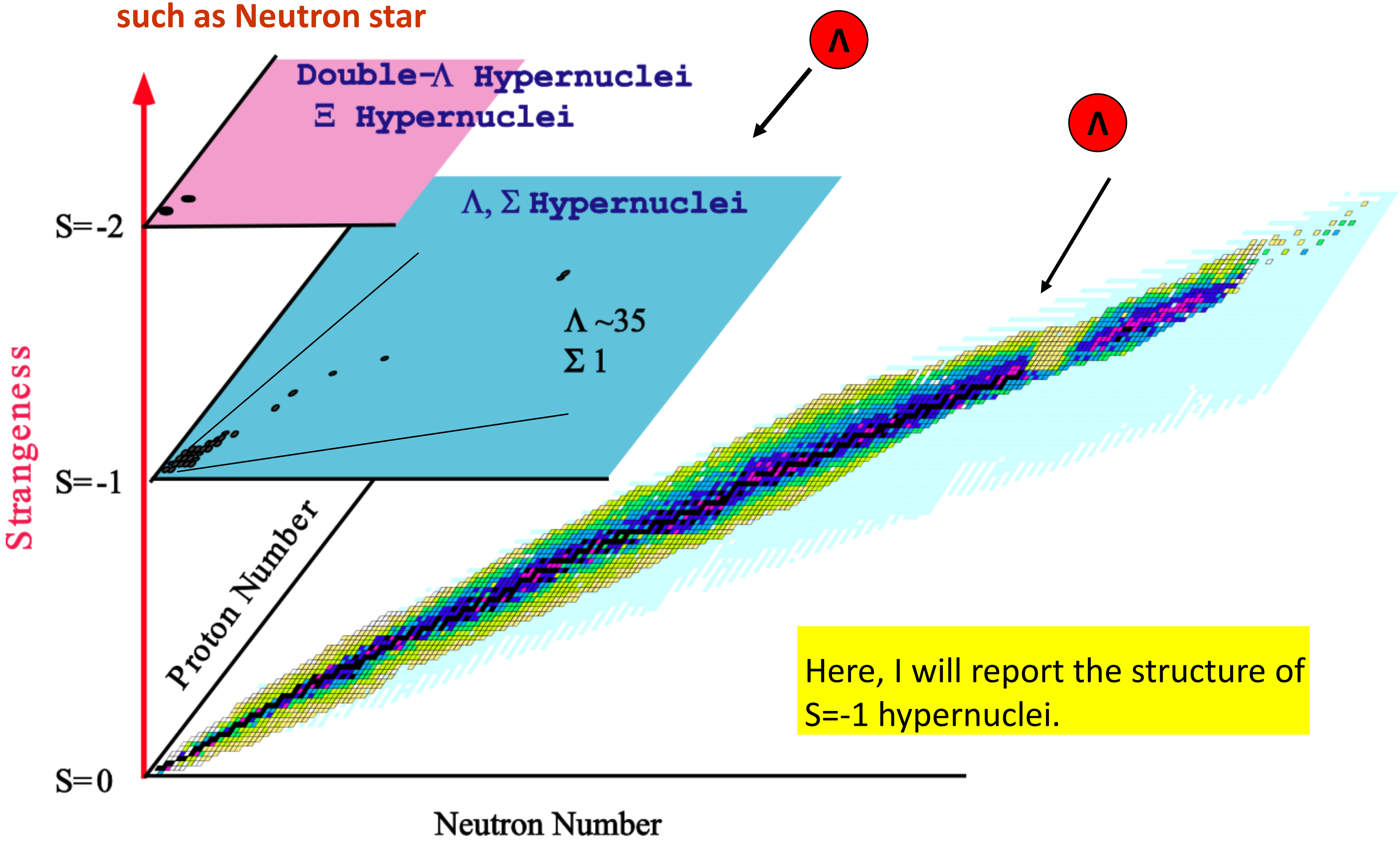
Structure of neutron-rich Λ hypernuclei

Emiko Hiyama (RIKEN)

Nuclear chart with strangeness

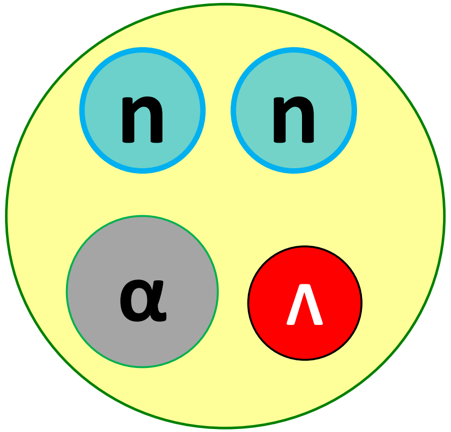
Multi-strange system
such as Neutron star



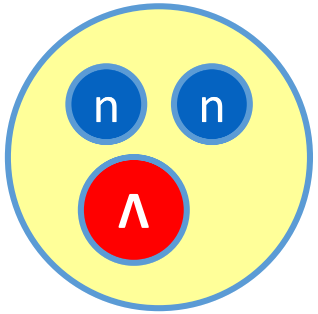
Here, I will report the structure of S=-1 hypernuclei.

Recently, we had three epoch-making data from the view point of few-body problems.

$^{7}_{\Lambda}\mathrm{He}$



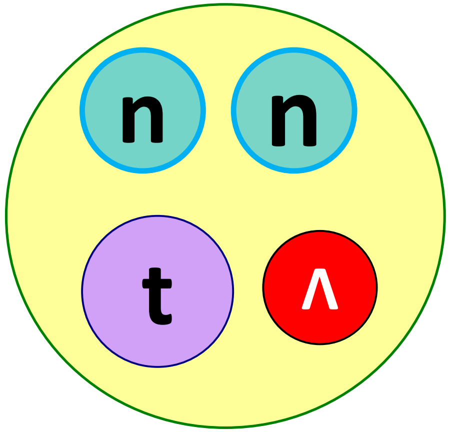
JLAB experiment-E011,
Phys. Rev. Lett. **110**,
12502 (2013).



$^{3}_{\Lambda}n$

C. Rappold et al.,
HypHI collaboration
Phys. Rev. C 88,
041001 (R) (2013)

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



FINUDA collaboration & A. Gal,
Phys. Rev. Lett. **108**,
042051 (2012).

Observation of Neutron-rich Λ-hypernuclei

These observations are interesting from the view points of few-body physics as well as unstable nuclear physics.

Resonant states of neutron-rich Λ hypernucleus ${}^{7}_{\Lambda}$He

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General Education, Faculty of Engineering, Osaka Institute of Technology, Osaka, 535-8585, Japan

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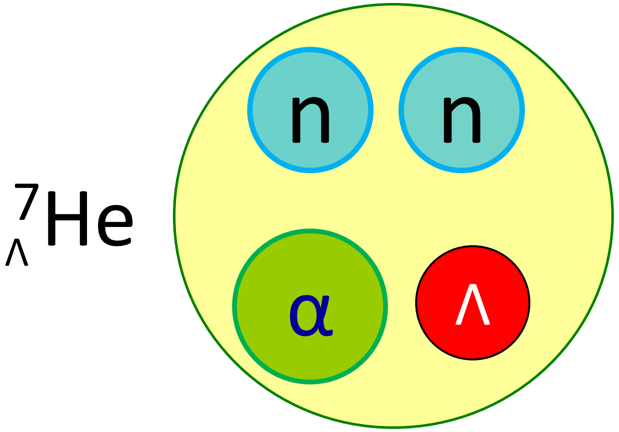
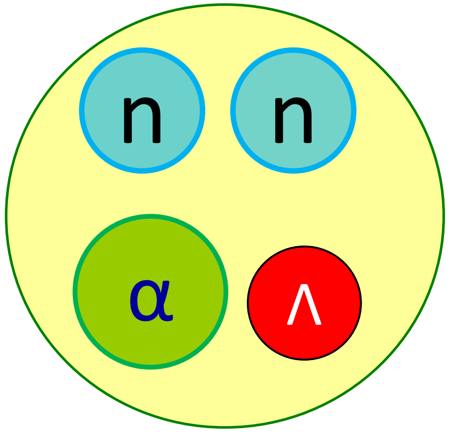
Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8317, Japan

Published in Physical Review C



${}^{7}_{\Lambda}\mathrm{He}$



${}^{7}_{\Lambda}\mathrm{He}$

What is interesting to study this hypernucleus?

It is important to obtain information about charge symmetry breaking effect of n-Λ and p-Λ.

