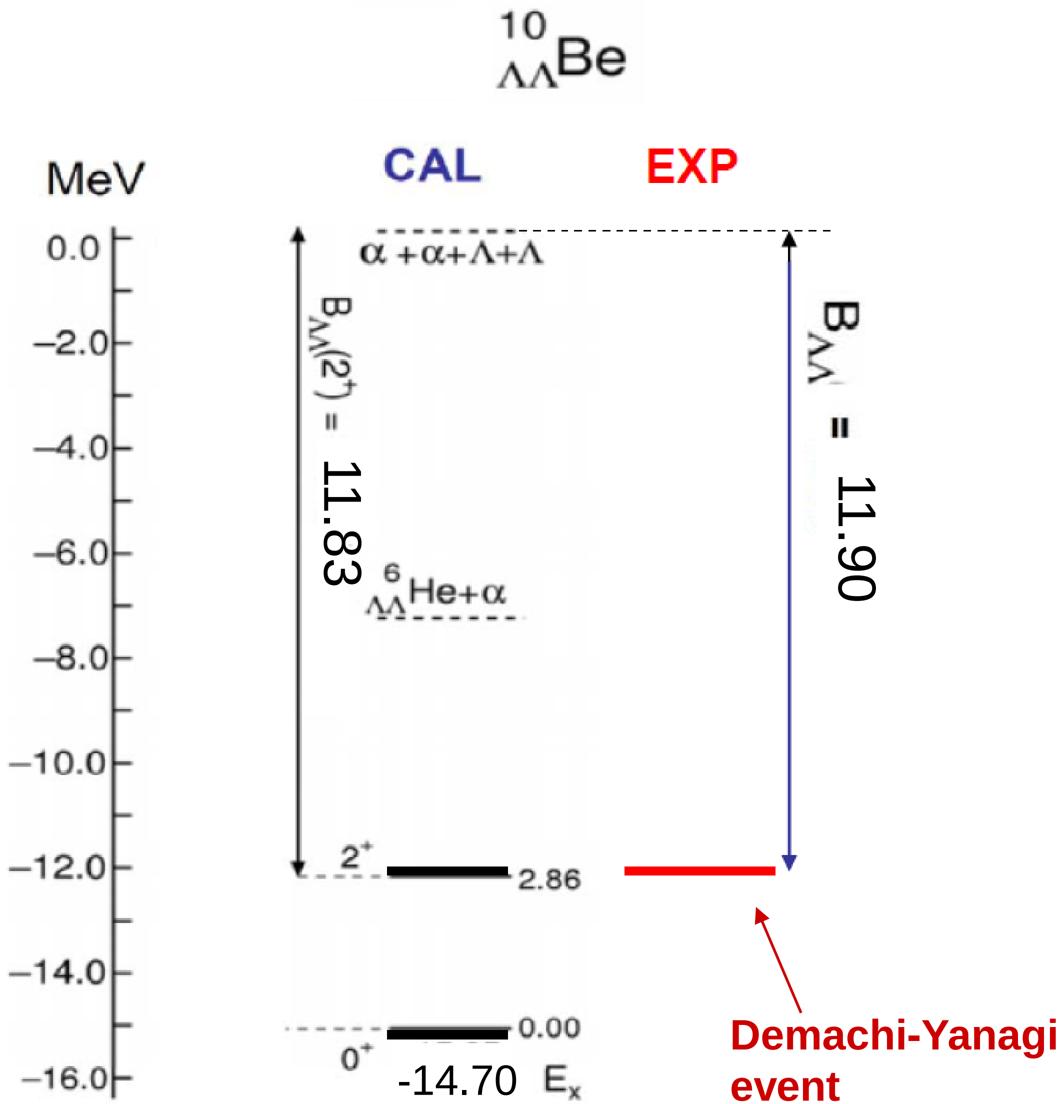


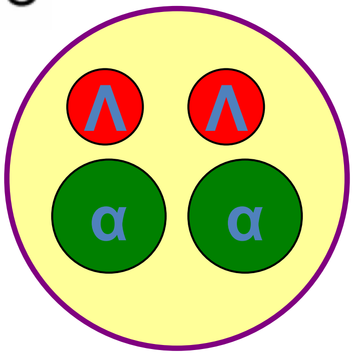
${}^{10}_{\Lambda\Lambda}\mathrm{Be}$



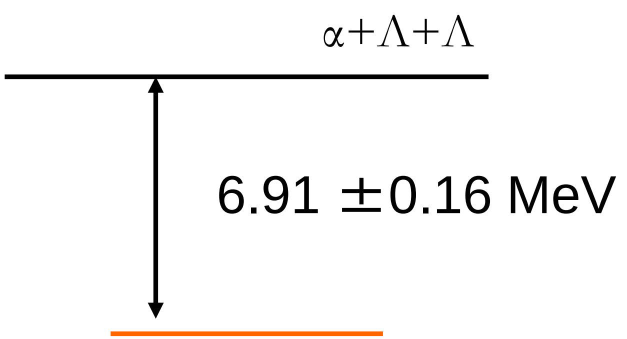
Demachi-Yanagi event

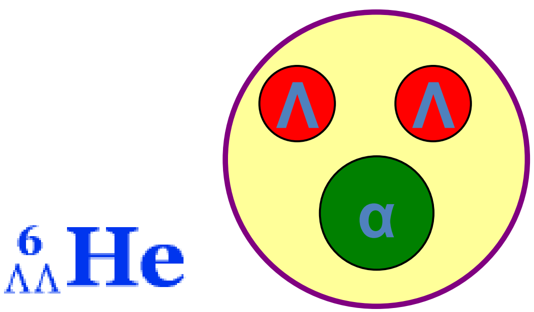
Successful interpretation of spin-parity of $^{10}_{\Lambda\Lambda}\mathrm{Be}$





