Structure of Ξ hypernuclei

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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

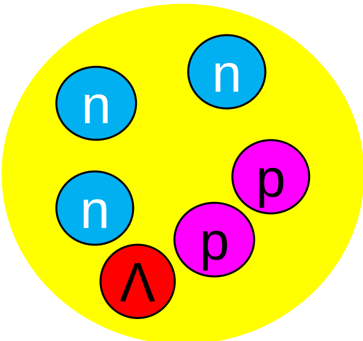
⇨ YN and YY potential models so far proposed (ex. Nijmegen, Julich, Kyoto-Niigata) have large ambiguity.

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

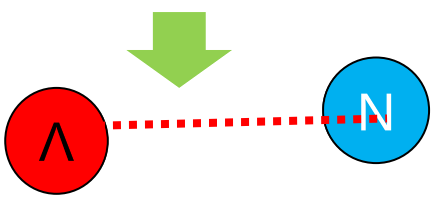
(it is planned to perform YN scattering data at J-PARC.)

Hypernuclear γ-ray data (2019)

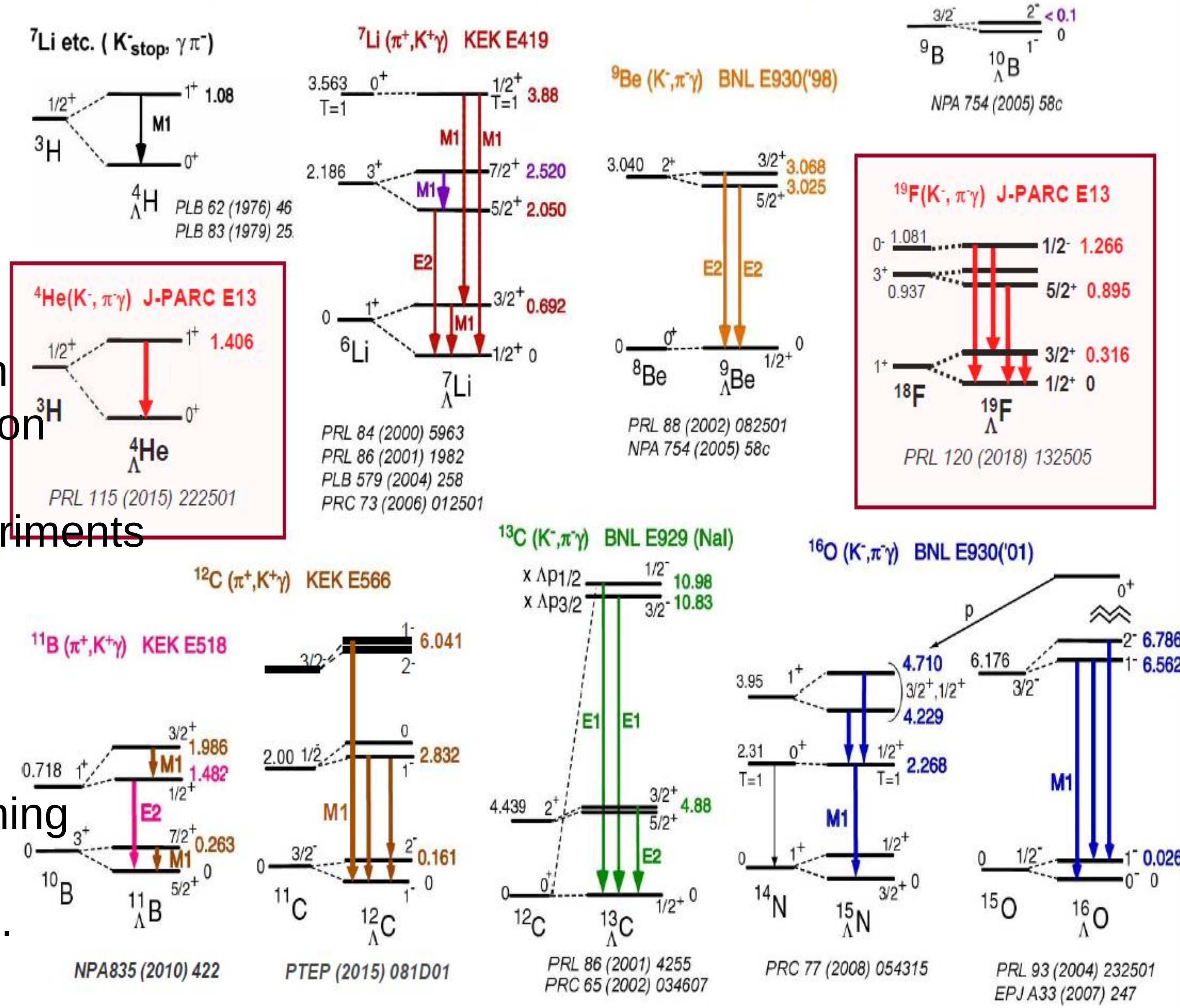
Since 1998



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

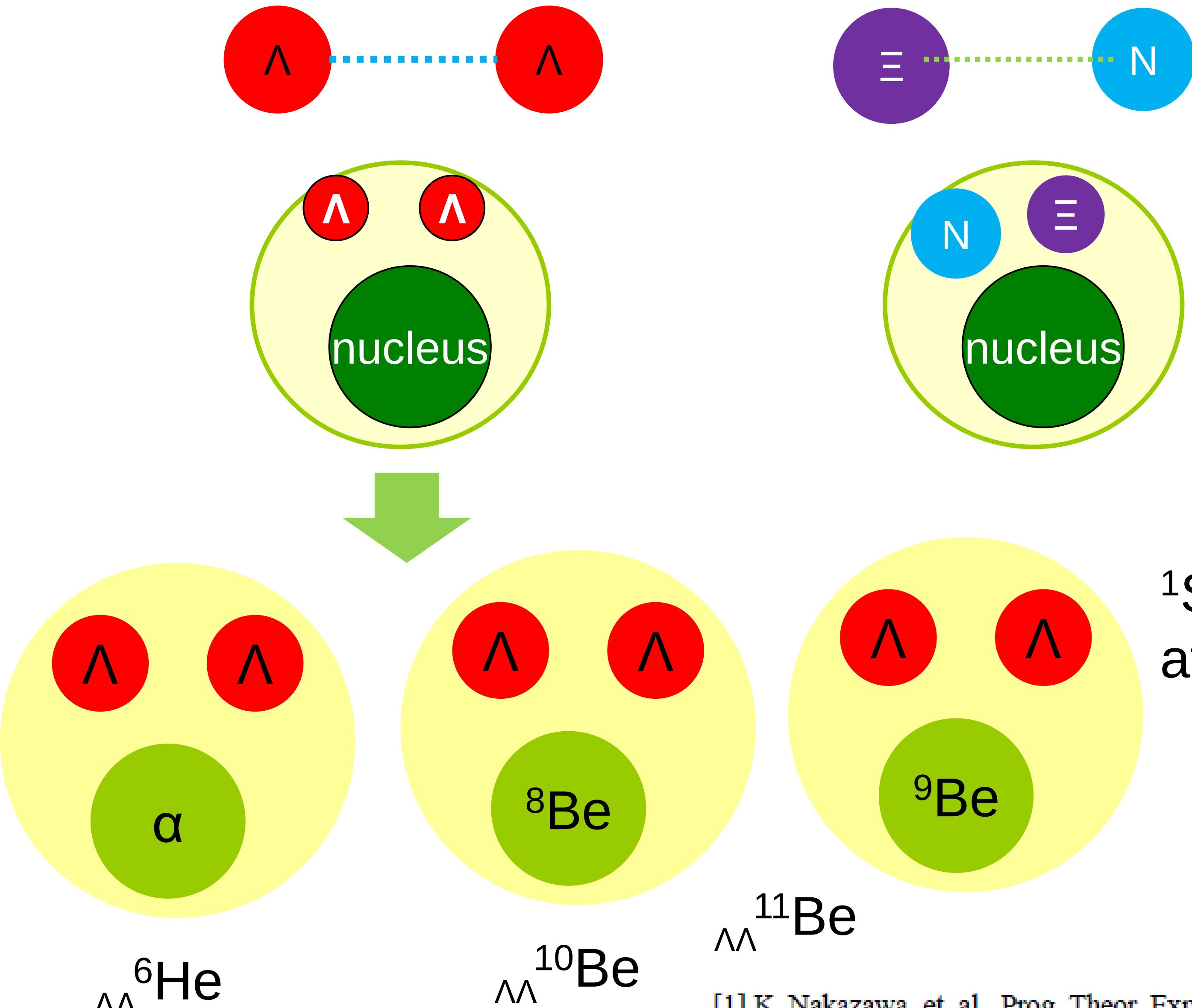


We have been obtaining information on ΛN two-body interaction.



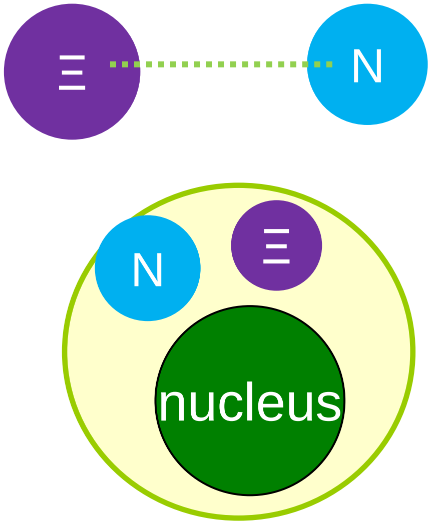
$$V_{\Lambda N} = V_0 + \boldsymbol{\sigma}_\Lambda \cdot \boldsymbol{\sigma}_N \, V_{\sigma\cdot\sigma} + \mathbf{L}\cdot(\mathbf{s}_\Lambda + \mathbf{s}_N)\, V_{\rm SLS} + \mathbf{L}\cdot(\mathbf{s}_\Lambda - \mathbf{s}_N)\, V_{\rm ALS} + S_{12}\, V_{\rm tensor} + \cdots\cdots$$

Next step: S=-2 sector



$^1S_0$ of ΛΛ interaction attractive

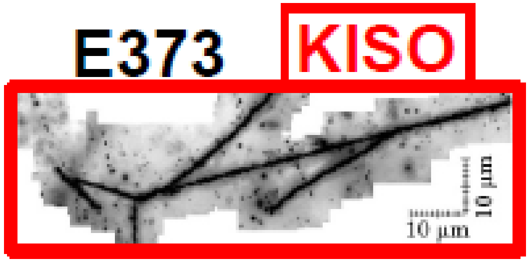
[1] K. Nakazawa, et. al., Prog. Theor. Exp. Phys. **2015**, 033D02 (2015), E. Hiyama and K. Nakazawa, Ann. Rev. Nucl. Part. Sci. **68**, 131 (2018).