The second major goal of hypernuclear physics

1) To understand baryon-baryon interactions

Fundamental and important for the study of nuclear physics

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

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

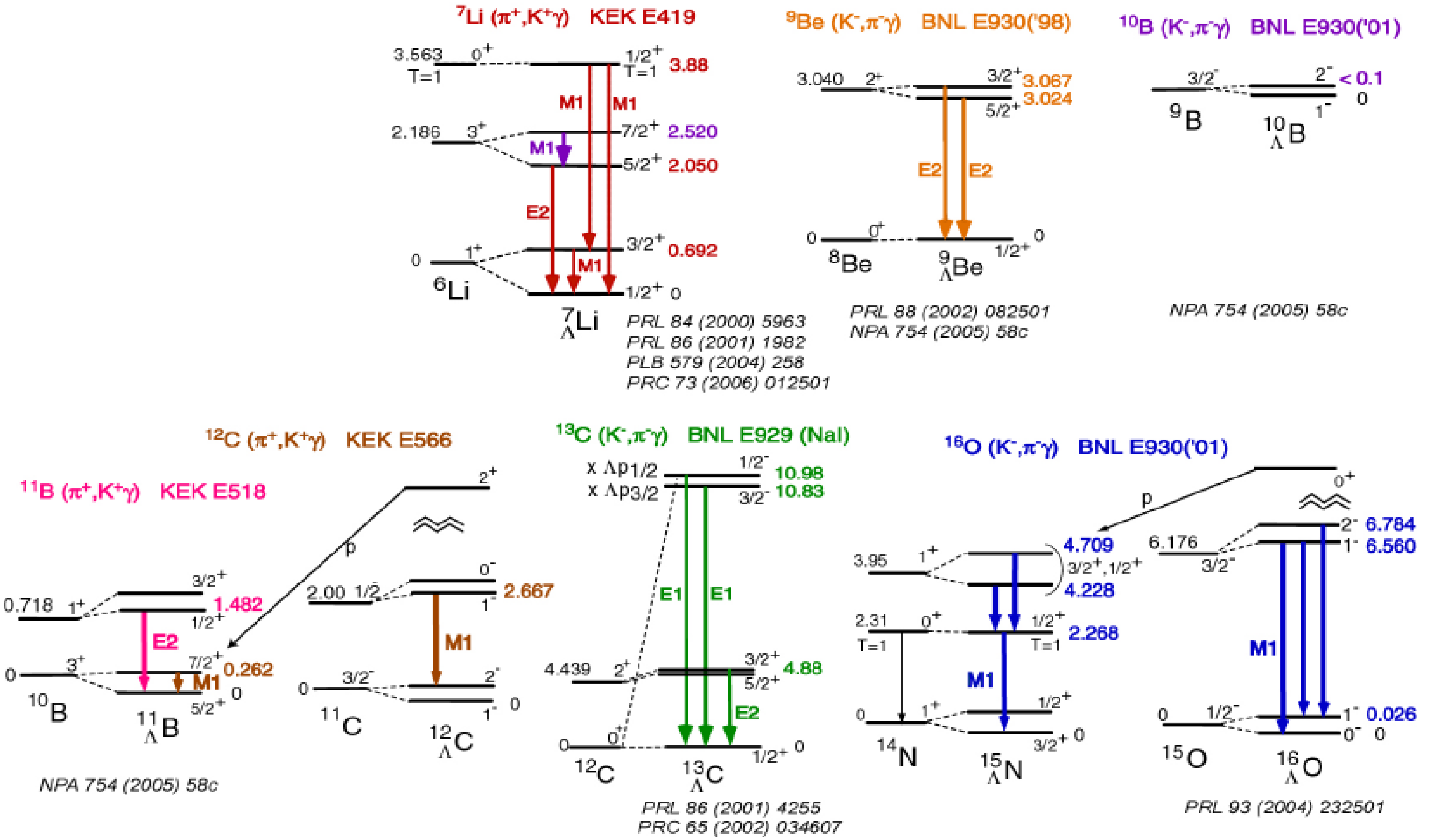
- Total number of differential cross section Hyperon (Y) -Nucleon (N) data: **40**
- **NO** YY scattering data

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

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

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

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



PRL 84 (2000) 5963
PRL 86 (2001) 1982
PLB 579 (2004) 258
PRC 73 (2006) 012501

PRL 88 (2002) 082501
NPA 754 (2005) 58c

NPA 754 (2005) 58c

NPA 754 (2005) 58c

PRL 86 (2001) 4255
PRC 65 (2002) 034607

PRL 93 (2004) 232501

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

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

In S= -1 sector,
what are important to study YN interaction?

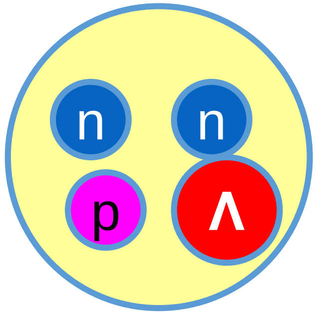
(1) Charge symmetry breaking

(2) $\Lambda N - \Sigma N$ coupling

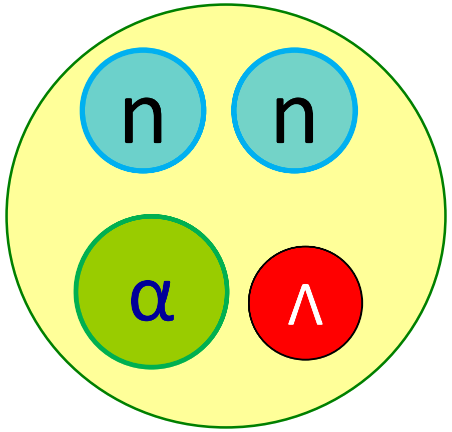
J-PARC : Day-1 experiment
E13

Jlab E05-115,

Mainz



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

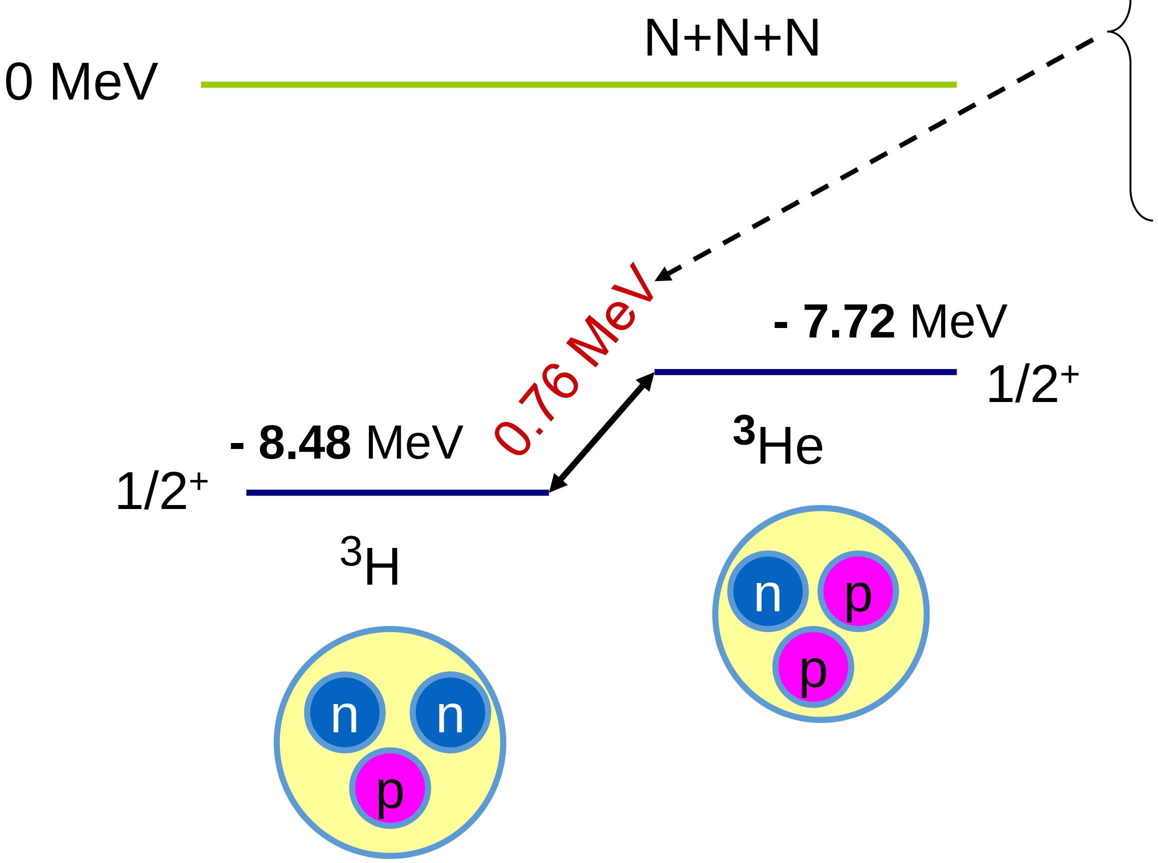


$^{7}_{\Lambda}$He

(1) Charge Symmetry breaking

In S=0 sector

Exp.