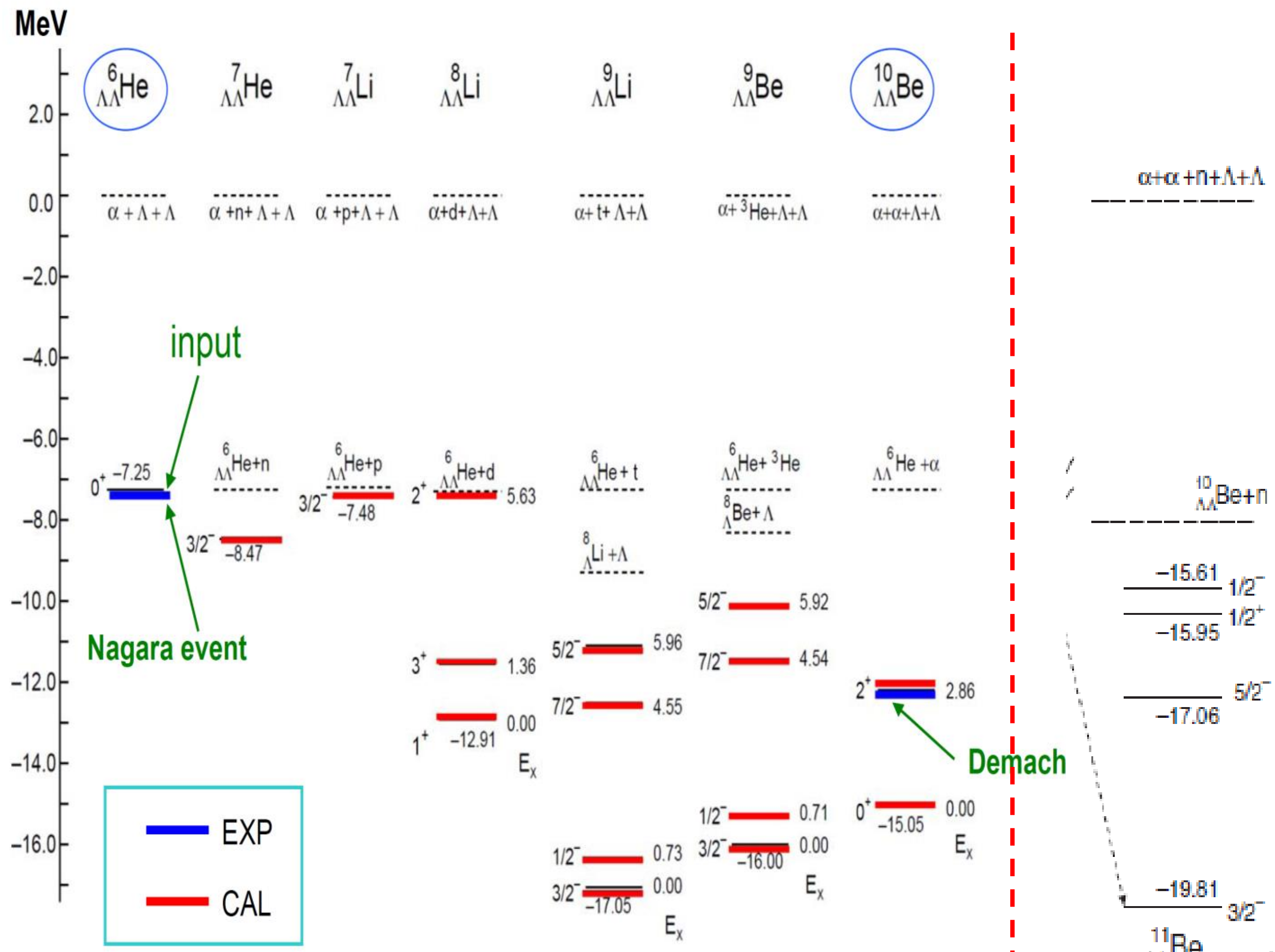
E. Hiyama, M. Kamimura,T.Motoba, T. Yamada and Y. Yamamoto Phys. Rev. 66 (2002) , 024007





Spectroscopy of ΛΛ-hypernuclei

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

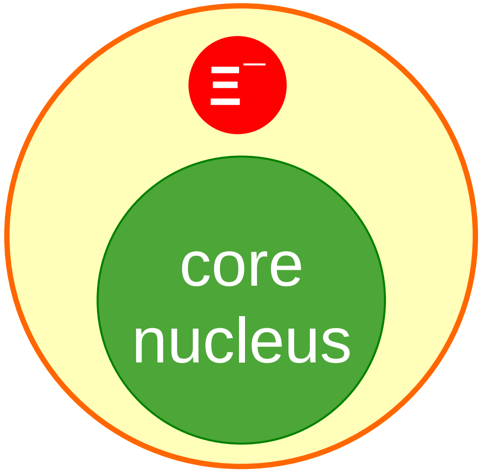


New data:
-20.64 MeV

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

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

Ξ hypernuclei

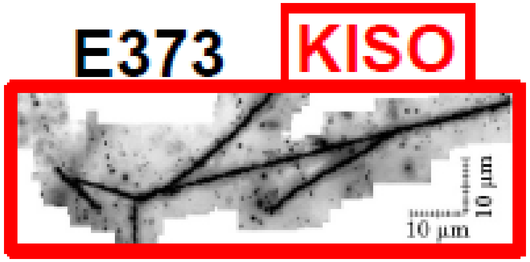


For the study of ΞN interaction, it is important to study the structure of Ξ hypernuclei.

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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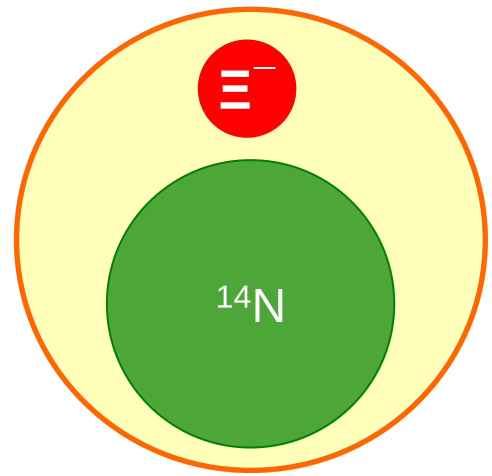
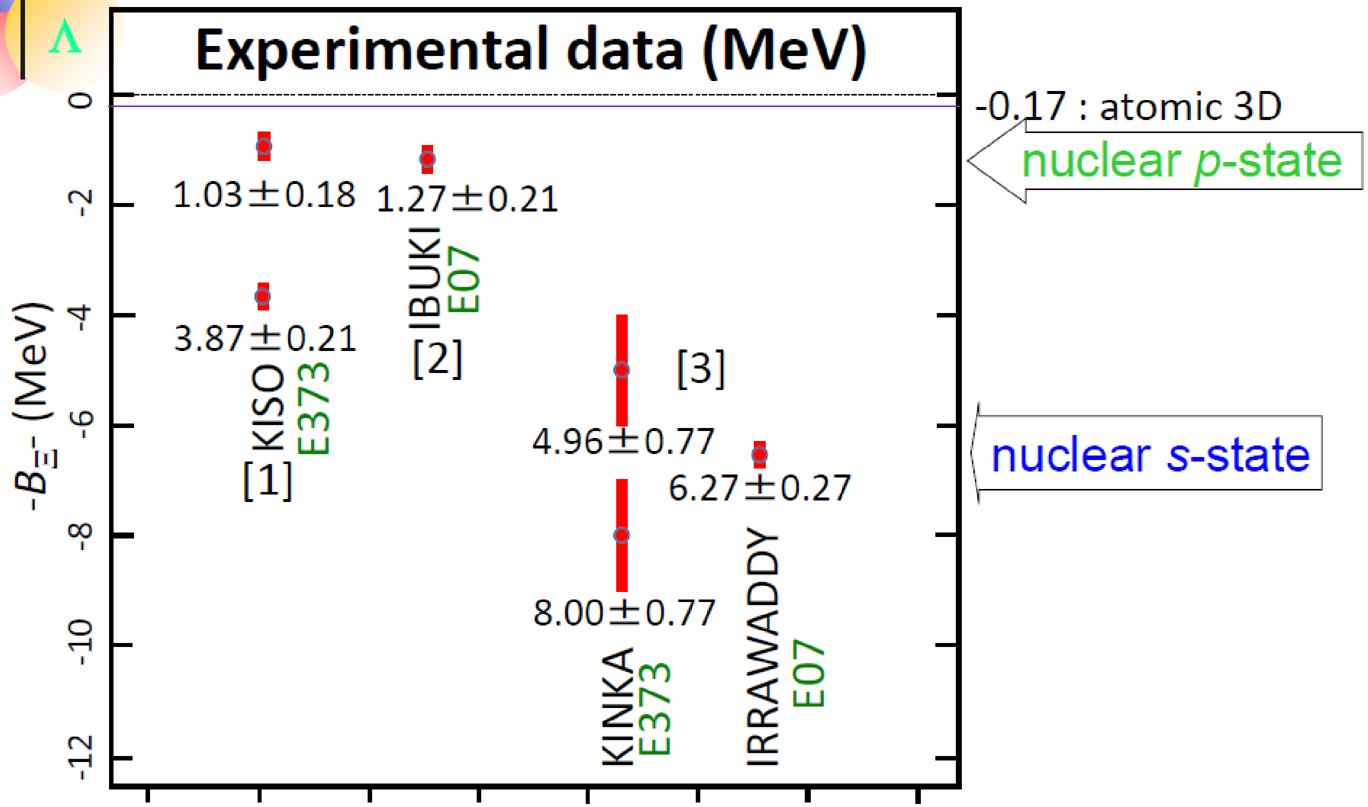