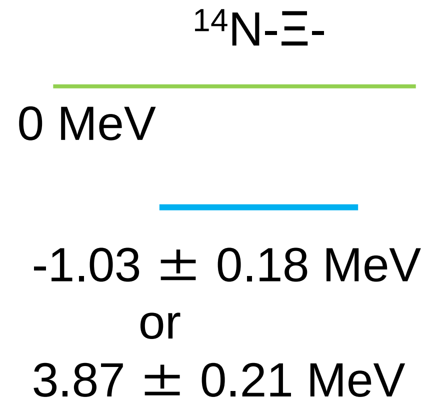


Before 2015, there was no confirmed bound Ξ hypernucleus. Then, we do not know ΞN potential should be repulsive or attractive?

Study of ΞN interaction is one of the important issue in hypernuclear physics.

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





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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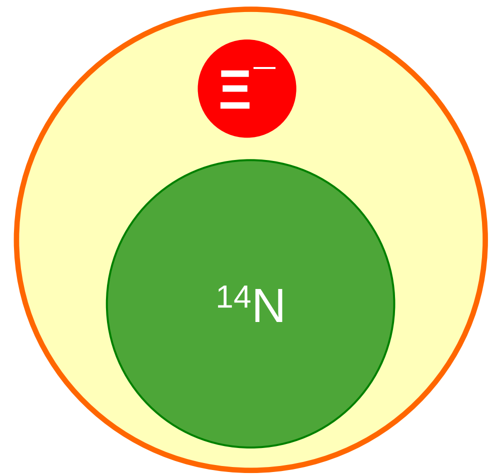
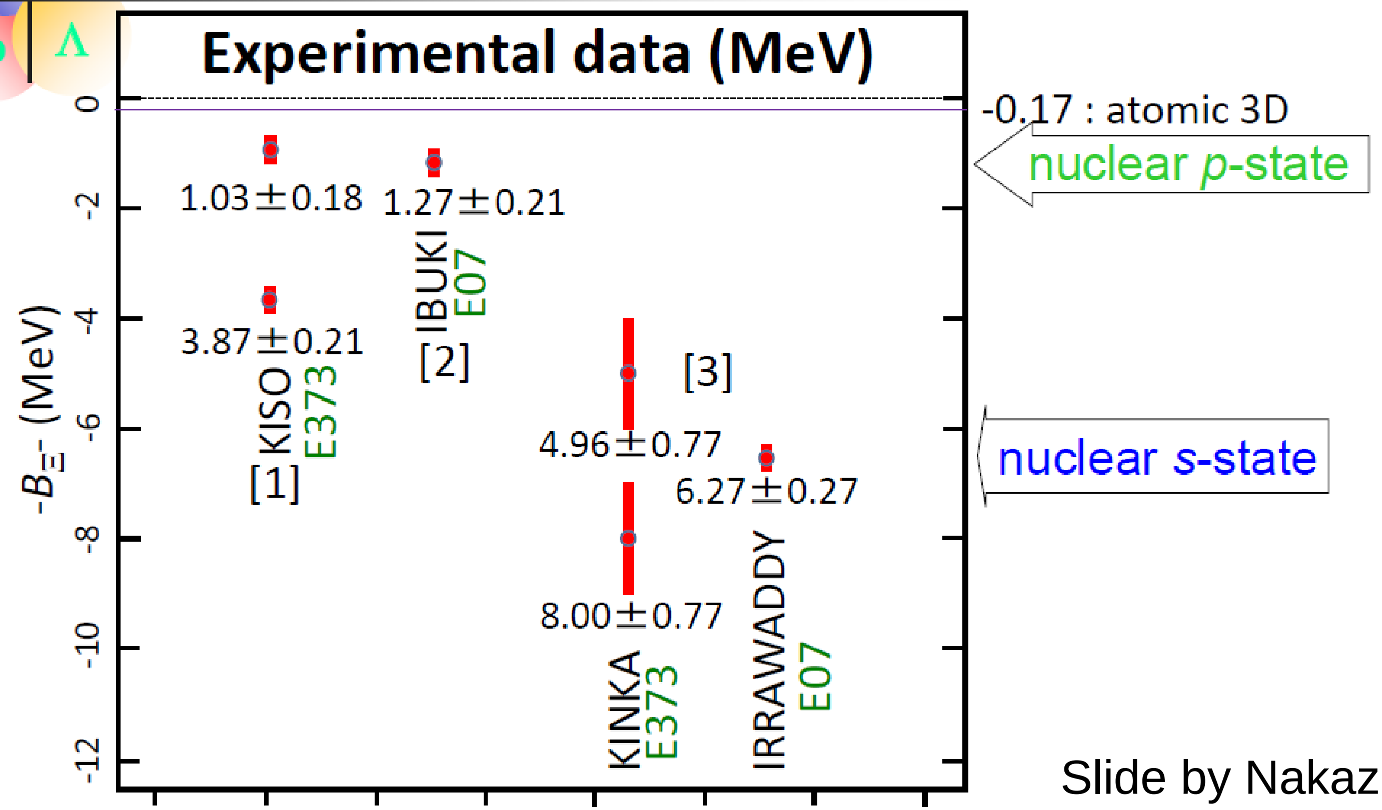


We understood Ξ-nuclear potential should be attractive.

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

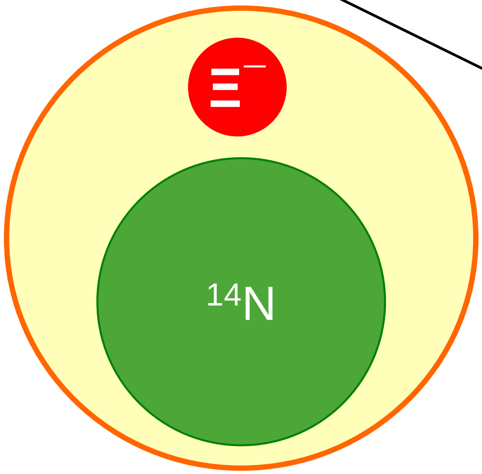
Level scheme of Ξ hypernucleus ($^{15}_{\Xi}C$ [Ξ^{-}-^{14}N])



[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

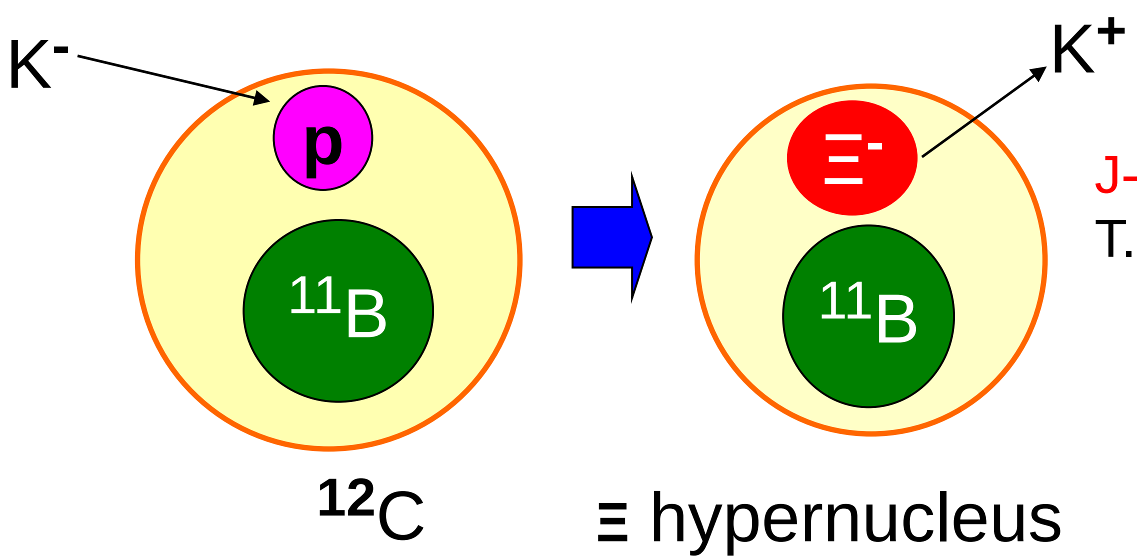
$$V_{\Xi N} = V_0 + \boldsymbol{\sigma}\cdot\boldsymbol{\sigma}\, V_{\sigma\cdot\sigma} + \boldsymbol{\tau}\cdot\boldsymbol{\tau}\, V_{\tau\cdot\tau} + (\boldsymbol{\sigma}\cdot\boldsymbol{\sigma})(\boldsymbol{\tau}\cdot\boldsymbol{\tau})\, V_{\sigma\cdot\sigma\ \tau\cdot\tau}$$



By observation of ^{14}N-Ξ, we understand

$V_{\Xi N}$ is attractive.

Based on this observation,
Now it is important to predict
the level structure of ^{11}B+Ξ system.