N+N+N

0 MeV

0.76 MeV

- 7.72 MeV

1/2$^+$

^{3}He

- 8.48 MeV

1/2$^+$

^{3}H

n p p

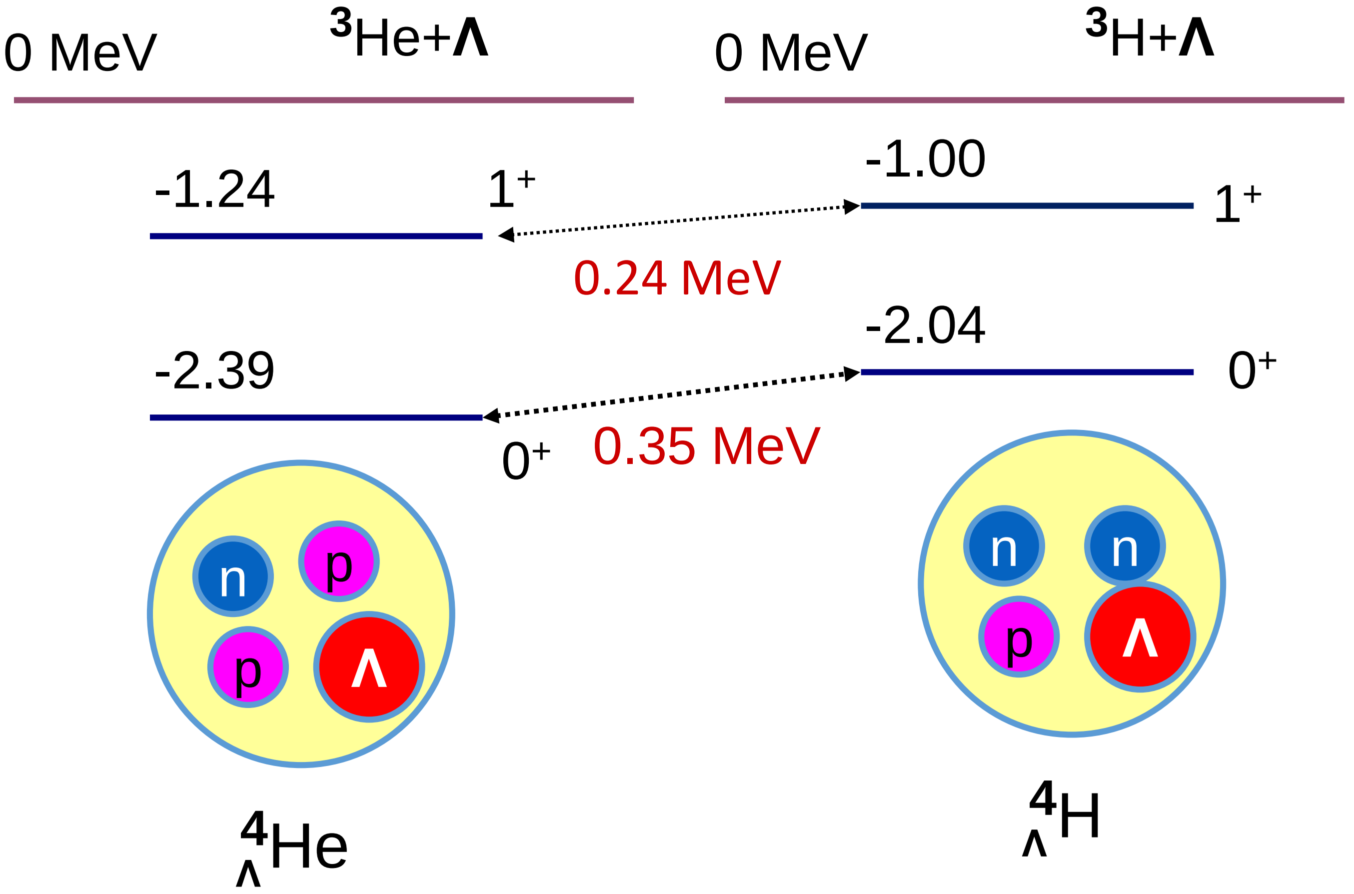
n n p

Energy difference comes from dominantly Coulomb force between 2 protons.

Charge symmetry breaking effect is small.

In S= -1 sector

Exp.



0 MeV ^{3}He+**Λ**

-1.24 1^+

-2.39 0^+

$^4_\Lambda$He

0 MeV ^{3}H+**Λ**

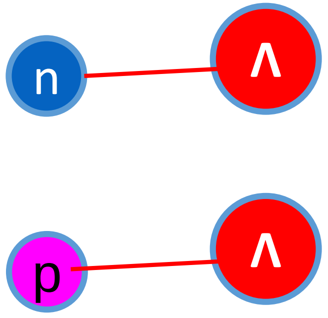
-1.00 1^+

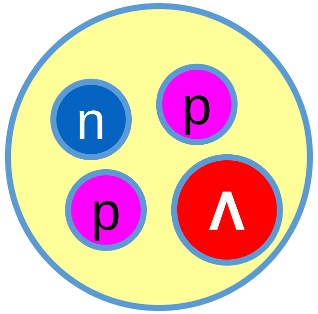
-2.04 0^+

$^4_\Lambda$H

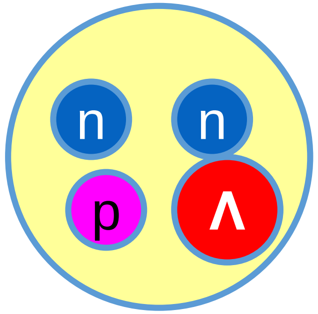
0.24 MeV

0.35 MeV





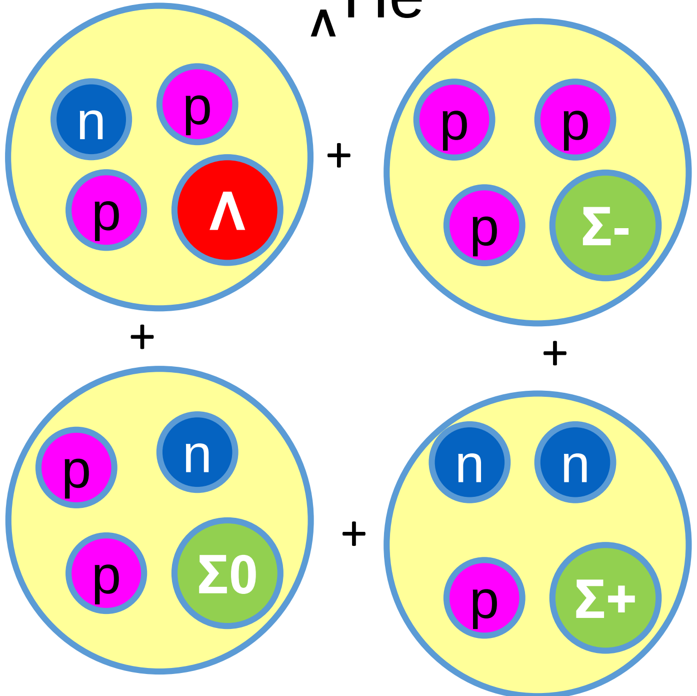
$^{4}_{\Lambda}$He



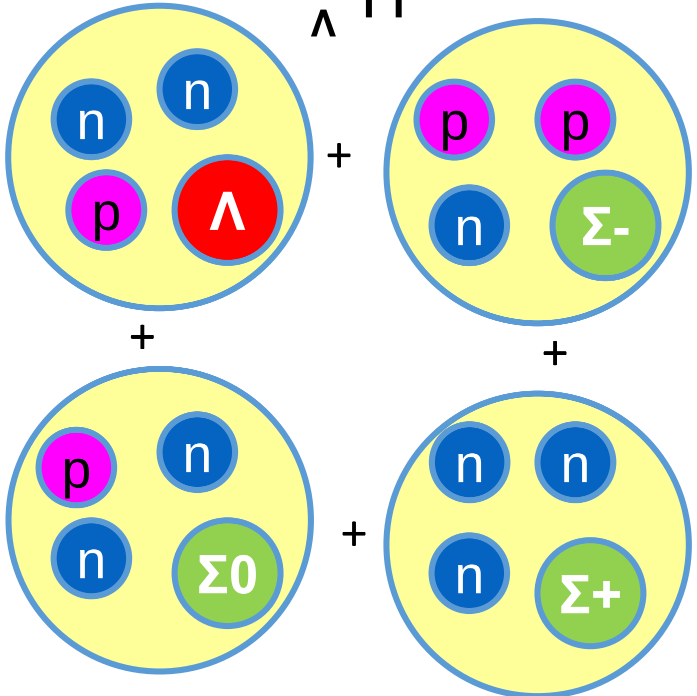
$^{4}_{\Lambda}$H

However, Λ particle has no charge.