We understood Ξ-nuclear potential should be attractive.

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

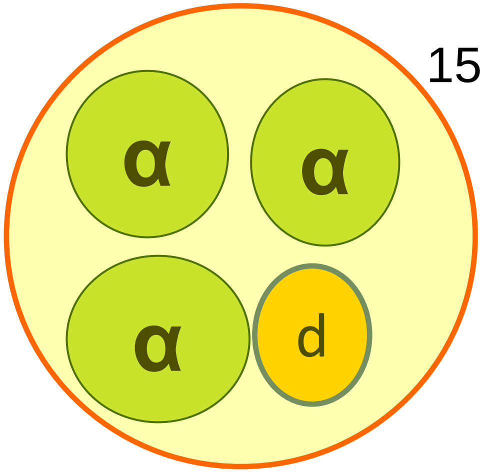


[1] K. Nakazawa, et. al., Prog. Theor. Exp. Phys. **2015**, 033D02 (2015),
E. Hiyama and K. Nakazawa, Ann. Rev. Nucl. Part. Sci. **68**, 131 (2018).
[2] S. Hayakawa, et. al., Phy. Rev. Lett., **126**, 062501 (2021).
[3] M. Yoshimoto, et. al., Prog. Theor. Exp. Phys. **2021**, 073D02 (2021).

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.

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



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

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

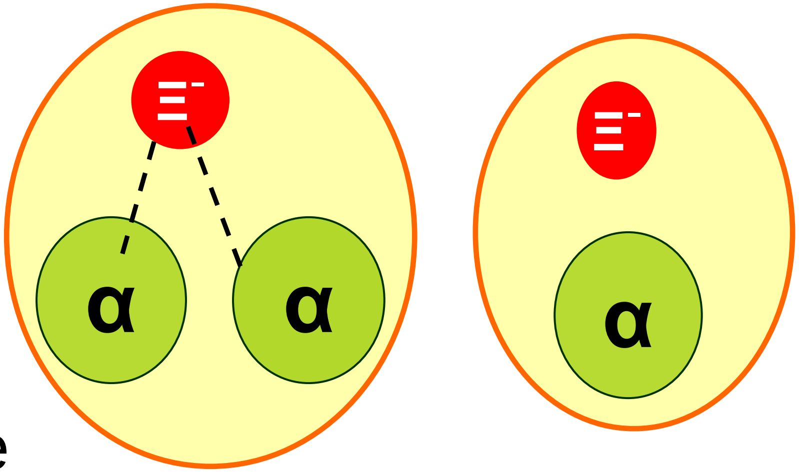
Because,
All of the terms contribute to binding energy of ${}^{15}_{\Xi}C$ (${}^{14}N$ is not spin-, isospin- saturated).

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.



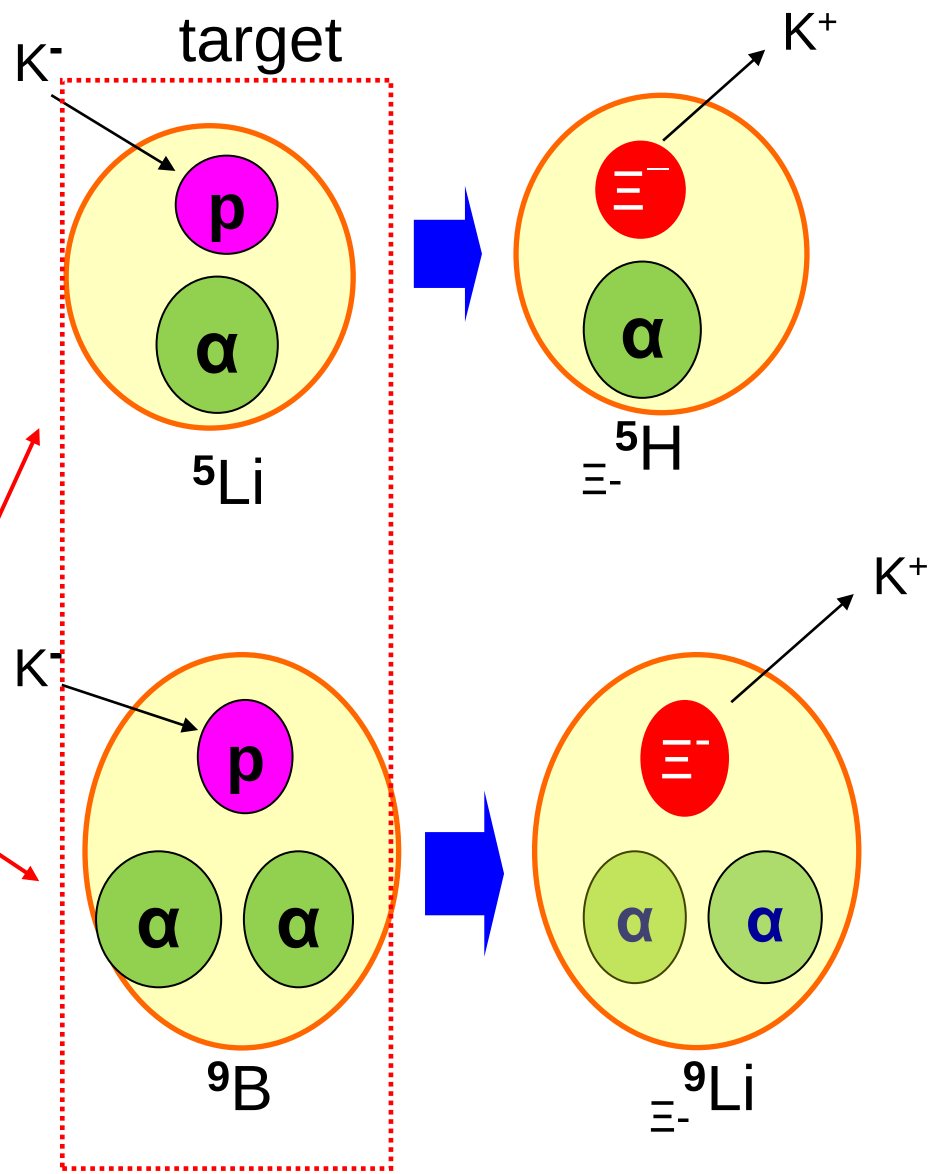
problem : there is NO target to produce them by the (K^-, K^+) experiment .