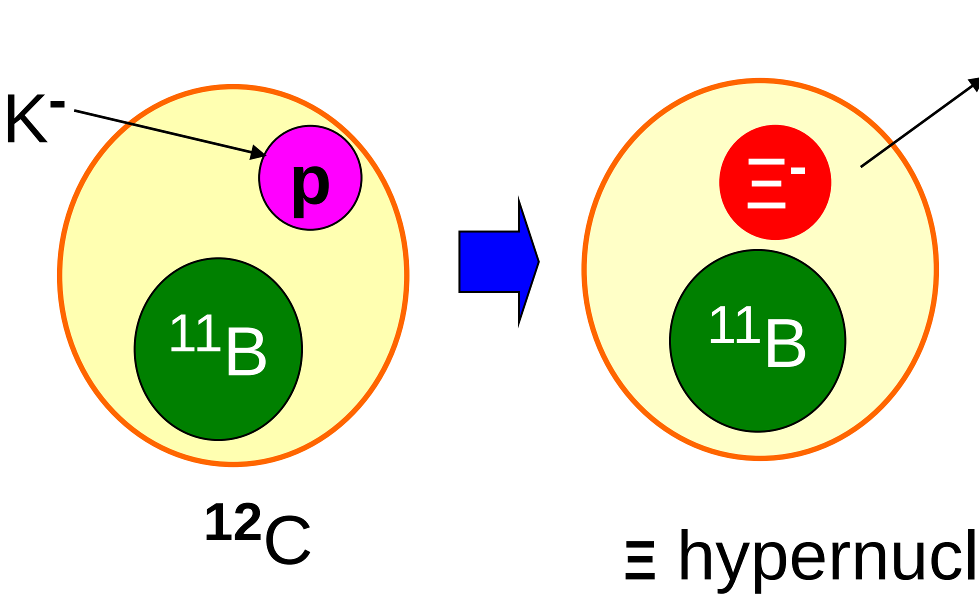


J-PARC: E70: spokesperson
T. Nagae

Total isospin of ^{11}B : ½

Isospin of Ξ: ½

Total isospin of ^{11}B+Ξ: 1 and 0

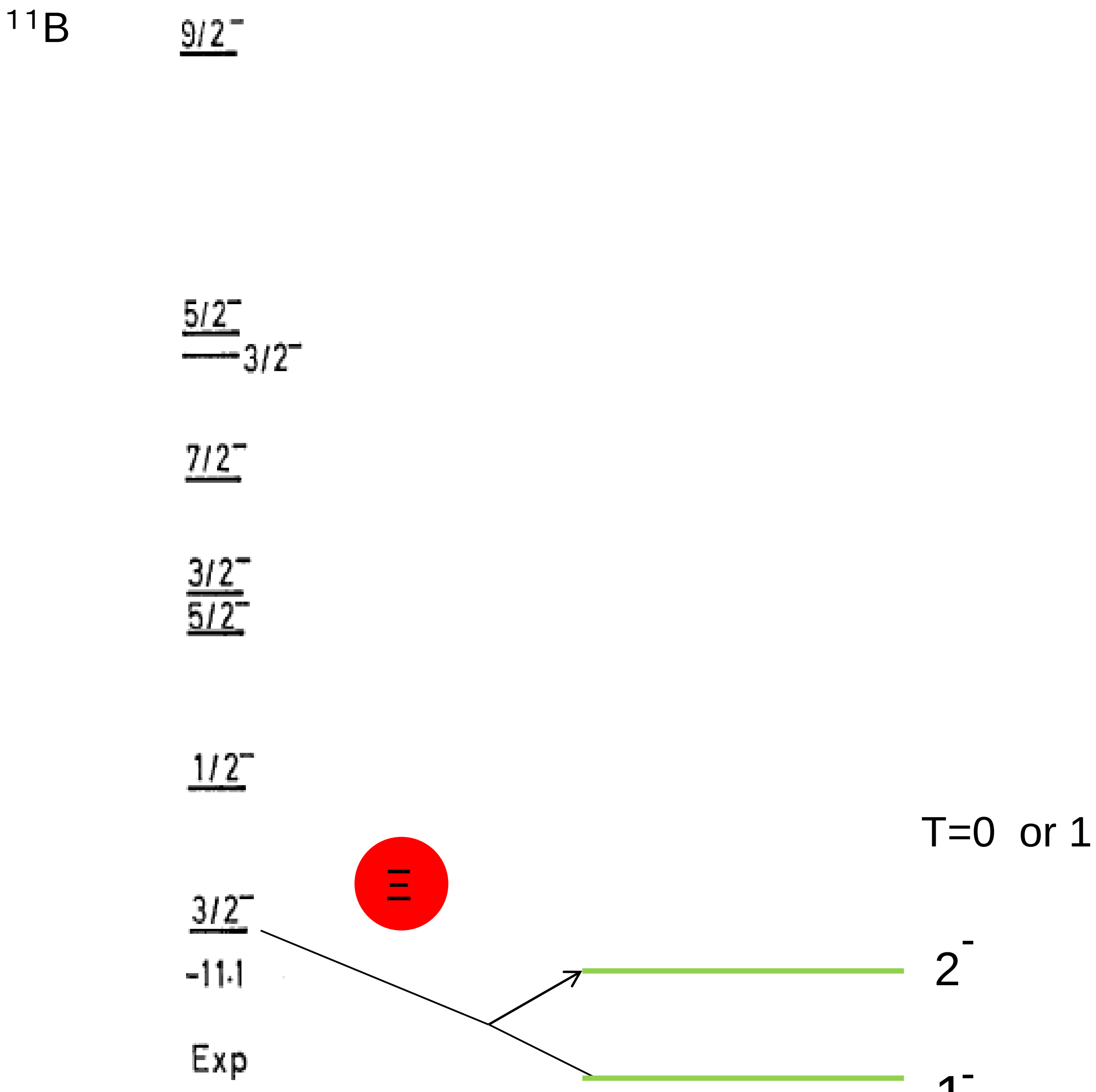


T_z of ^{11}B: -1/2

Ξ-: -1/2

Total t_z of ^{11}B+Ξ : -1

Then, by the experiment, T=1 state of ^{11}B+Ξ- can be produced.



^{11}B
$9/2^-$
$5/2^-$
$3/2^-$
$7/2^-$
$3/2^-$
$5/2^-$
$1/2^-$
$3/2^-$
-11.1
Exp
Ξ
T=0 or 1
2^-
1^-

PHYSICAL REVIEW C **105**, 044324 (2022)

Ξ hypernuclei $^{15}_{\Xi}$C and $^{12}_{\Xi}$Be, and the Ξ*N* two-body interaction

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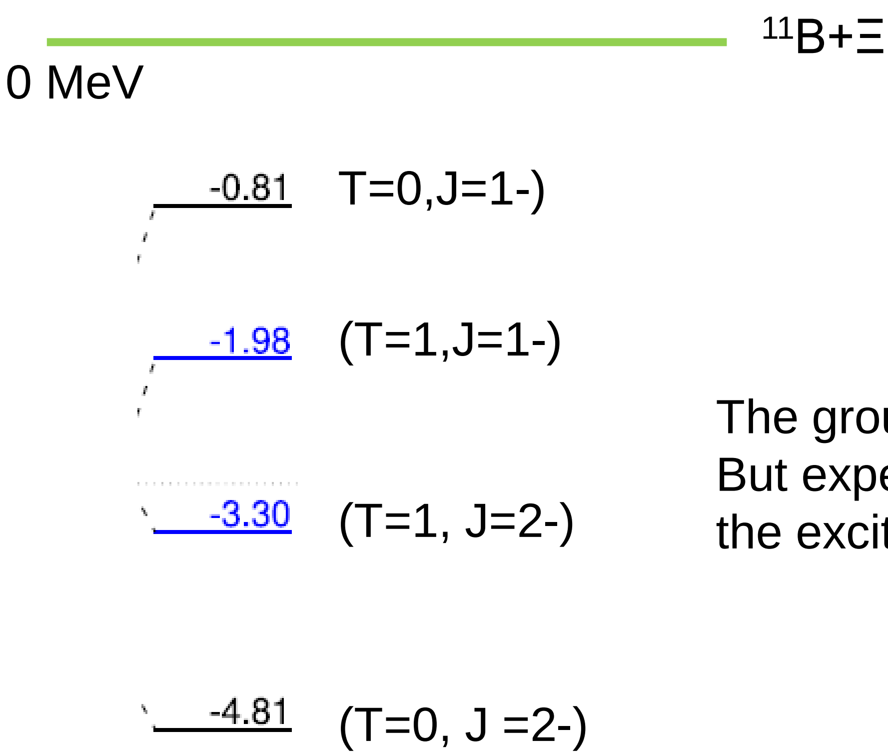


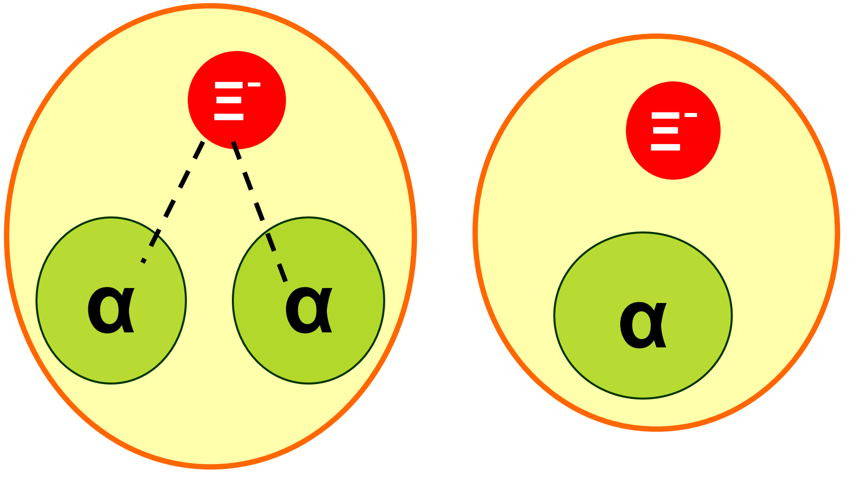
RMF calculation
ΞN interaction; fix so as to reproduce the data of ^{14}N-Ξ system

The ground state of ^{11}B+Ξ is T=0, J=2-.
But experimentally, T=1 states are produced, the excited states.

After observation of ^{11}B-Ξ(J-PARC-E70 exp.), we want to know V_0 term, first.

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

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



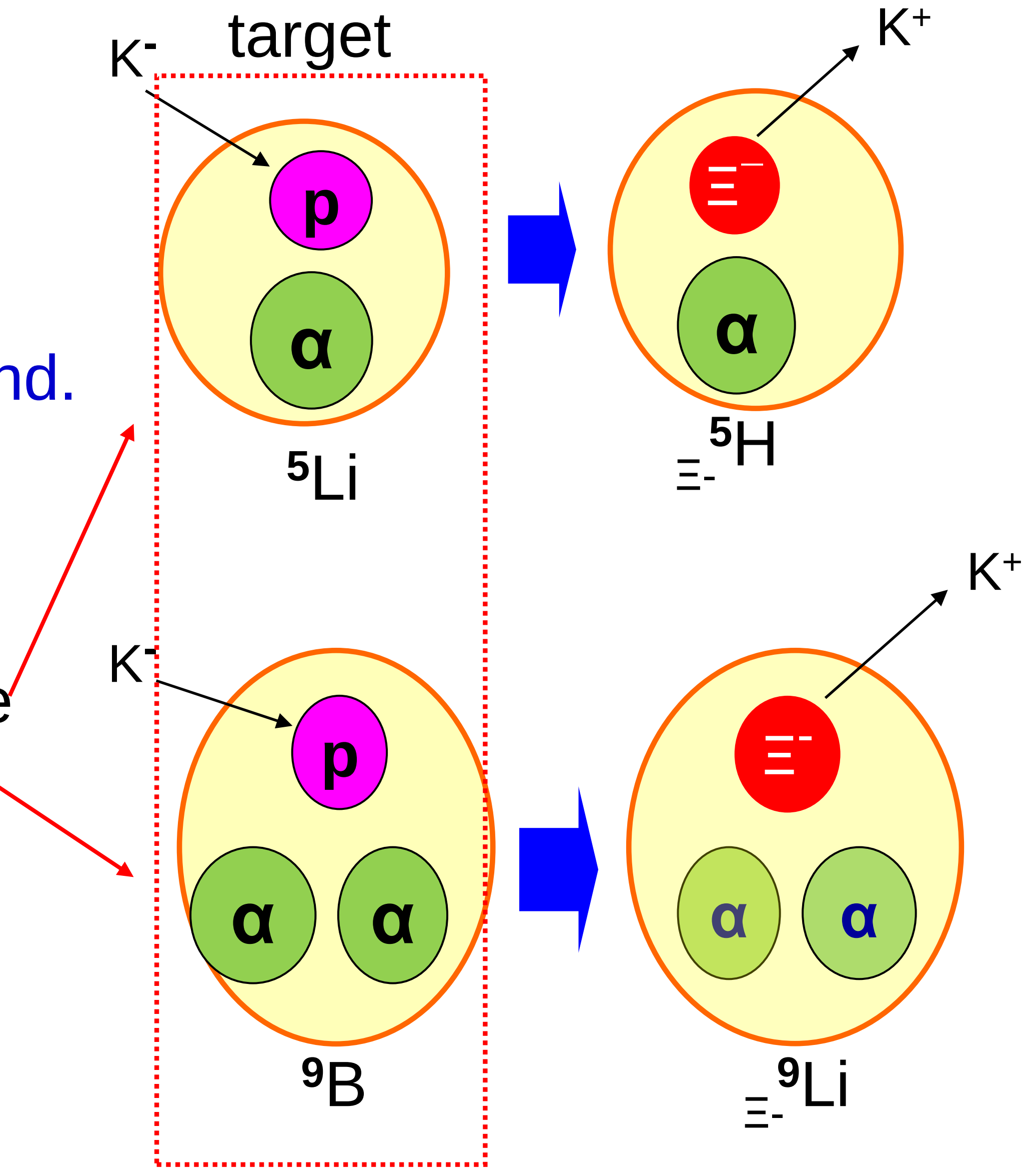
problem : there is NO target to produce them by the (K^-, K^+) experiment .