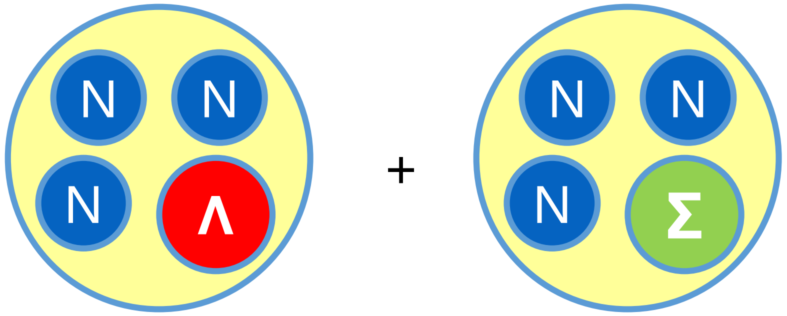
$^{4}_{\Lambda}$He



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



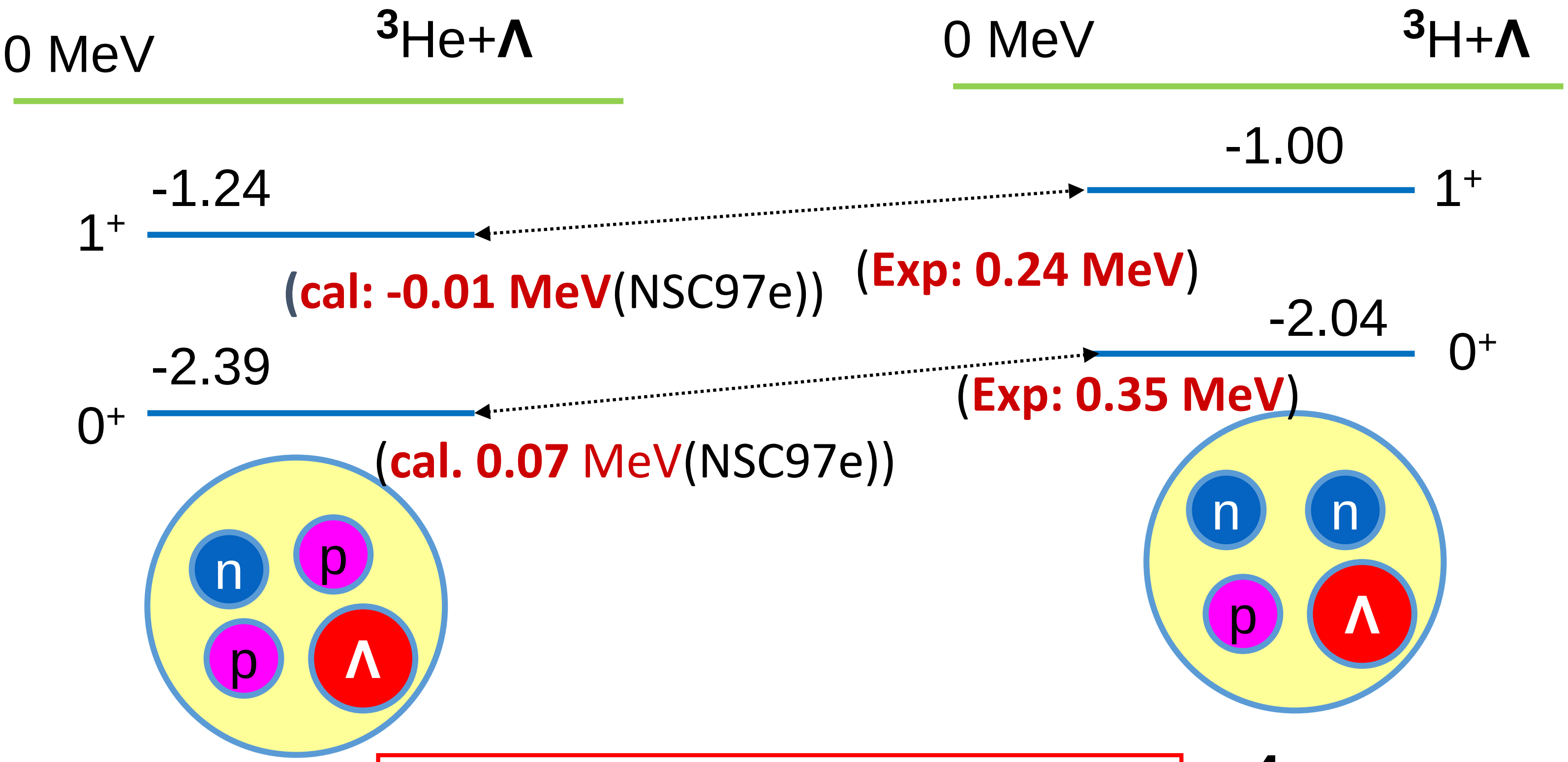
In order to explain the energy difference, 0.35 MeV,



(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.



0 MeV ^{3}He+**Λ**

0 MeV ^{3}H+**Λ**

1^+ -1.24

-1.00 1^+

(**cal: -0.01 MeV**(NSC97e))

(**Exp: 0.24 MeV**)

0^+ -2.39

-2.04 0^+

(**Exp: 0.35 MeV**)

(**cal. 0.07** MeV(NSC97e))

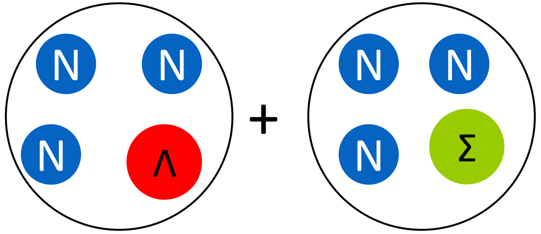
$^4_\Lambda$He

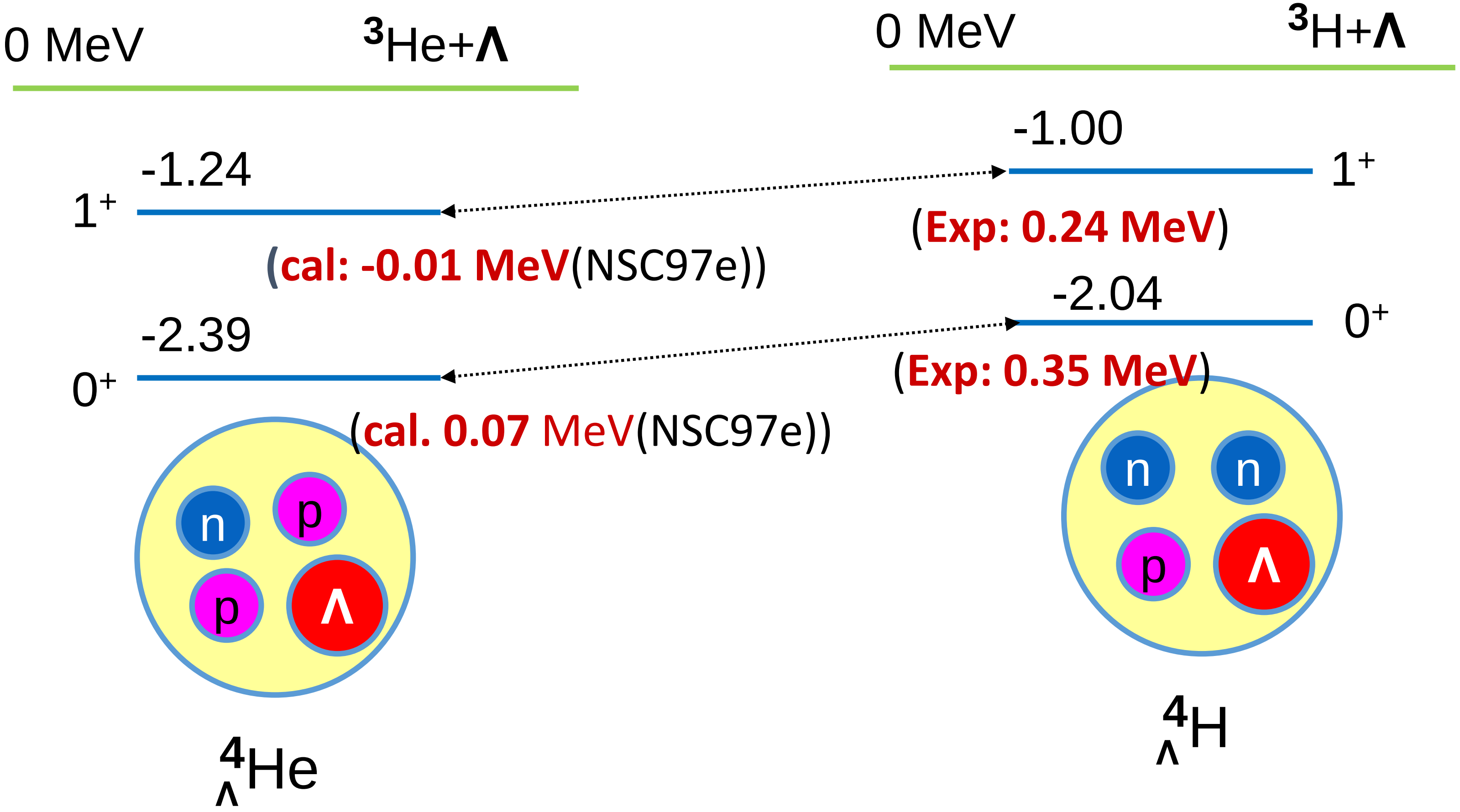
- A. Nogga, H. Kamada and W. Gloeckle, Phys. Rev. Lett. 88, 172501 (2002)

$^4_\Lambda$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).





0 MeV $^{3}\mathrm{He}+\Lambda$

1^{+} -1.24

(cal: -0.01 MeV(NSC97e))

0^{+} -2.39

(**cal. 0.07** MeV(NSC97e))

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

0 MeV $^{3}\mathrm{H}+\Lambda$

-1.00 1^{+}

(**Exp: 0.24 MeV**)

-2.04 0^{+}

(**Exp: 0.35 MeV**)

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

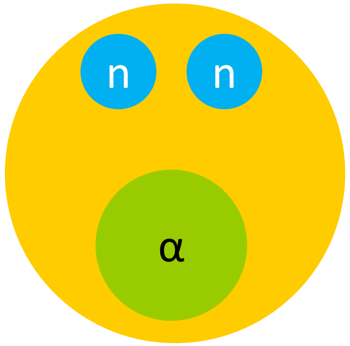
There exist NO YN interaction to reproduce the data.

For the study of CSB interaction, we need more data.

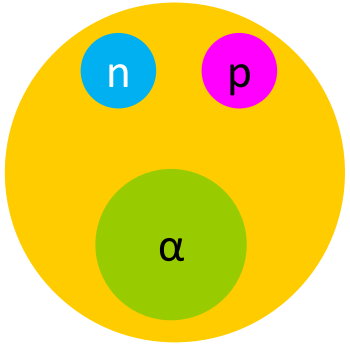
It is interesting to investigate the charge symmetry breaking effect in p-shell Λ hypernuclei as well as s-shell Λ hypernuclei.

For this purpose, to study structure of A=7 Λ hypernuclei is suited.

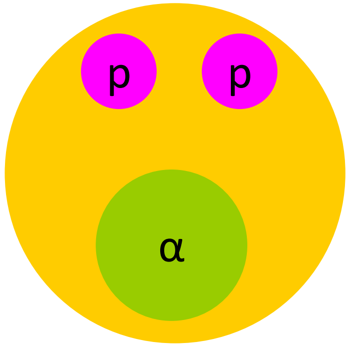
Because, core nuclei with A=6 are iso-triplet states.