Because, ･･･

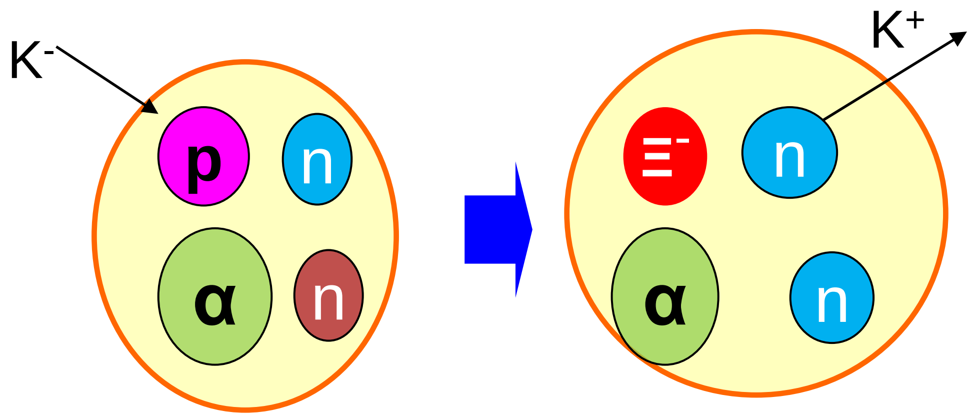
To produce **αΞ⁻** and **ααΞ⁻** systems by (K^-, K^+) reaction,

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…

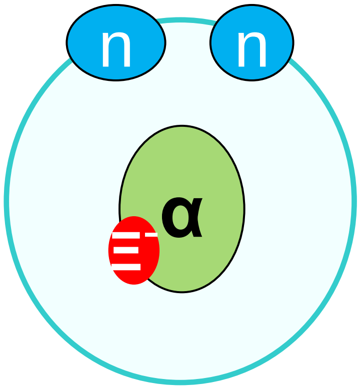


^{7}Li (T=1/2)

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

Why they are suited for investigating V_0?

(more realistic illustration)



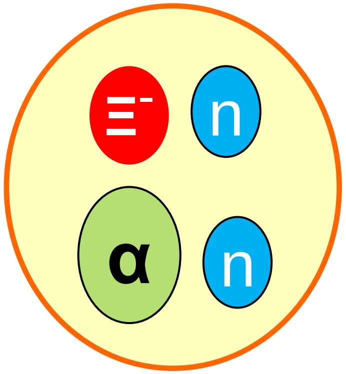
$^{7}_{\Xi^-}H$ (T=3/2)

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.



$^{7}_{\Xi^-}H$ (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 (based on Lattice QCD)

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

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 models are very different (due to the different meson contributions),

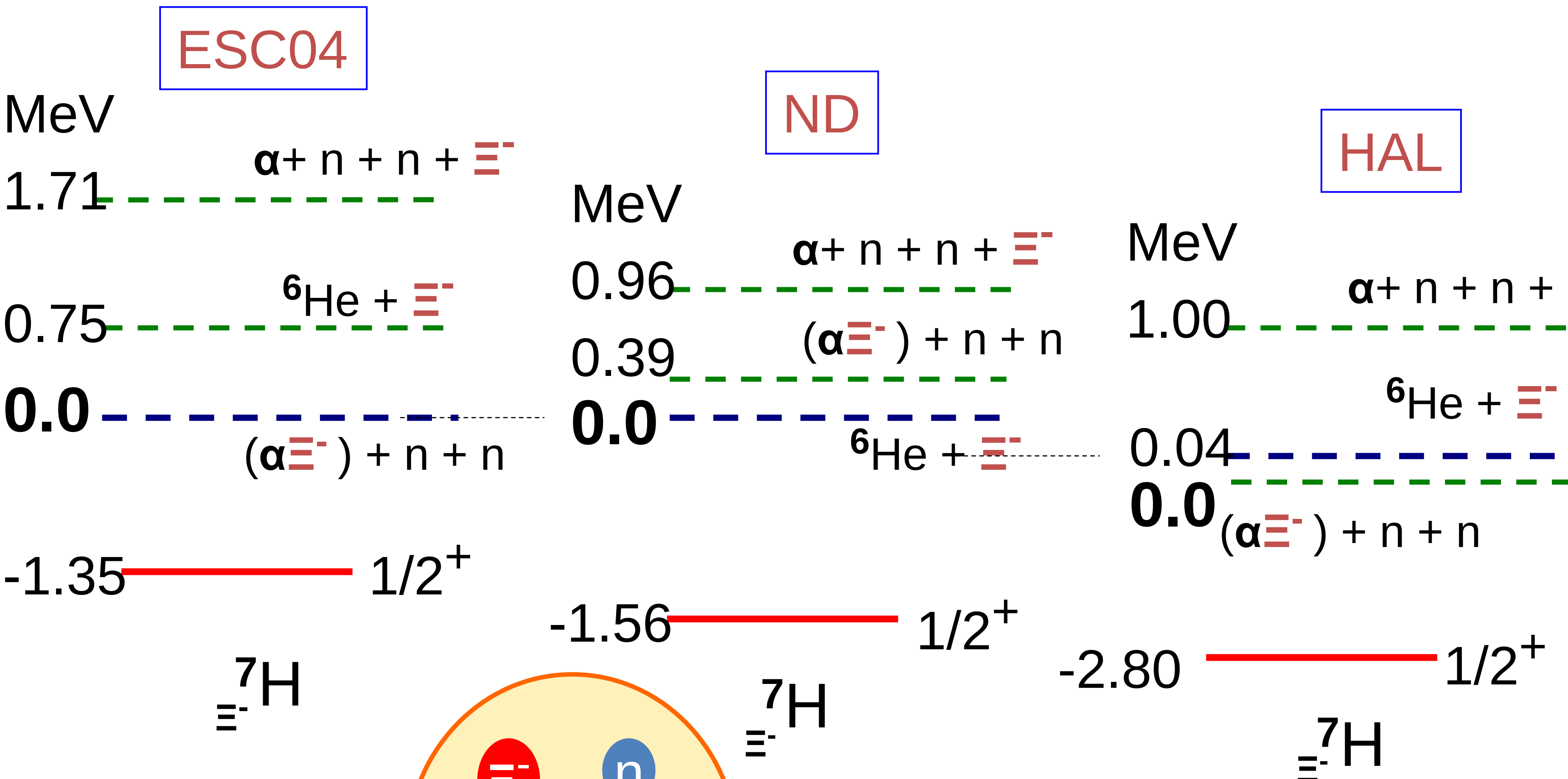
we find that the spin- and isospin-averaged property,