Because, ・・・

To produce $\alpha\Xi^-$ and $\alpha\alpha\Xi^-$ systems by (K^-, K^+) reaction,

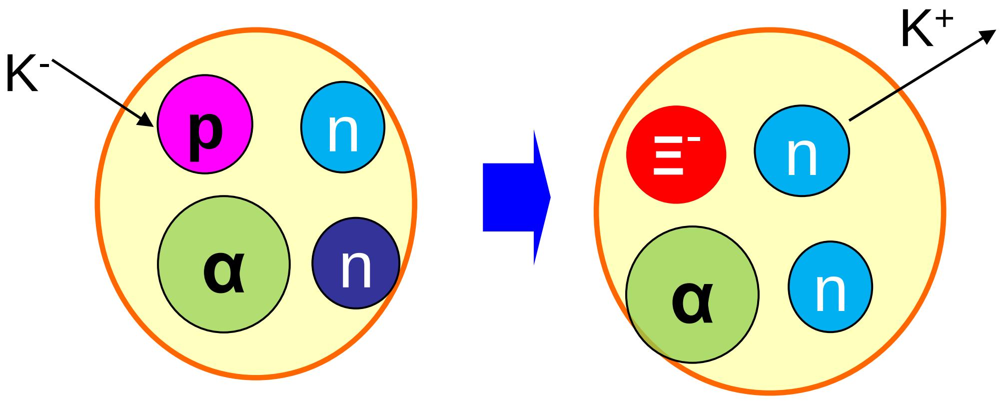
These systems are unbound.

Then, we cannot use them as targets.



Second candidate target to obtain information on V_0 term, first.

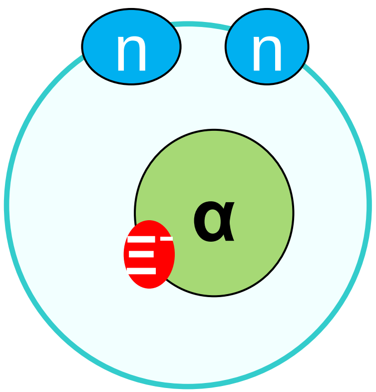
$$V_{\Xi N} = V_0 + \boldsymbol{\sigma}\cdot\boldsymbol{\sigma}\, V_{\sigma\cdot\sigma} + \boldsymbol{\tau}\cdot\boldsymbol{\tau}\, V_{\tau\cdot\tau} + (\boldsymbol{\sigma}\cdot\boldsymbol{\sigma})(\boldsymbol{\tau}\cdot\boldsymbol{\tau})\, V_{\sigma\cdot\sigma\ \tau\cdot\tau}$$



^{7}Li (T=1/2) ^{7}H (T=3/2)

E. H. PRC78,054316(2008).

(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 Ξ particle Ξ^- is located in 0s-orbit.

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

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

ΞN interaction

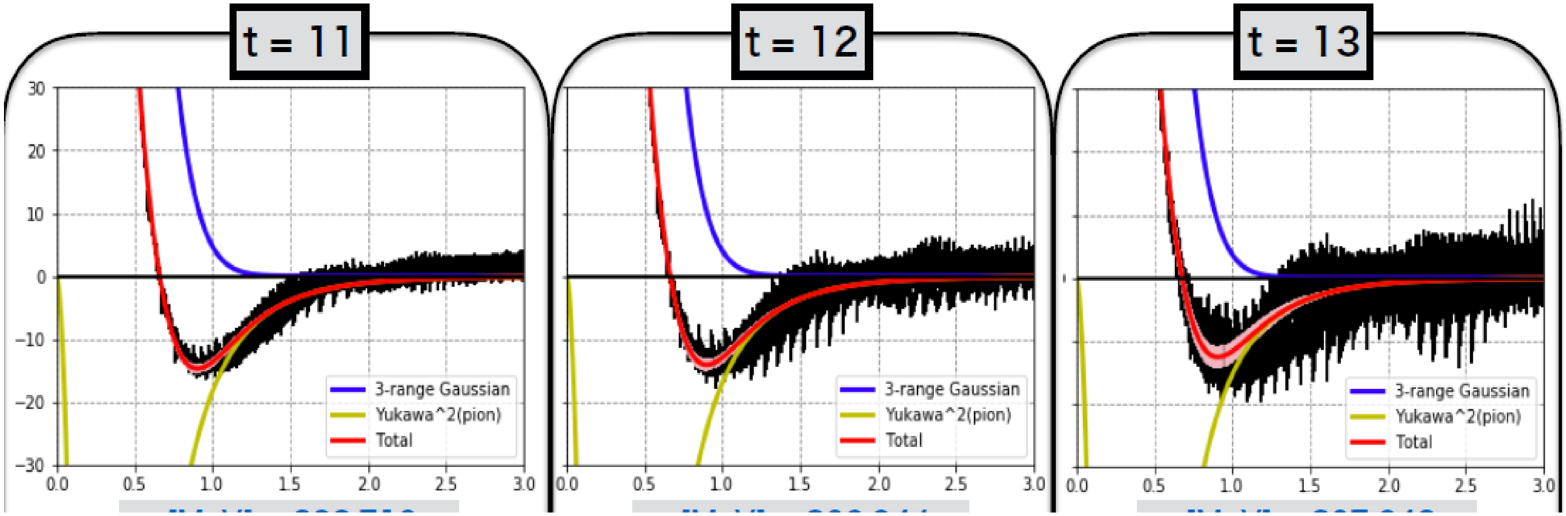
Nijmegen potential : Nijmegen model-D(ND), Extended soft core '04d

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

HAL potential(Base on Lattice QCD potential:HAL collaboration) by K. Sasaki, Miyamoto, T. Doi, T. Hatsuda et al.

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

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 (all four components)	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 potentials are very different (due to the different meson contributions),

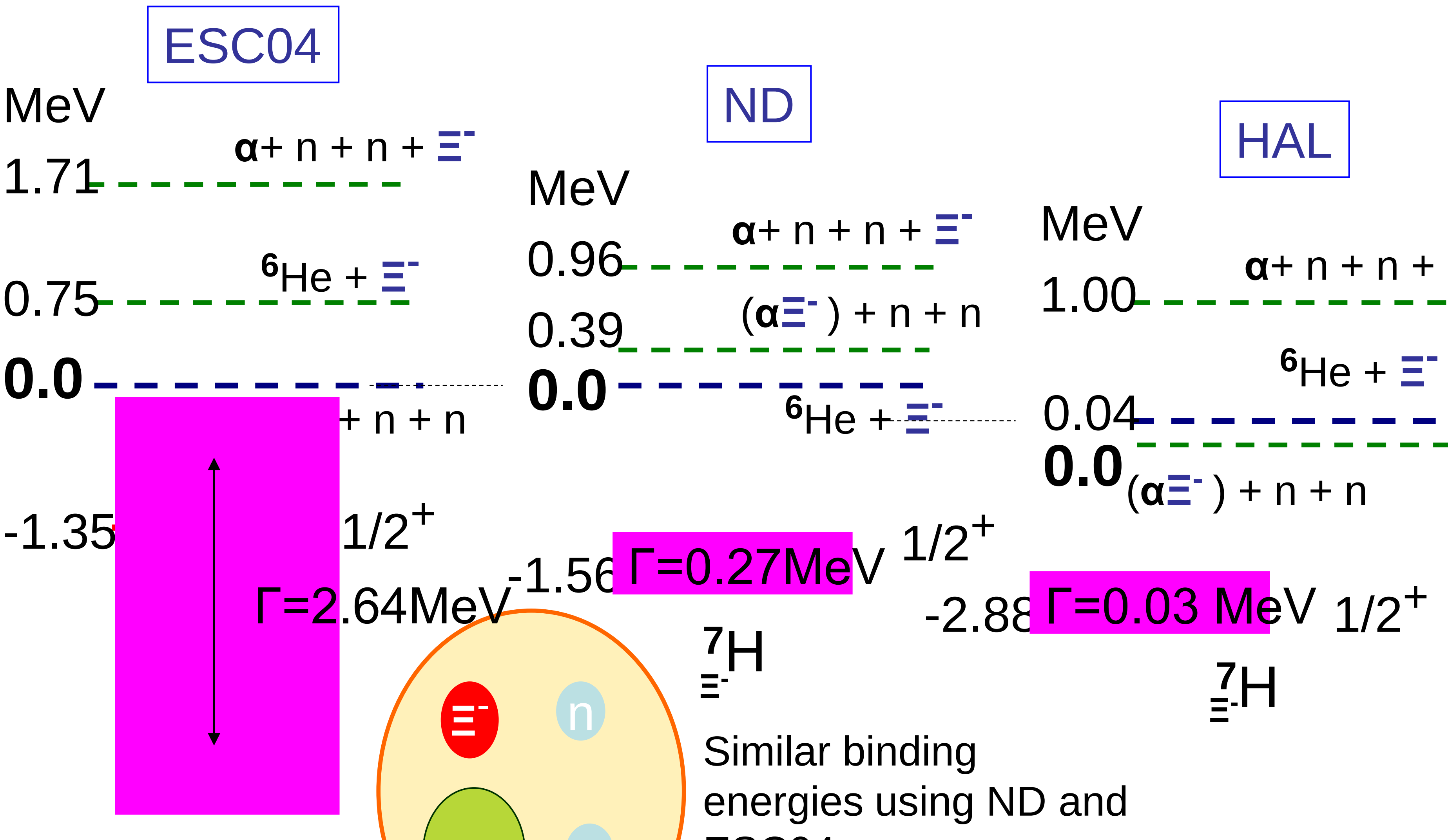
we find that the spin- and isospin-averaged property,