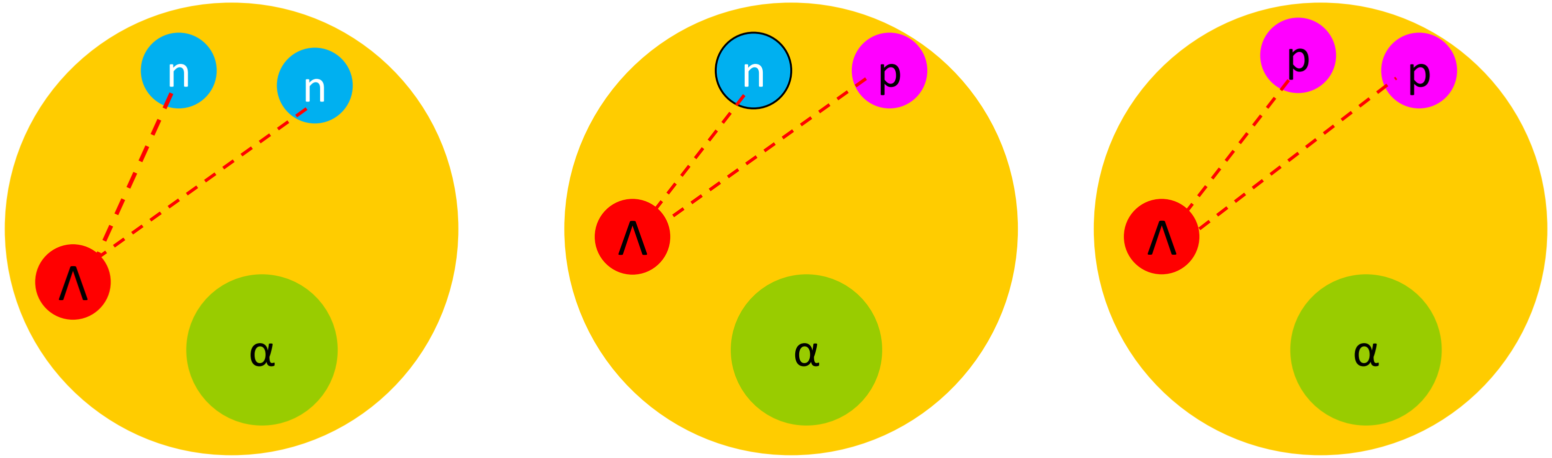
^{6}He



^{6}Li(T=1)



^{6}Be

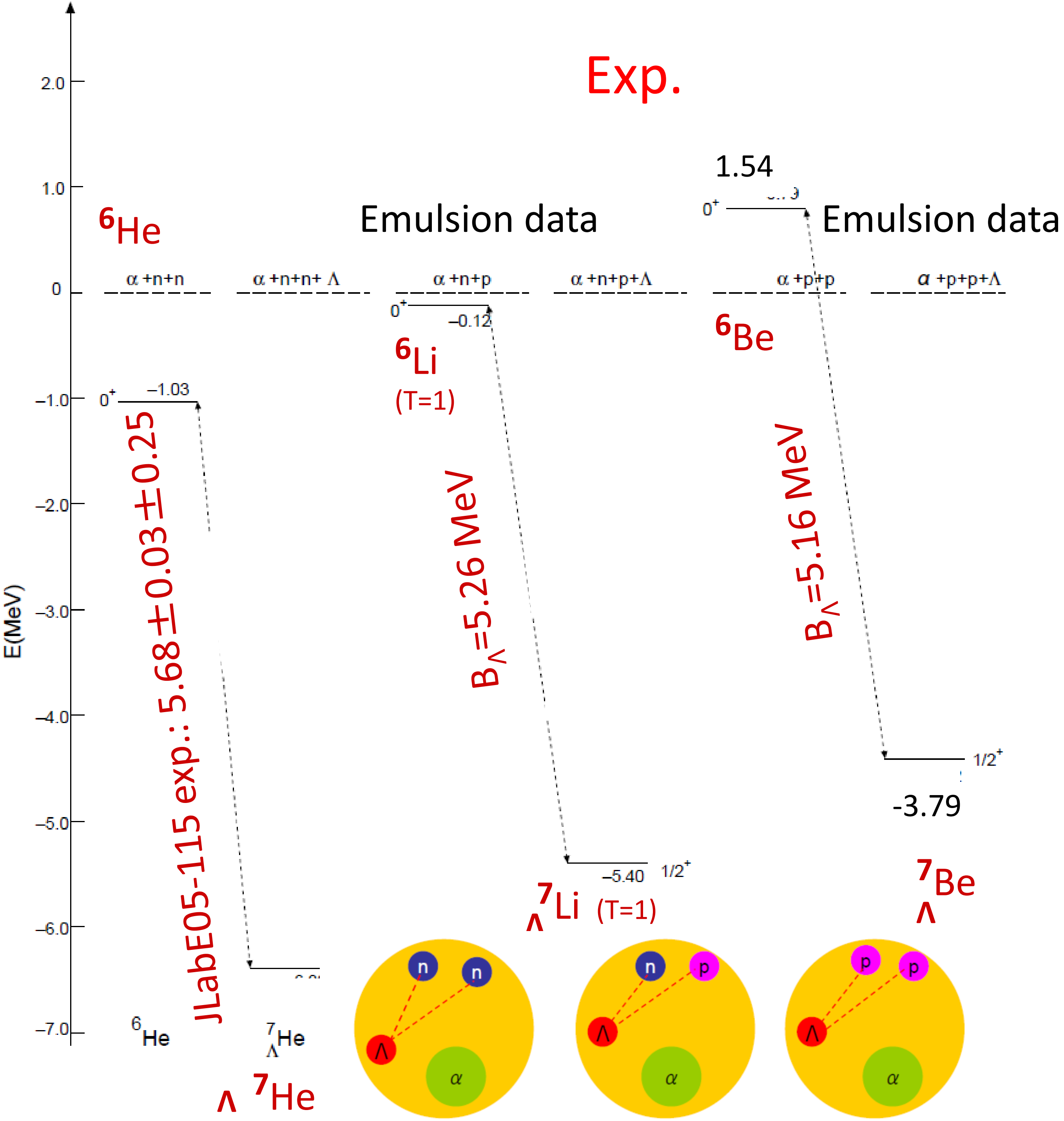


${}^{7}_{\Lambda}\mathrm{He}$ ${}^{7}_{\Lambda}\mathrm{Li}(T=1)$ ${}^{7}_{\Lambda}\mathrm{Be}$

Then, A=7 Λ hypernuclei are also iso-triplet states.

It is possible that CSB interaction between Λ and valence nucleons contribute to the Λ-binding energies in these hypernuclei.

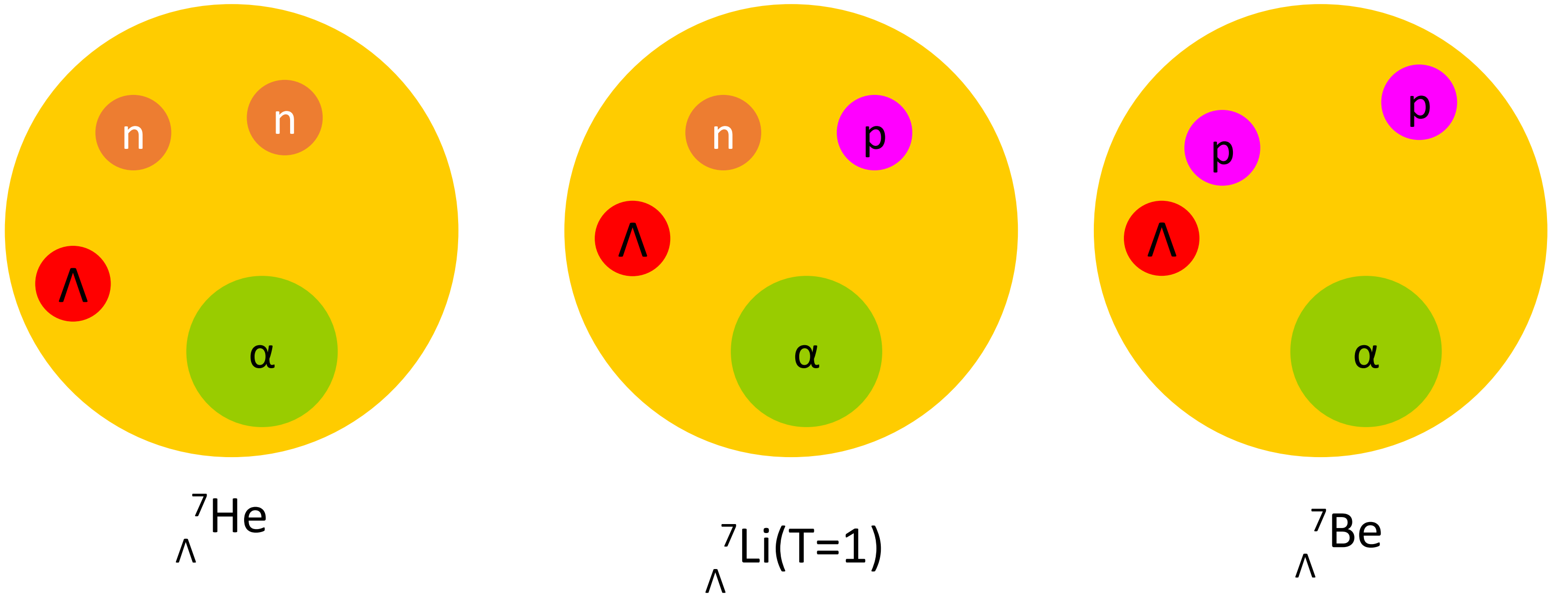
Exp.