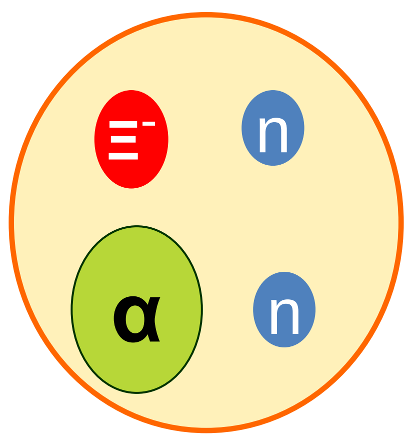
$$V_0 = [\, V(0,0) + 3V(0,1) + 3V(1,0) + 9V(1,1)\,] / 16,$$

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.

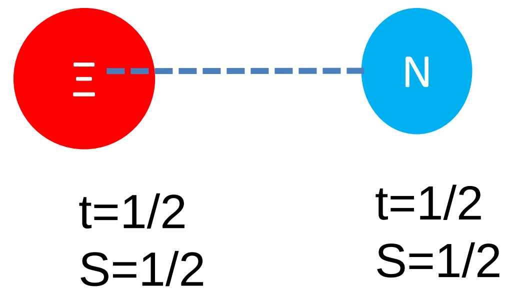
T S

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

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



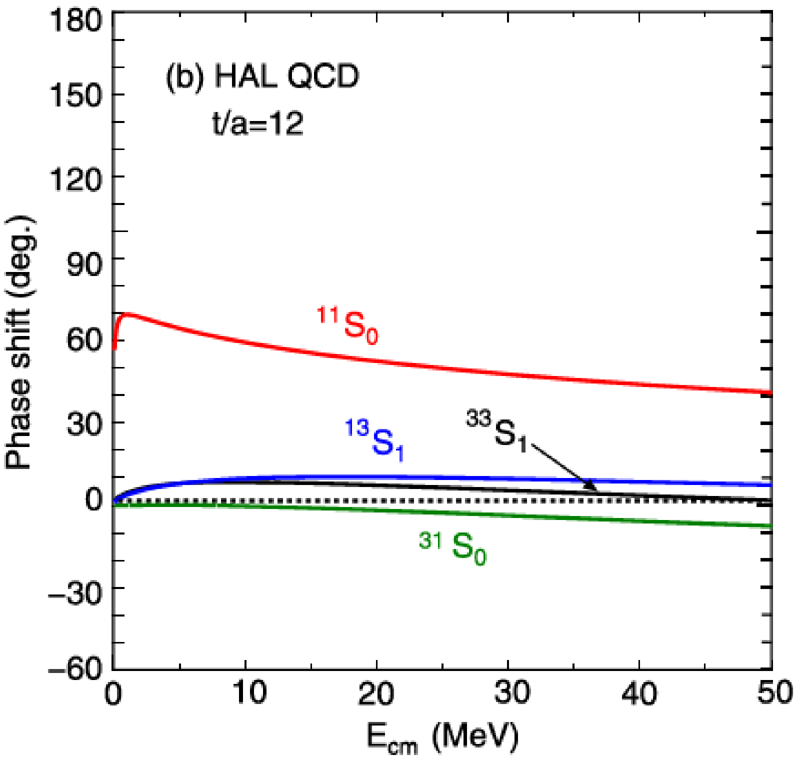
we have a two-body bound state for ΞN system?
No idea

Cf. NN interaction

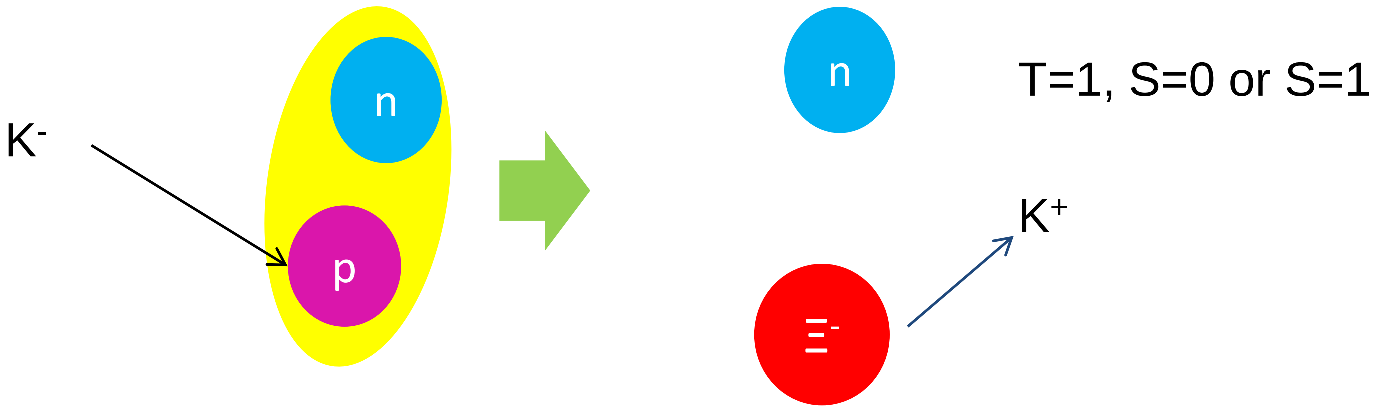
T=0, S=0,l=odd
T=0, S=1 → strong attraction to have a bound state as a deuteron
T=1, S=0
T=1,S=1,l=odd

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



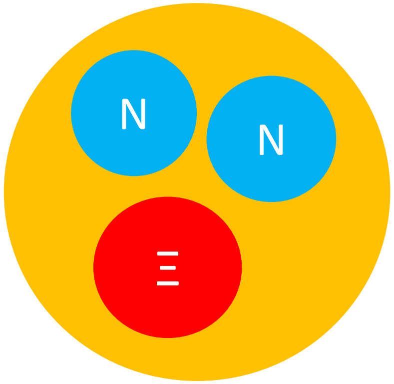
To investigate bound state of ΞN system, it might be possible to perform the following experiment:

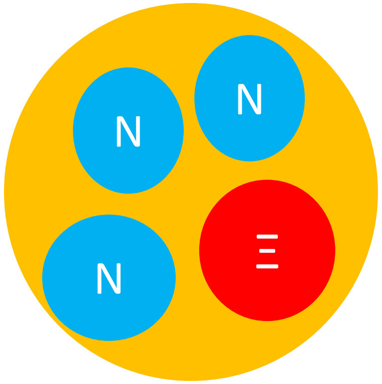


It would be difficult to obtain information on ΞN interaction (T=1,S=0 or 1). Because, there might be no bound state for this system.