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

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



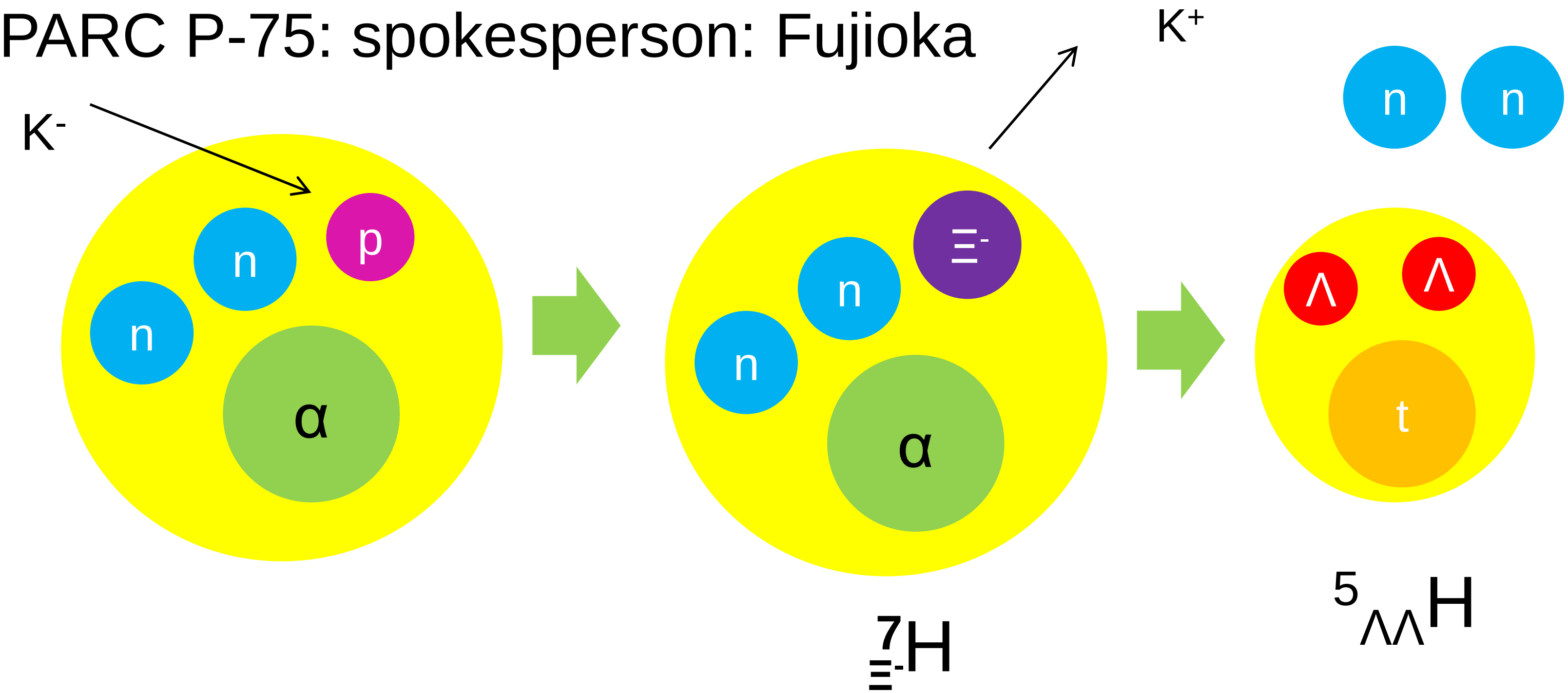
In experiments,
we can expect
a bound state.

Similar binding
energies using ND and
ESC04.

However, decay width is dependent on
on employed ΞN potential

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

J-PARC P-75: spokesperson: Fujioka



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

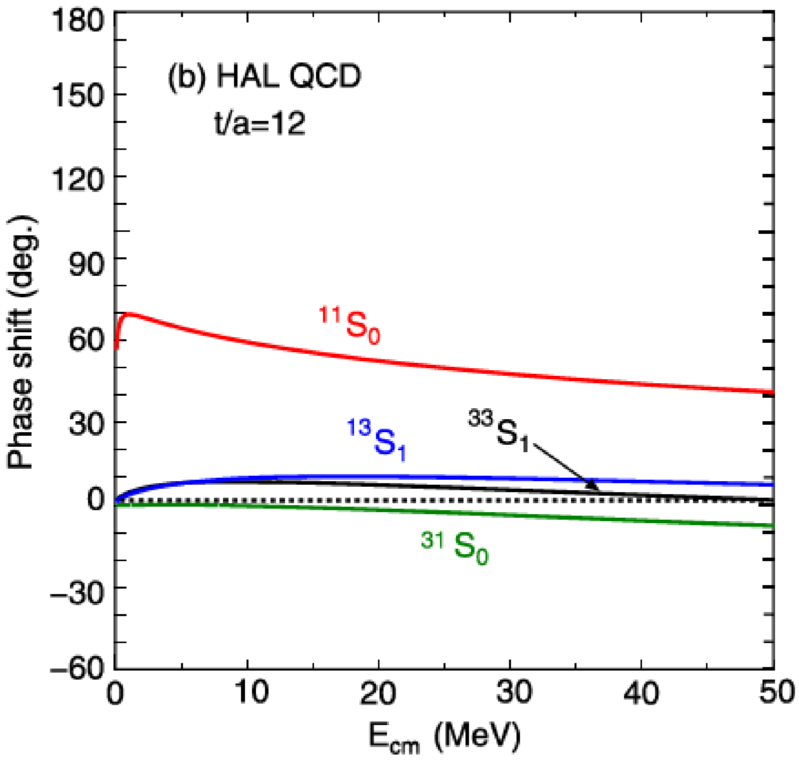
we have a two-body bound state for ΞN system?
No idea

Cf. NN interaction

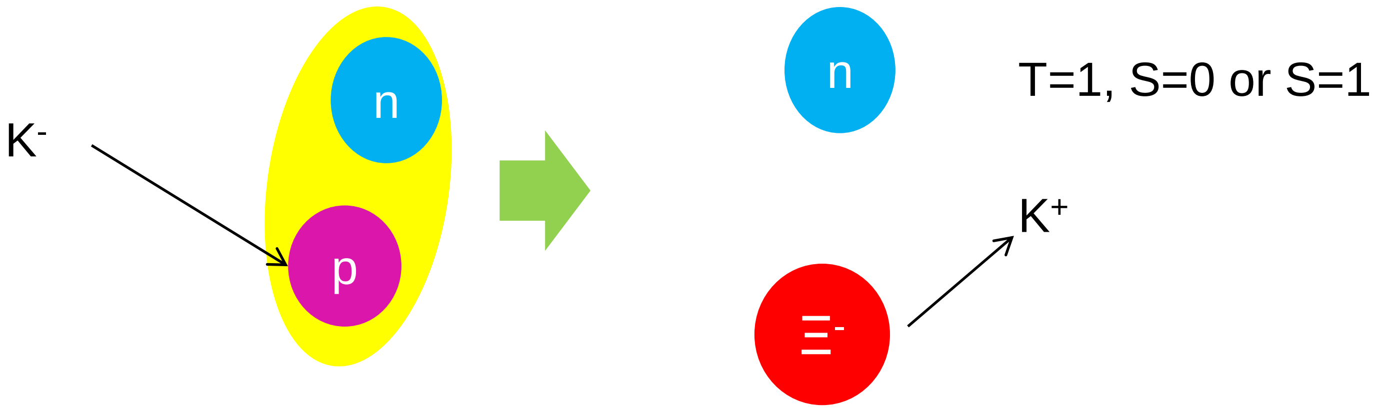
T=0, S=0
T=0, S=1 ➡ strong attraction to have a bound state as a deuteron
T=1, S=0
T=1,S=1

Property of the spin- and isospin-components of HAL

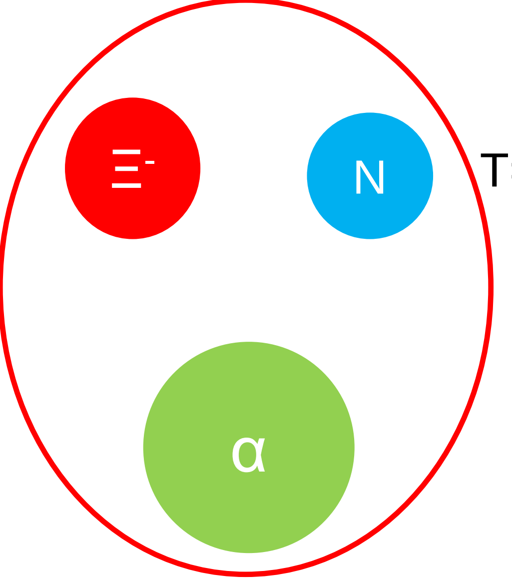
V(T,S)	HAL
T=0, S=1	Weakly attractive
T=0, S=0	Strongly attractive
T=1, S=1	Weakly attractive
T=1, S=0	Weakly repulsive



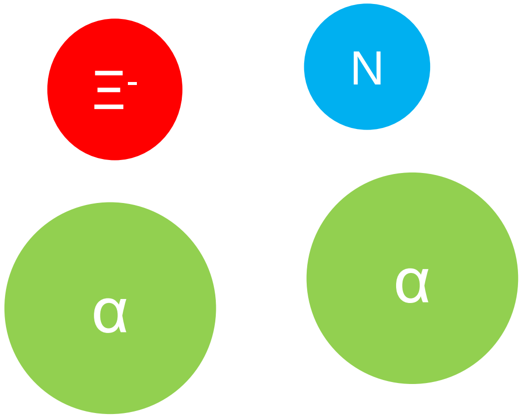
To investigate bound state of ΞN system, it might be possible to perform the following experiment:



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.