E(MeV)
2.0
1.0
0
–1.0
–2.0
–3.0
–4.0
–5.0
–6.0
–7.0
6He
Emulsion data
1.54
0+
Emulsion data
α +n+n
α +n+n+ Λ
α +n+p
α +n+p+Λ
α +p+p
α +p+p+Λ
0+
–0.12
6Be
6Li
(T=1)
0+
–1.03
JLabE05-115 exp.: 5.68±0.03±0.25
B_Λ=5.26 MeV
B_Λ=5.16 MeV
1/2+
-3.79
–5.40
1/2+
7ΛLi (T=1)
7ΛBe
6He
7ΛHe
Λ 7He
n
n
Λ
α
n
p
Λ
α
p
p
Λ
α

Important issue:

Can we describe the Λ binding energy of ${}^{7}_{\Lambda}$He observed at JLAB using ΛN interaction to reproduce the Λ binding energies of ${}^{7}_{\Lambda}$Li (T=1) and ${}^{7}_{\Lambda}$Be ?

To study the effect of CSB in iso-triplet A=7 hypernuclei.



For this purpose, we study structure of A=7 hypernuclei within the framework of α+Λ+N+N 4-body model.

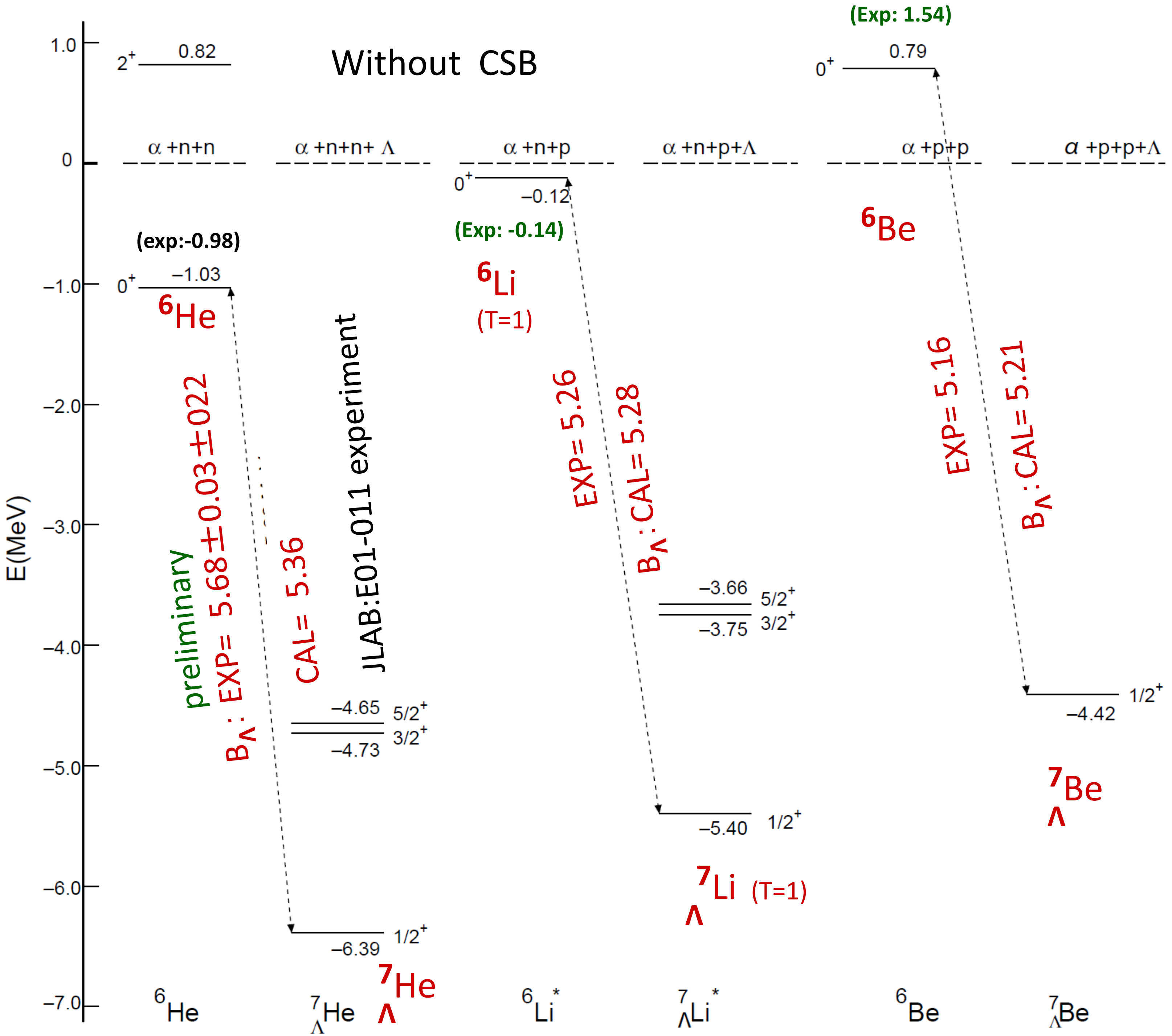
E. Hiyama, Y. Yamamoto, T. Motoba and M. Kamimura,PRC80, 054321 (2009)

Now, it is interesting to see as follows:

(1)What is the level structure of A=7 hypernuclei
without CSB interaction?

(2) What is the level structure of A=7 hypernuclei
with CSB interaction?

Without CSB


E(MeV)
1.0
0
−1.0
−2.0
−3.0
−4.0
−5.0
−6.0
−7.0
2+ 0.82
α +n+n
α +n+n+ Λ
α +n+p
α +n+p+Λ
α +p+p
α +p+p+Λ
(exp:-0.98)
0+ −1.03
6He
preliminary
BΛ : EXP= 5.68±0.03±022
CAL= 5.36
JLAB:E01-011 experiment
−4.65 5/2+
3/2+ −4.73
1/2+ −6.39
7ΛHe
0+ −0.12
(Exp: -0.14)
6Li
(T=1)
EXP= 5.26
BΛ :CAL= 5.28
−3.66 5/2+
3/2+ −3.75
1/2+ −5.40
7ΛLi (T=1)
(Exp: 1.54)
0+ 0.79
6Be
EXP= 5.16
BΛ :CAL= 5.21
1/2+ −4.42
7ΛBe
6He
7ΛHe
6Li*
7ΛLi*
6Be
7ΛBe

Now, it is interesting to see as follows:

(1)What is the level structure of A=7 hypernuclei without CSB interaction?

(2) What is the level structure of A=7 hypernuclei with CSB interaction?

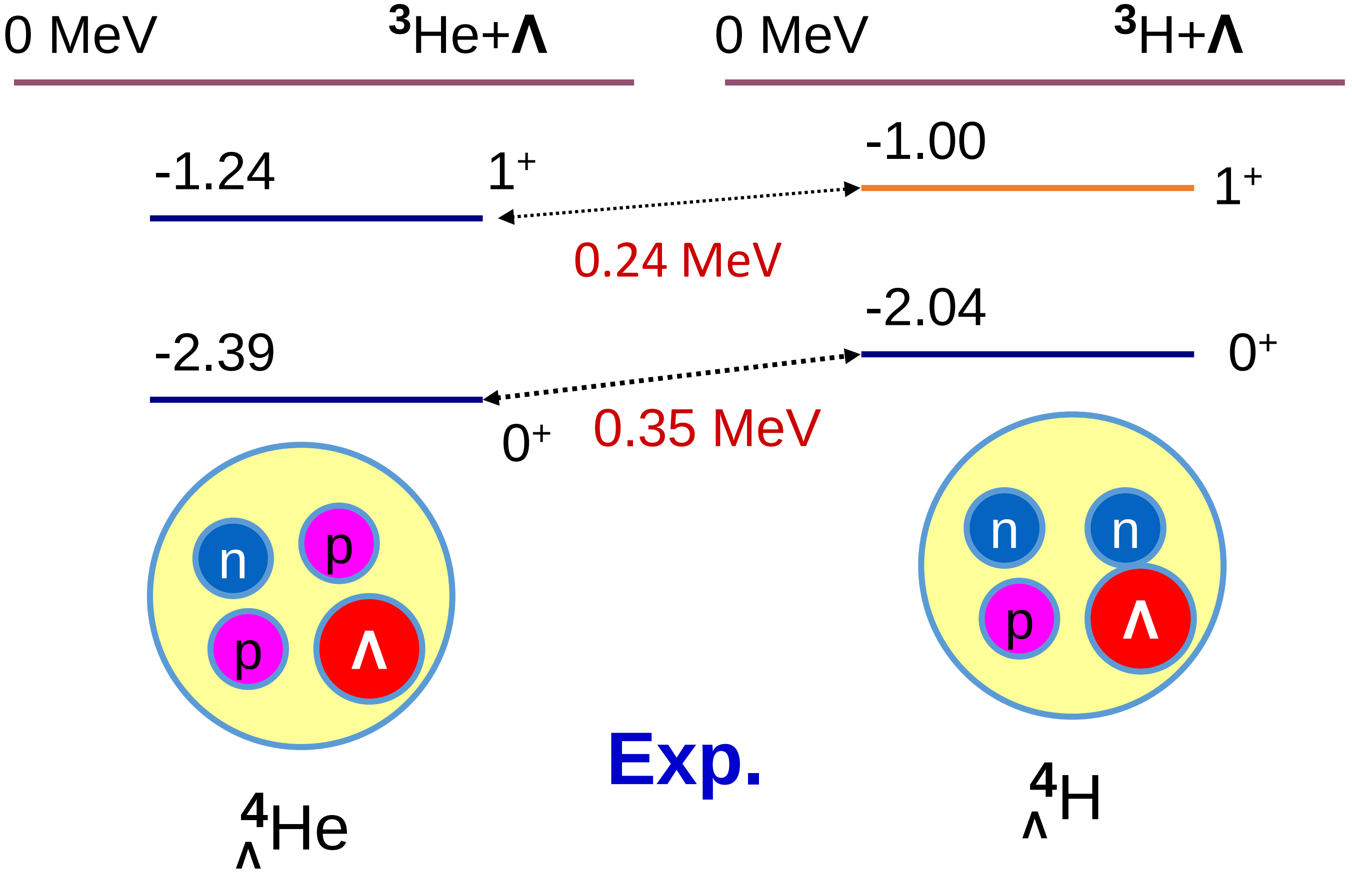
Next we introduce a phenomenological CSB potential with the central force component only.