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 results of these light systems.

NN interaction: AV8 potential

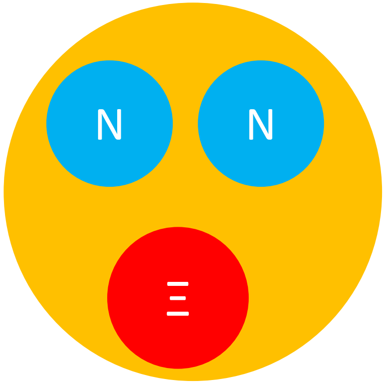
ΞN interaction :

Nijimegen extended soft core potential (ESC08c)

Realistic potential (only ΞN channel)

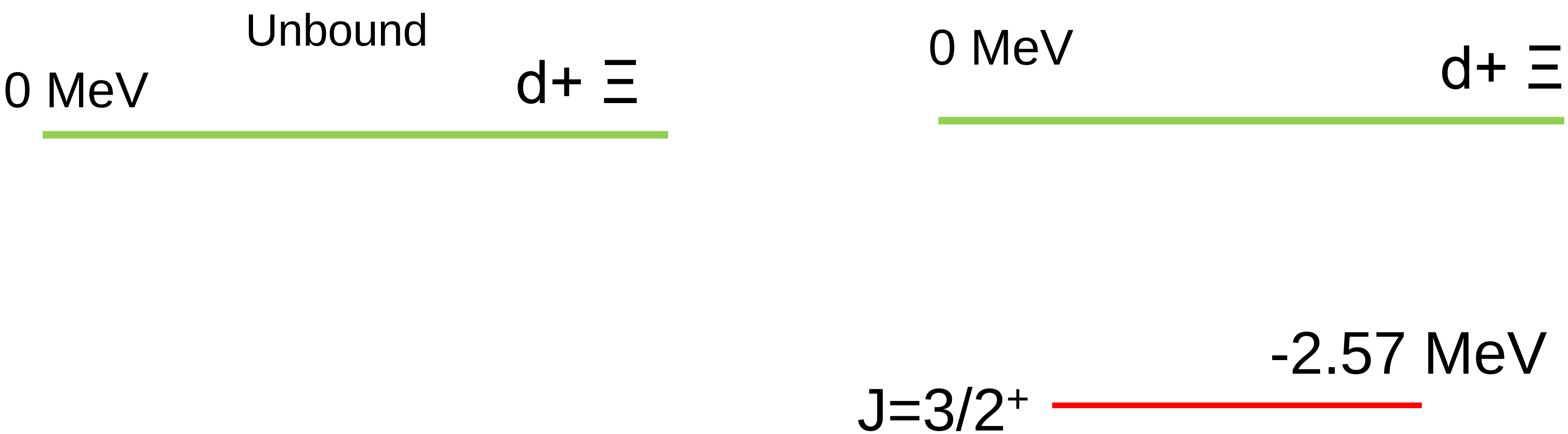
ΞN interaction by HAL collaboration (Lattice QCD calculation)

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

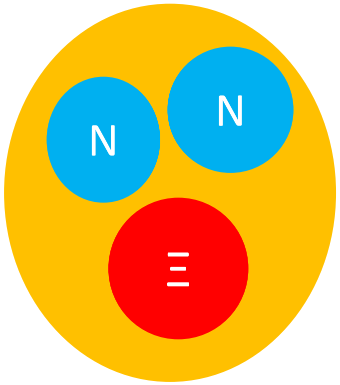


T=1/2, J=1/2$^+$ and J=3/2$^+$

ESC08c



However, I also have two bound states in three-body system.