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.

arXiv:submit/4494111 [nucl-th] 14 Sep 2022

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

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[2] *Nishina Center for Accelerator-Based Science, RIKEN, Wako, 351-0198, Japan*
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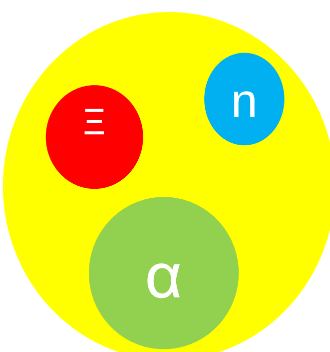
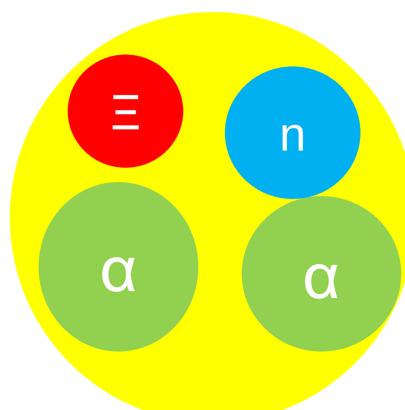
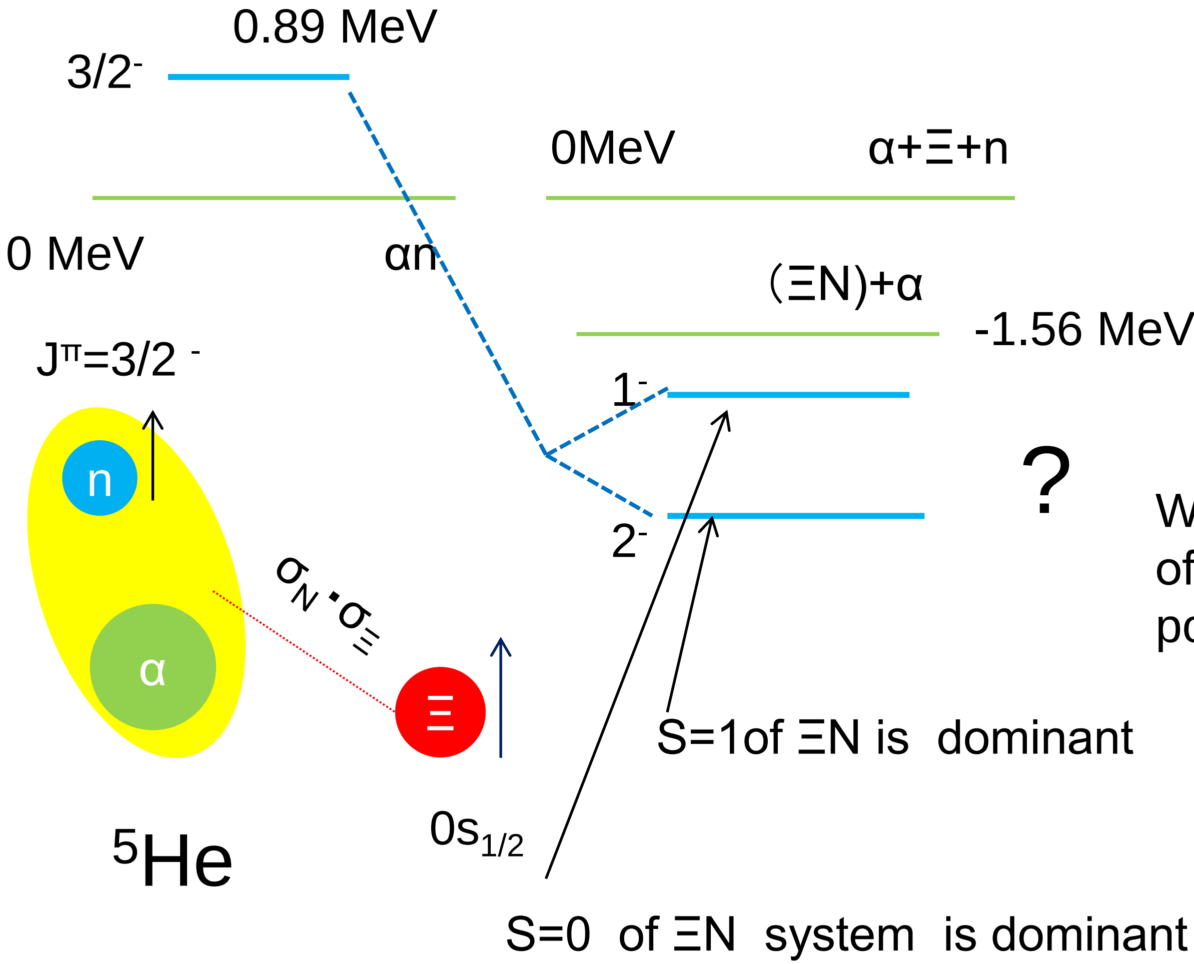
[4] *Interdisciplinary Theoretical and Mathematical Sciences Program (iTHEMS), RIKEN, Wako 351-0198, Japan*

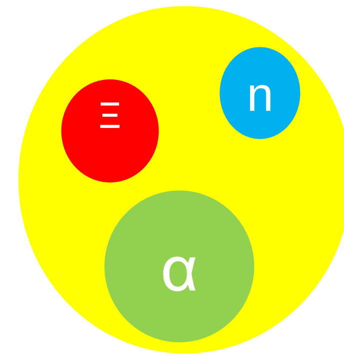
(Dated: September 14, 2022)

Submitted to arXiv on 14th Sep.









What about level structure of αΞN system using HAL potential?

0MeV α+Ξ+n

No bound

-1.22

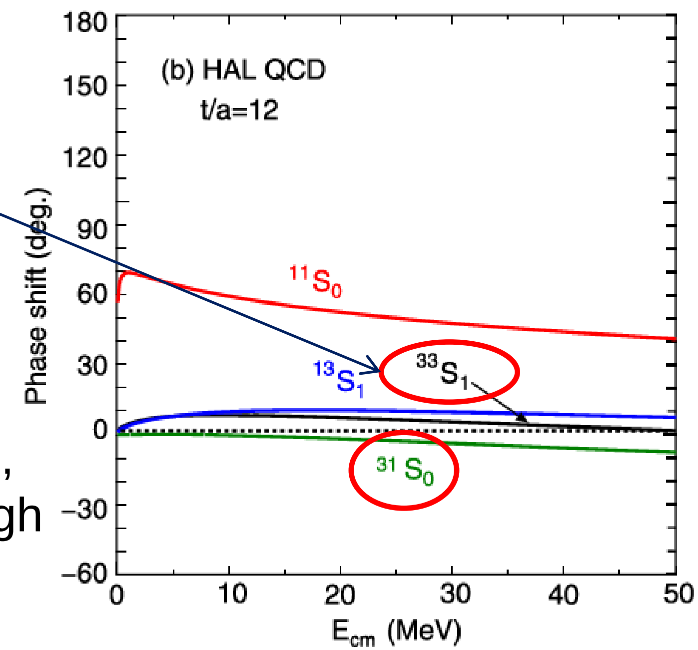
(αΞ)+n

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

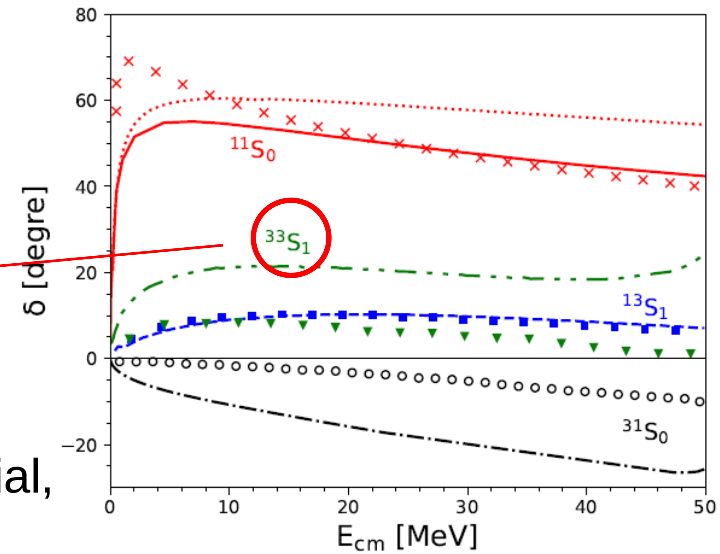
(αΞ)+n

-1.22

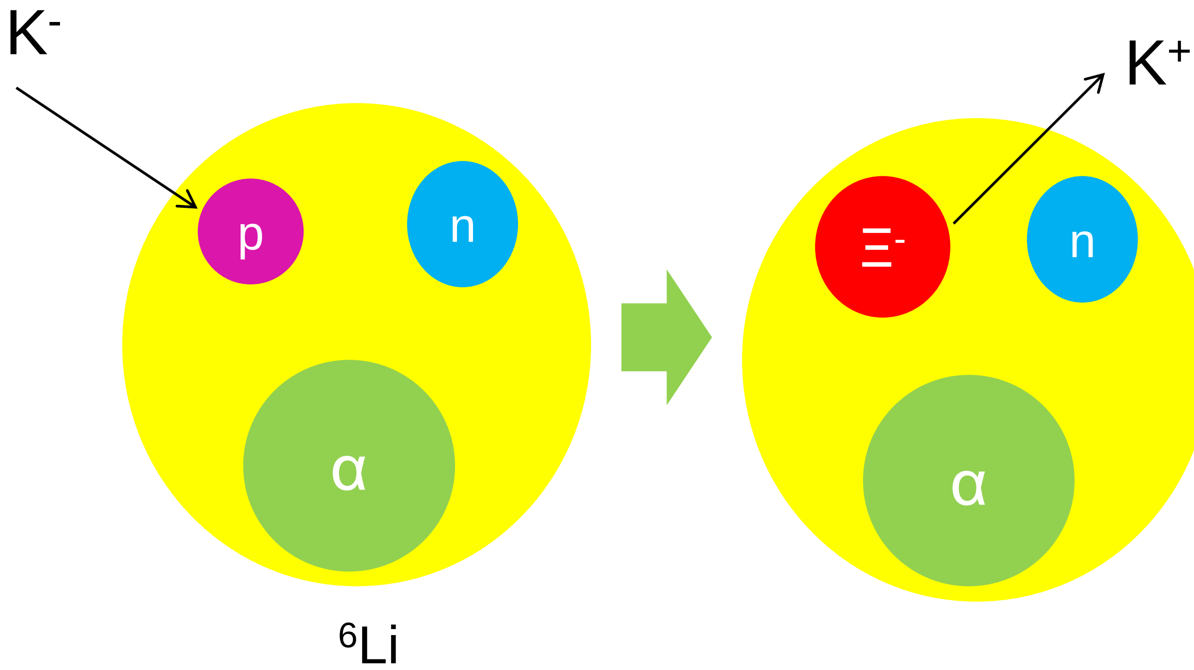
2^-

-1.47 MeV

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

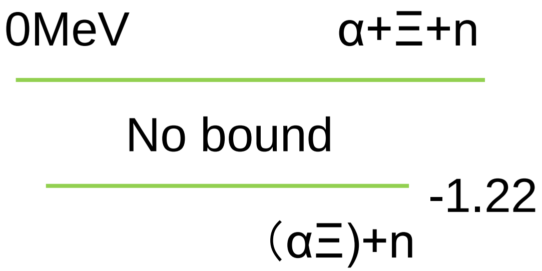


H. Le, et al., EPJA57,339(2021)
Chiral EFT ΞN interaction.

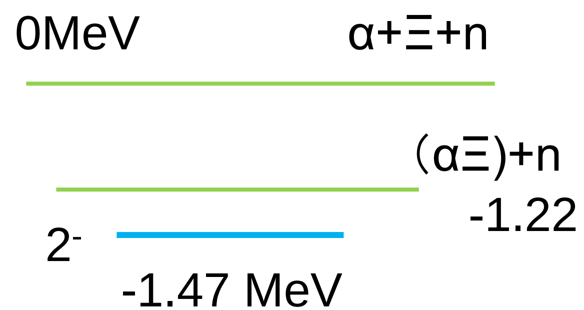


T=1,S=0 or S=1

Experimentally,
It is possible to
produce Ξ hypernucleus.