$$V_{\Lambda N}^{\mathrm{CSB}}(r) = \tag{3.3}$$

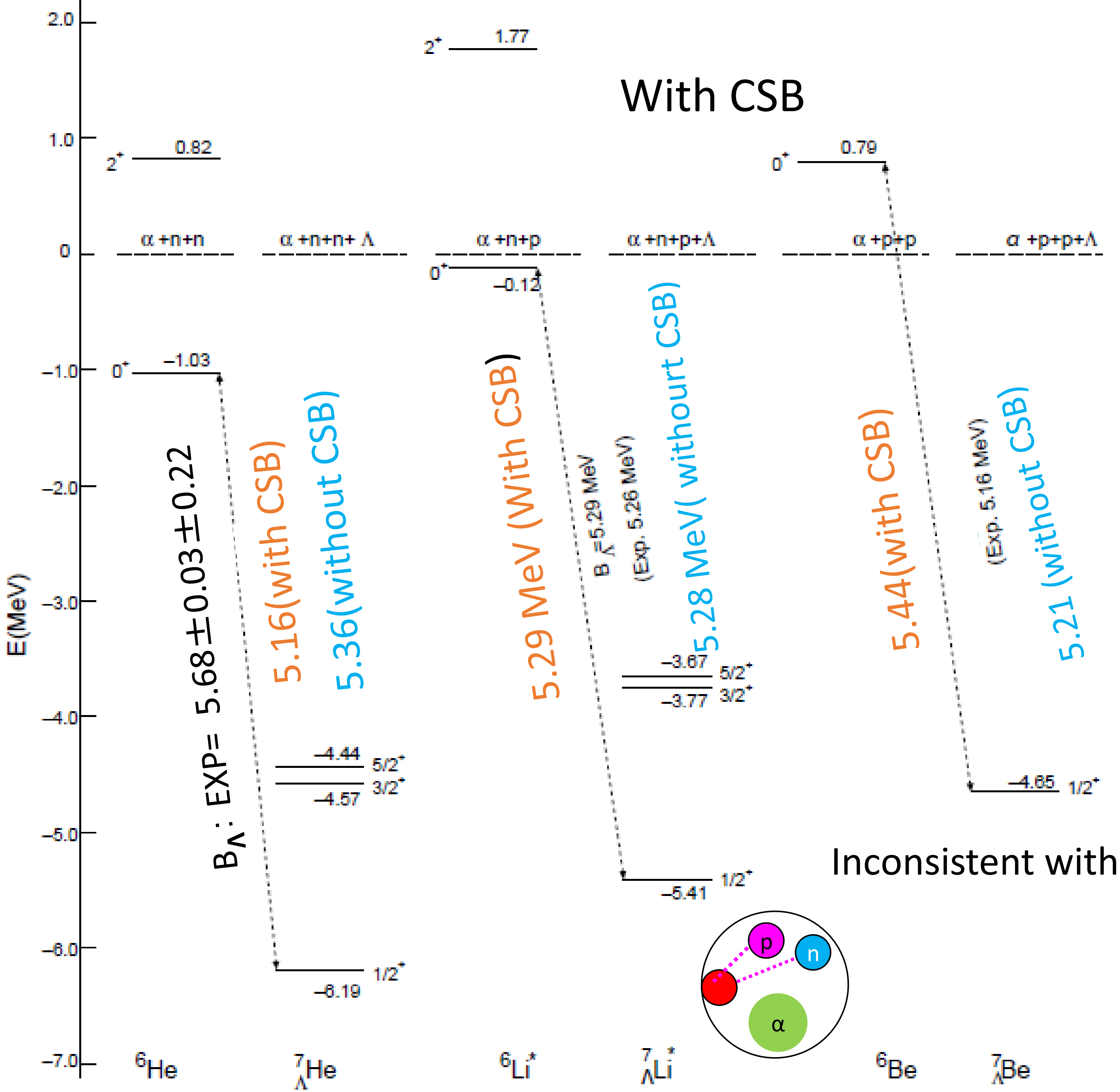
$$-\frac{\tau_z}{2}\Big[\frac{1+P_r}{2}\big(v_0^{\mathrm{even,CSB}} + \boldsymbol{\sigma}_\Lambda\cdot\boldsymbol{\sigma}_N\, v_{\sigma_\Lambda\cdot\sigma_N}^{\mathrm{even,CSB}}\big)\, e^{-\beta_{\mathrm{even}}\, r^2}$$

$$+\ \frac{1-P_r}{2}\big(v_0^{\mathrm{odd,CSB}} + \boldsymbol{\sigma}_\Lambda\cdot\boldsymbol{\sigma}_N\, v_{\sigma_\Lambda\cdot\sigma_N}^{\mathrm{odd,CSB}}\big)\, e^{-\beta_{\mathrm{odd}}\, r^2}\Big],$$

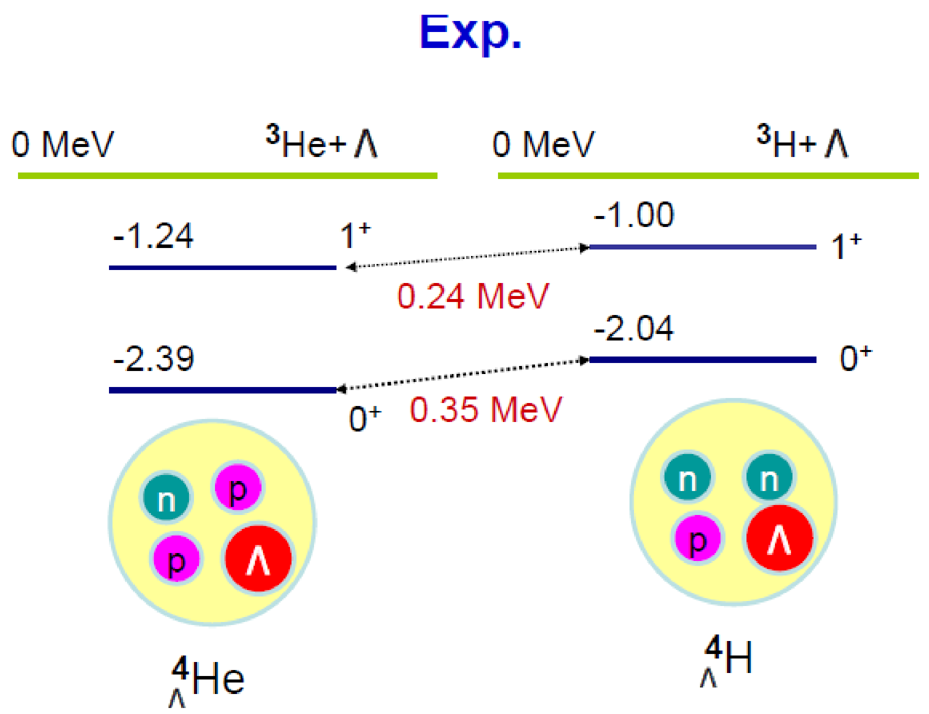
Strength, range are determined so as to reproduce the data.

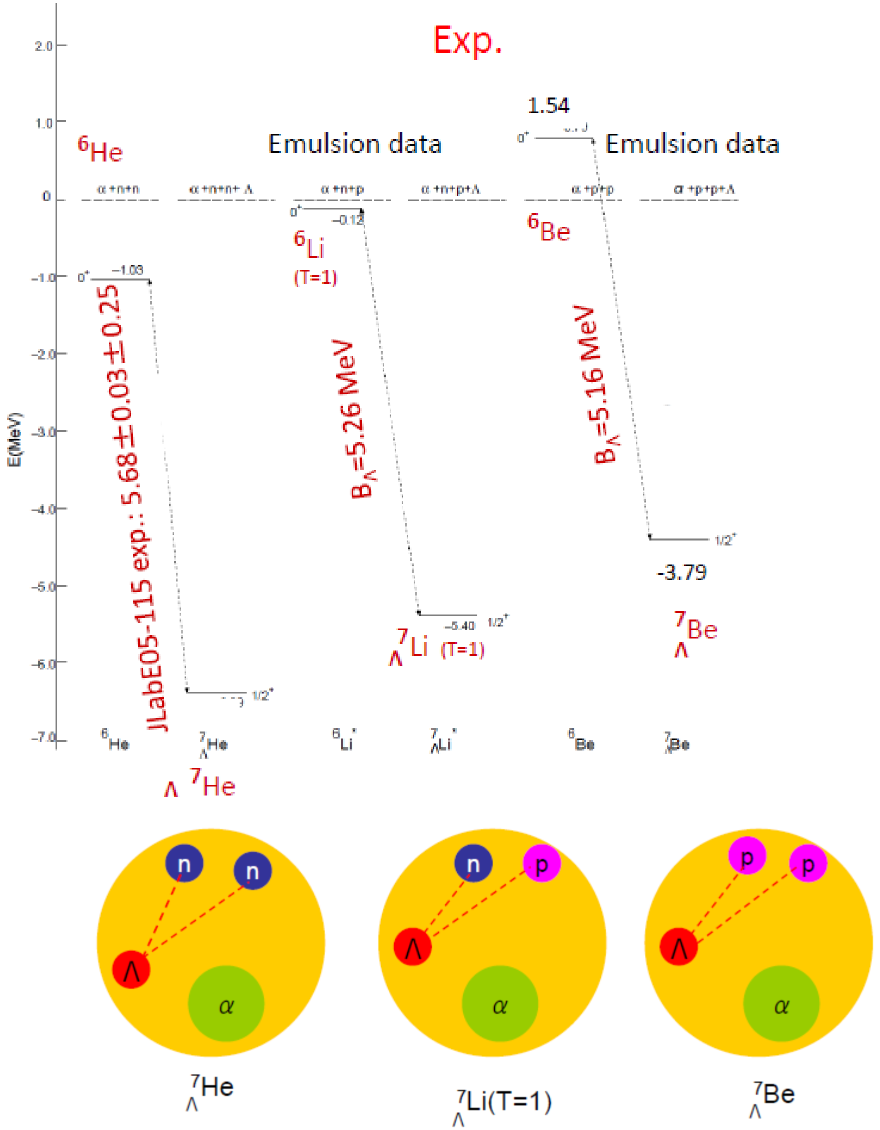


With CSB



Inconsistent with the data





Comparing the data of A=4
and those of A=7,
tendency of B_Λ is opposite.