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

HAL potential

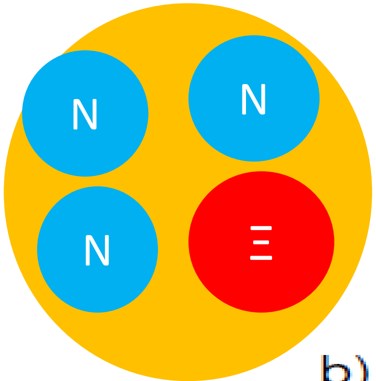
0 MeV d+ Ξ

0 MeV d+ Ξ

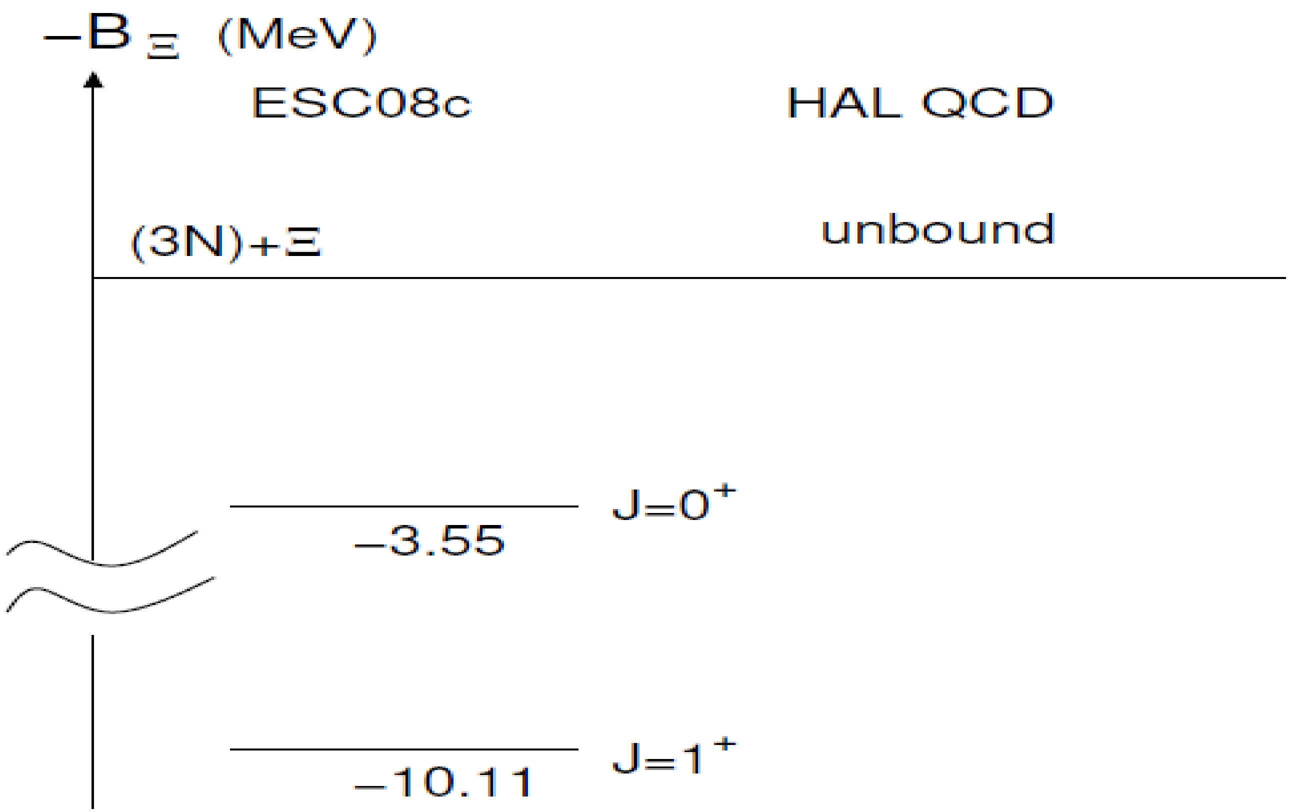
No bound state

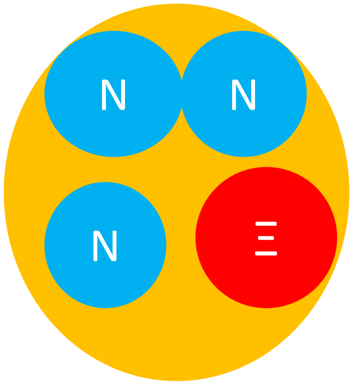
J=3/2$^+$

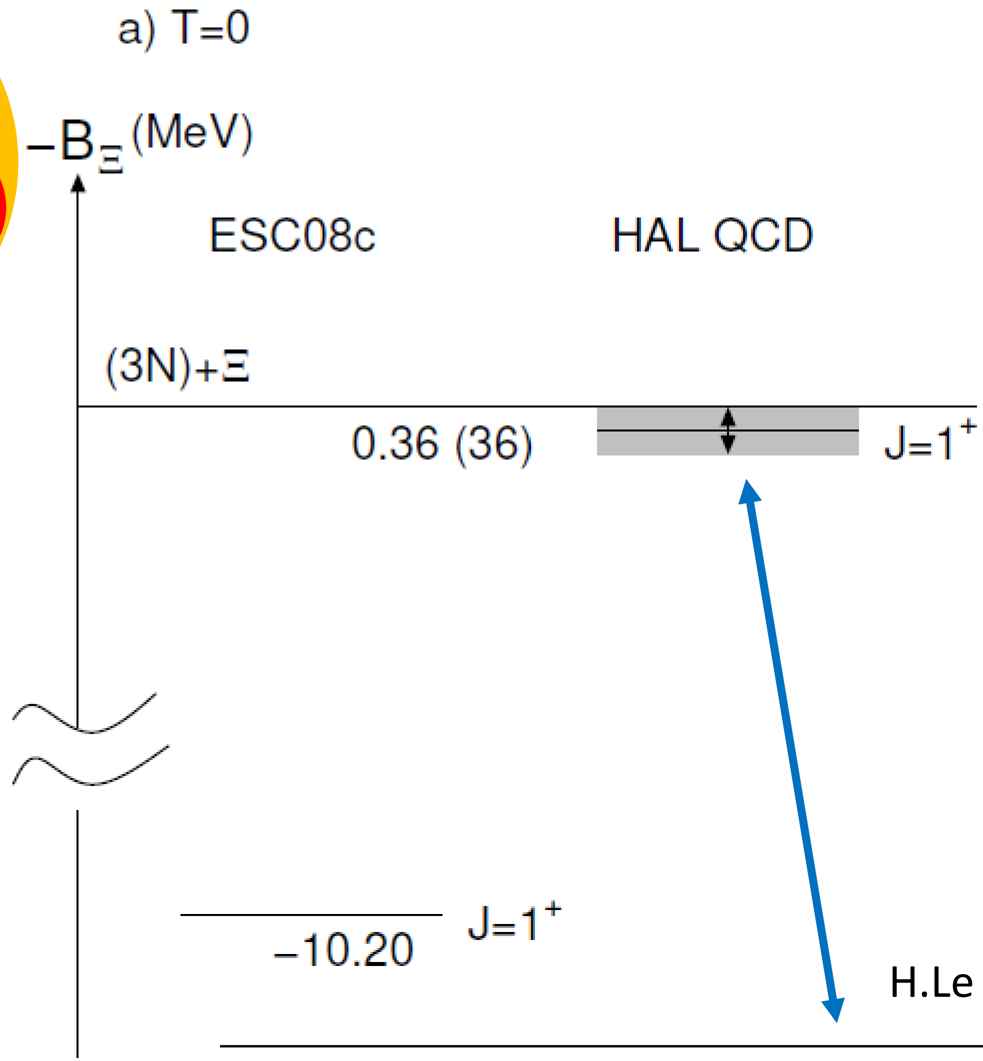
J=1/2+



b) T=1

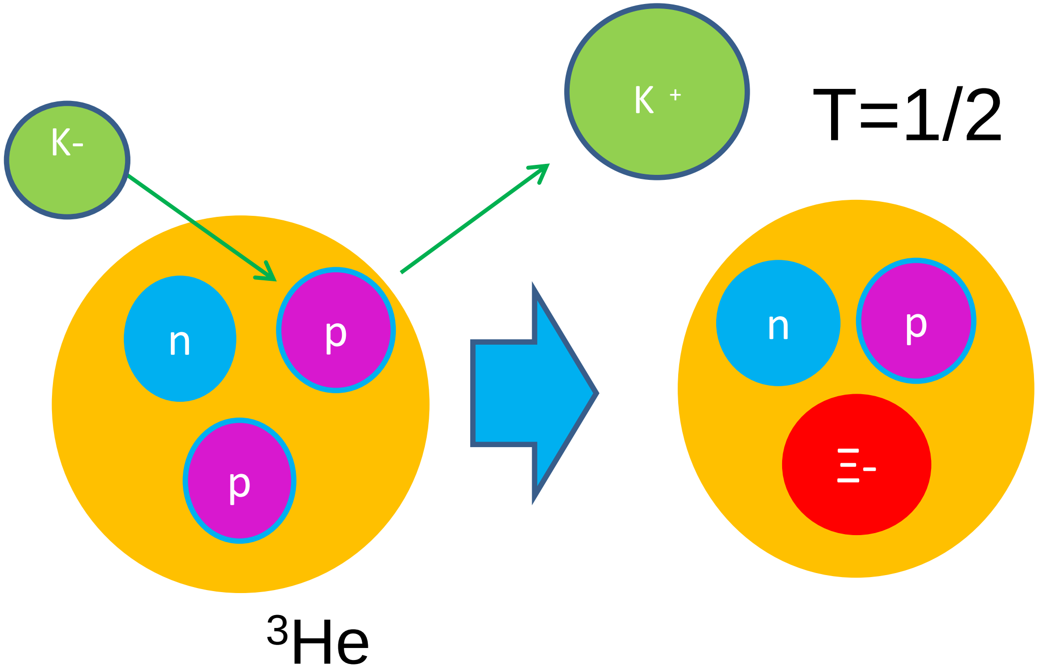






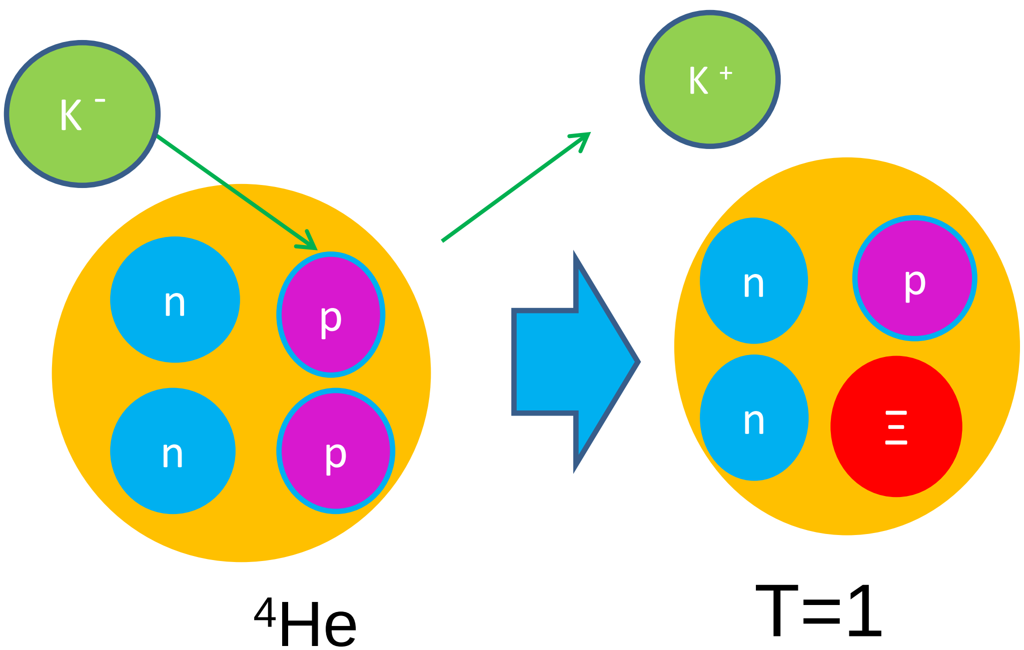
H.Le et al., EPJA57, 339 (2021).

		B_{Ξ} [MeV]	Γ [MeV]
${}^{4}_{\Xi}\mathrm{H}(1^{+},0)$	NNNΞ	0.48 ± 0.01	0.74