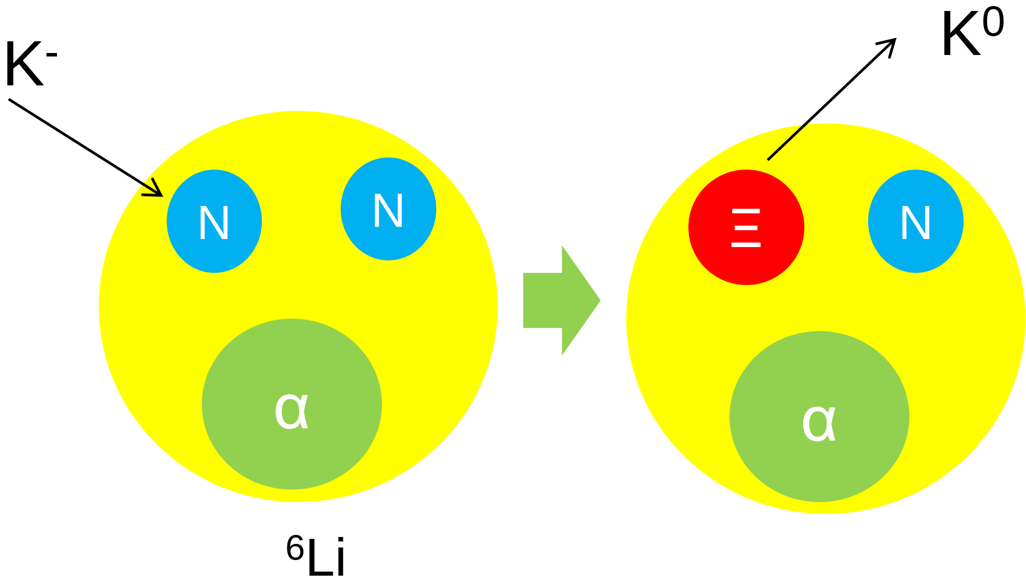


HAL



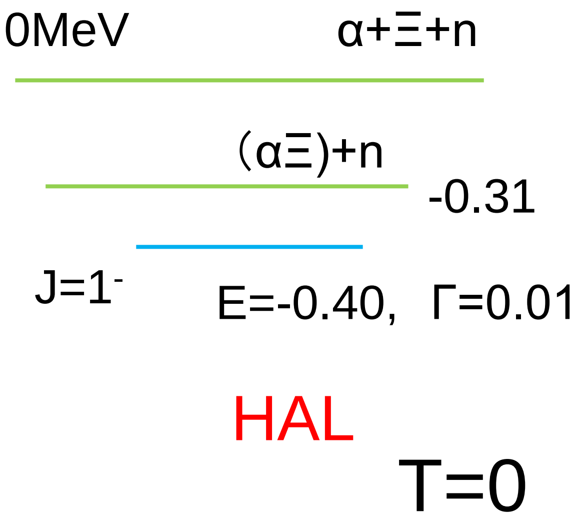
Chiral EFT

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

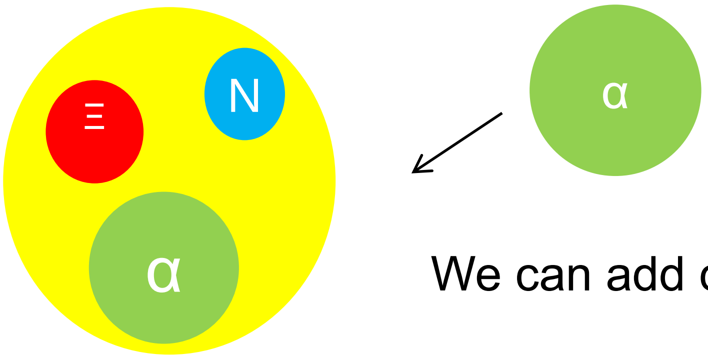
We can obtain information on T=0, S=0 and S=1 ΞN interaction.



T=0,S=0 of ΞN interaction dominant

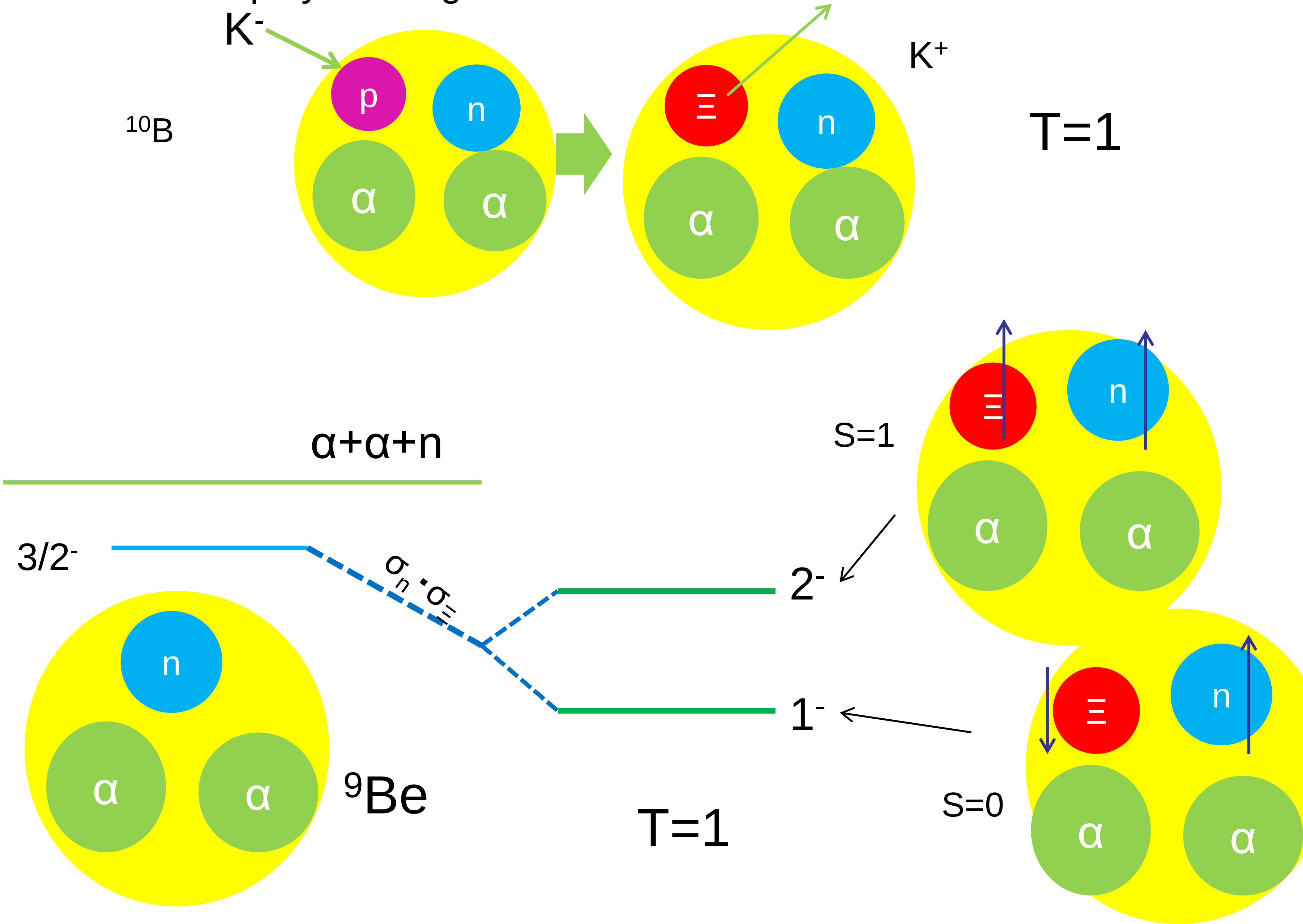
Currently, (K^-,K^0) reaction would be difficult experiment. Then, it might be risky to use ^6Li target.

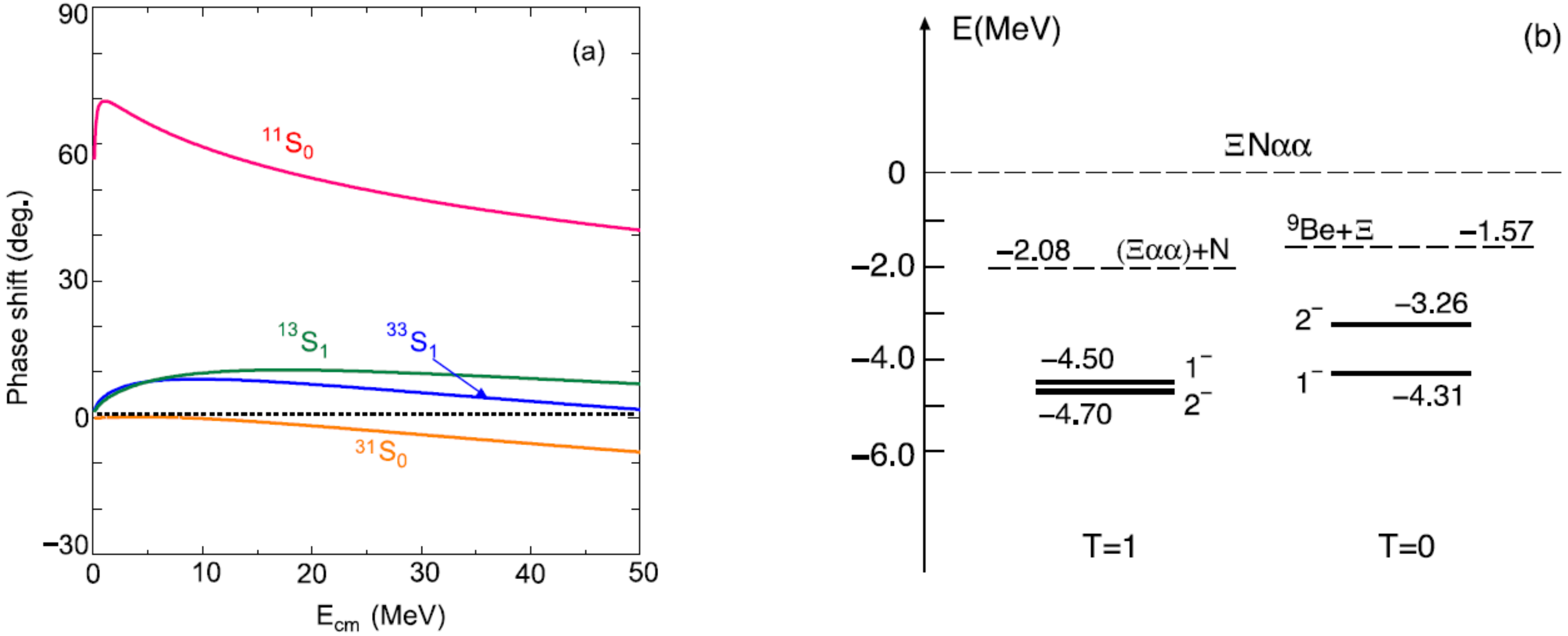
To extract ΞN interaction, we need deeper binding energy.