${}^{4}_{\Xi}\mathrm{n}(0^{+},1)$		0.71 ± 0.08	0.2
${}^{4}_{\Xi}\mathrm{n}(1^{+},1)$		0.64 ± 0.11	0.01
${}^{4}_{\Xi}\mathrm{H}(0^{+},0)$		–	–



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.

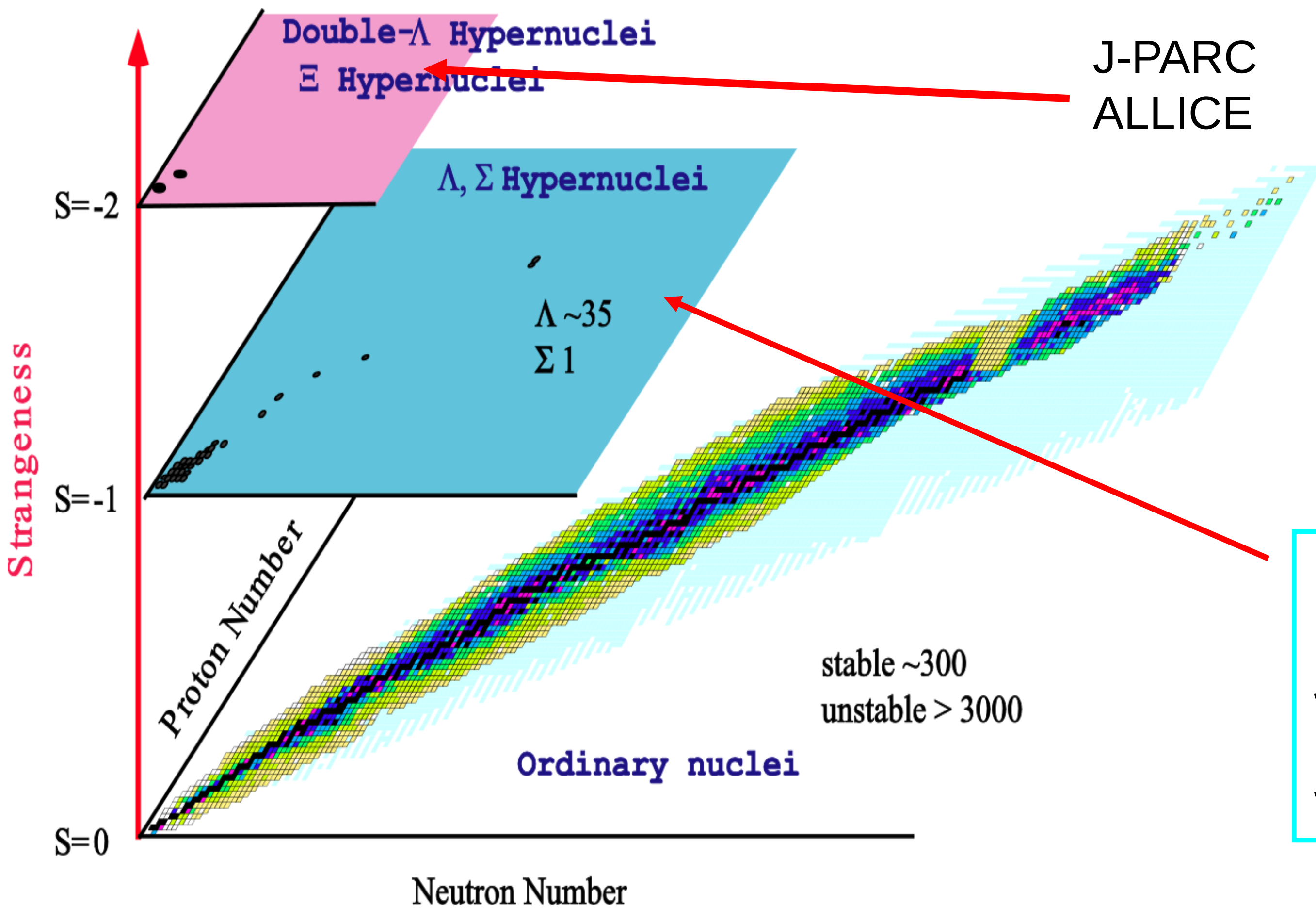


In the future,
we hope to observe
these light Ξ hypernuclei.

Concluding remark

Multi-strangeness system
such as Neutron star

Three-Dimensional Nuclear Chart



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Thank you