We can add one more α particle.

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





If the level structure of
A=10 Ξ hypernuclei,
we obtain information
on partial wave of
ΞN interaction.
Level ordering is important.

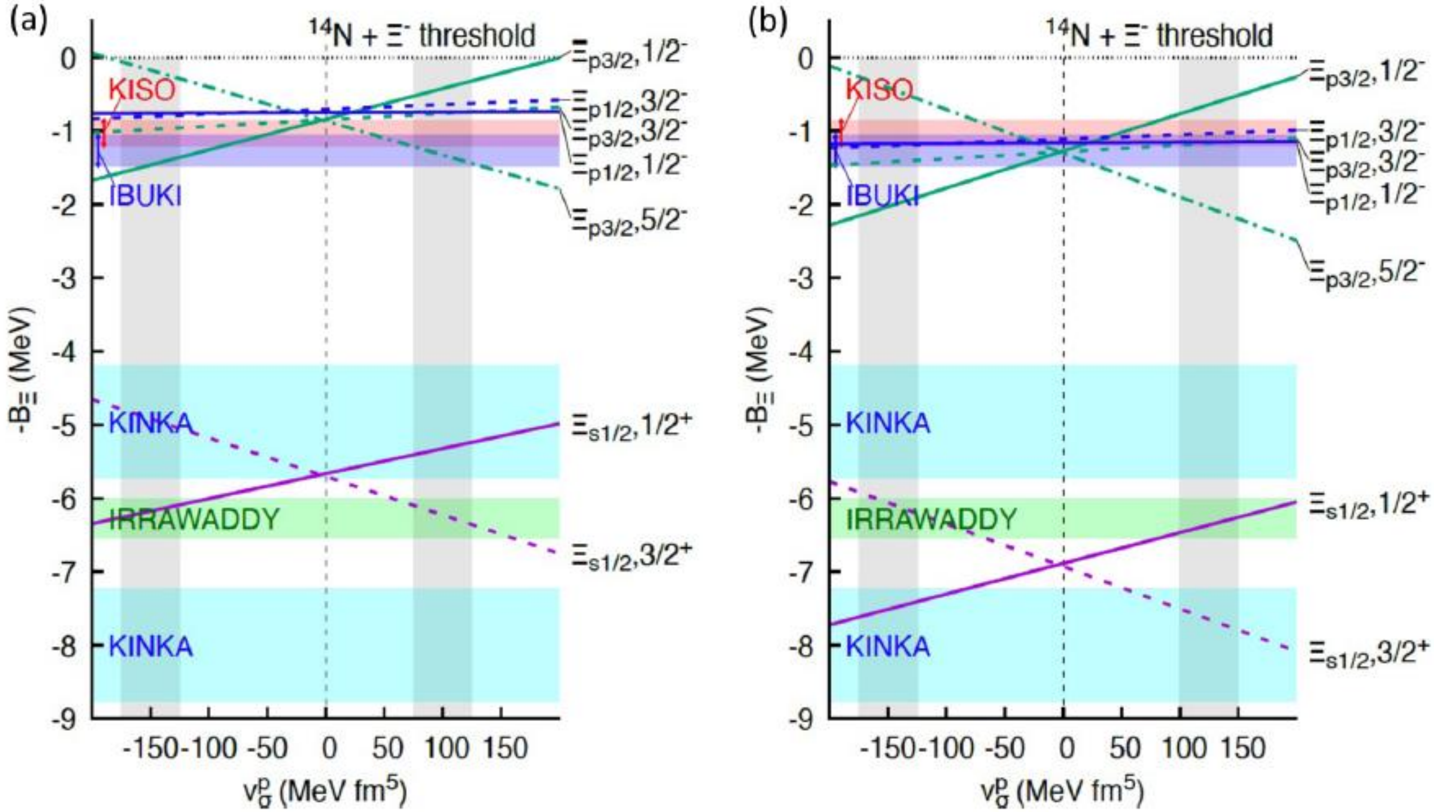
Conlcusion

Since the observation of ^{14}N+Ξ hypernucleus, it is important to obtain information on ΞN interaction. In this talk, I introduce the study of A=6 and 10 Ξ hyperuclei, to obtain information on partial wave of ΞN interaction.

Currently, the production experiments of A=7 and 12 Ξ hypernuclei at J-PARC are planned.
Since the bound states of A=6 Ξ hypernuclei are dependent on ΞN potentials employed, then it would be risky to perform experiment using ^{6}Li target.

Then, I suggest to perform experiment using ^{10}B target by (K^-,K^+) reaction at J-PARC.

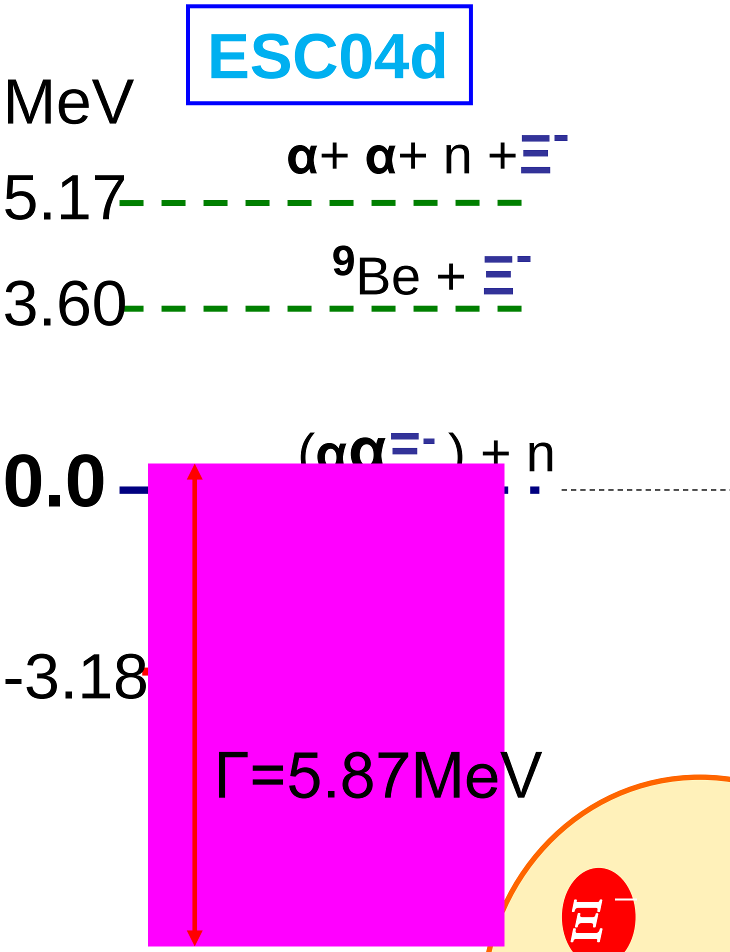
Thank you!

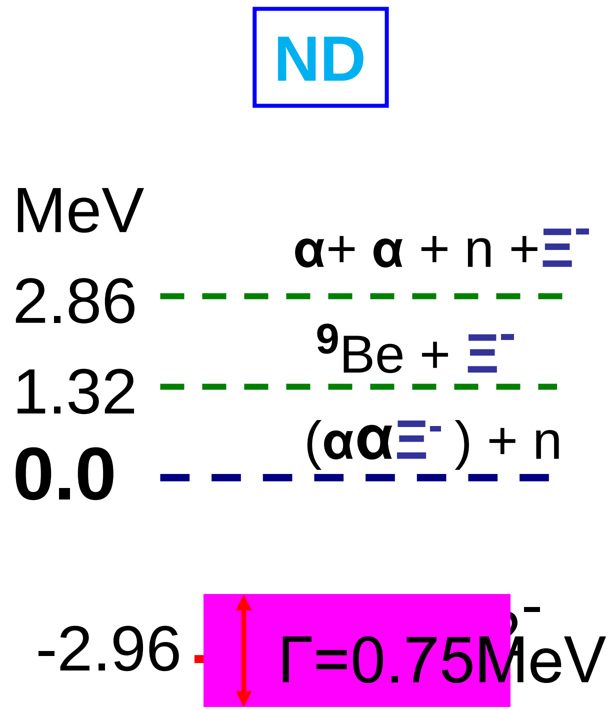


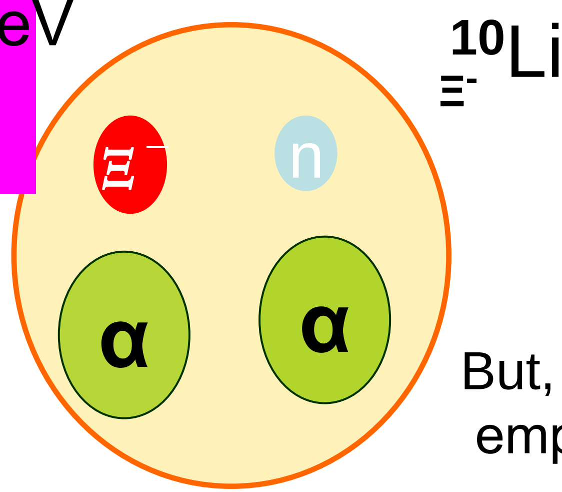
(a)
(b)
$^{14}N + \Xi^-$ threshold
$-B_\Xi$ (MeV)
v_σ^p (MeV fm^5)
KISO
IBUKI
KINKA
IRRAWADDY
KINKA
$\Xi_{p3/2}$,1/2$^-$
$\Xi_{p1/2}$,3/2$^-$
$\Xi_{p3/2}$,3/2$^-$
$\Xi_{p1/2}$,1/2$^-$
$\Xi_{p3/2}$,5/2$^-$
$\Xi_{s1/2}$,1/2$^+$
$\Xi_{s1/2}$,3/2$^+$

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

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







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.