How do we understand these difference?

We get binding energy by decay π spectroscopy.

${}^{4}_{\Lambda}\mathrm{He} \xrightarrow{\text{decay}} \pi^{-}+{}^{1}\mathrm{H}+{}^{3}\mathrm{He} \rightarrow 2.42 \pm 0.05\ \mathrm{MeV}$

$\rightarrow \pi^{-}+{}^{1}\mathrm{H}+{}^{1}\mathrm{H}+{}^{2}\mathrm{H} \rightarrow 2.44 \pm 0.09\ \mathrm{MeV}$

Total: 2.42 ±0.04 MeV

Then, binding energy of ${}^{4}_{\Lambda}\mathrm{He}$ is reliable.

${}^{4}_{\Lambda}\mathrm{H} \xrightarrow{\text{decay}} \pi^{-}+{}^{1}\mathrm{H}+{}^{3}\mathrm{H} \rightarrow 2.14 \pm 0.07\ \mathrm{MeV}$

$\rightarrow \pi^{-}+{}^{2}\mathrm{H}+{}^{2}\mathrm{H} \rightarrow 1.92 \pm 0.12\ \mathrm{MeV}$

Total: 2.08 ±0.06 MeV

$\}$ Two different modes give 0.22 MeV

↓

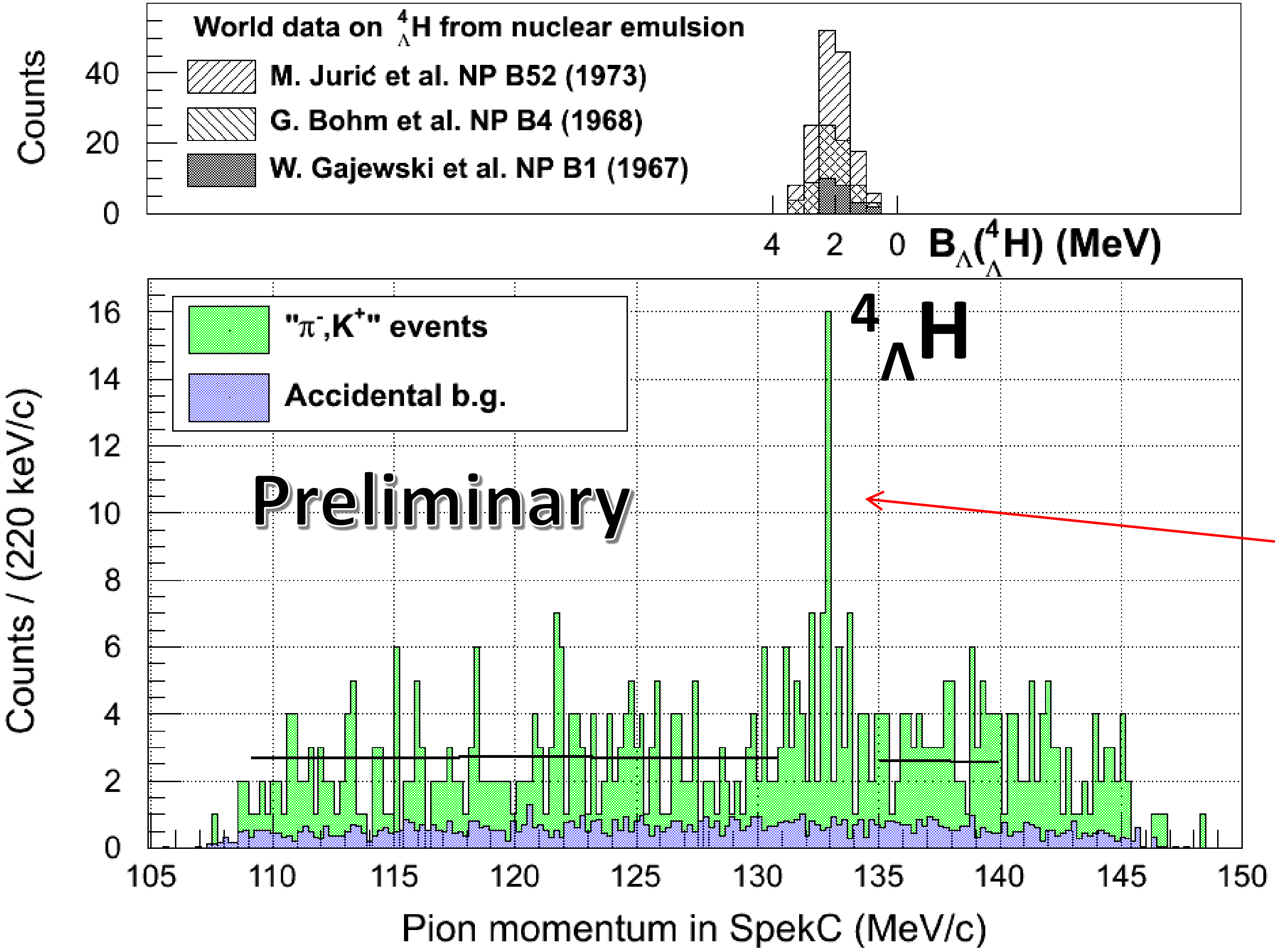
This value is so large to discuss CSB effect.

Then, for the detailed CSB study, we should perform experiment to confirm the Λ separation energy of ${}^{4}_{\Lambda}\mathrm{H}$.

For this purpose, the experiment at Mainz was performed. This year, we have new data.

${}^{4}\mathrm{He}\,(e, e'K^{+})\ {}^{4}_{\Lambda}\mathrm{H}$ ➡ Key experiment to get information about CSB.

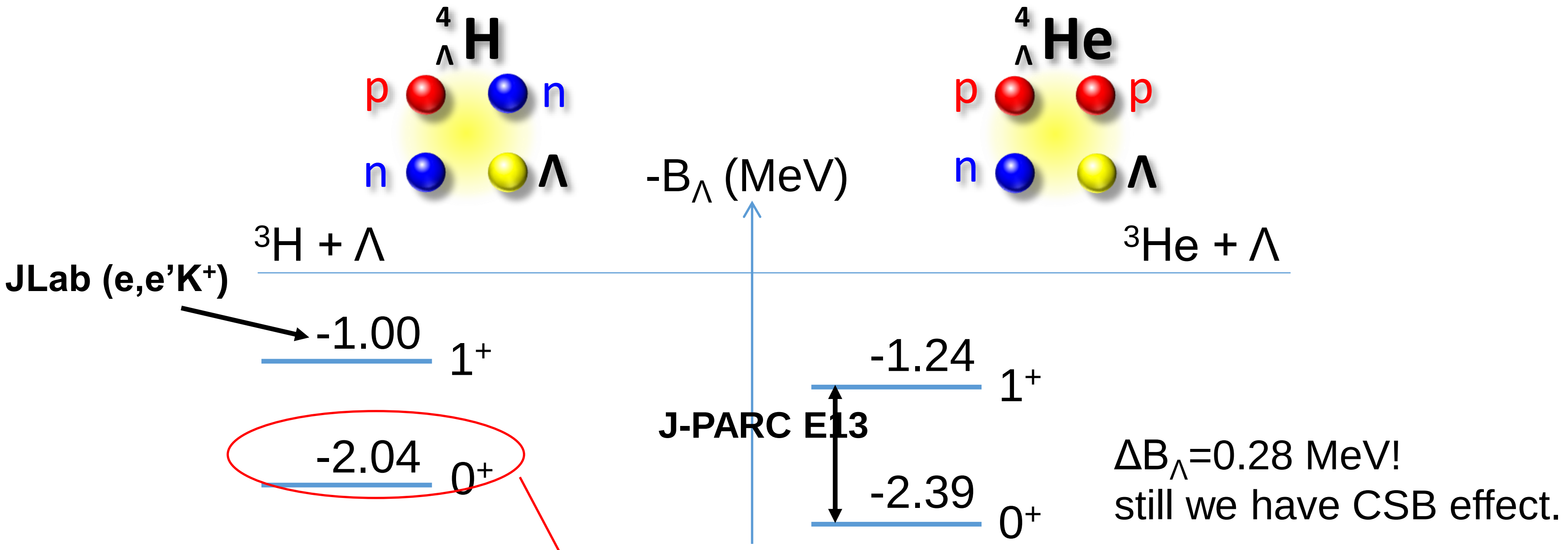
Preliminary data



0^+ state

Data was taken by Tohoku Univ. Group (S. Nagao et atl.) at Mainz.

A=4



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

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

p n n Λ

p p n Λ

$-B_{\Lambda}$ (MeV)

$^{3}H + \Lambda$

$^{3}He + \Lambda$

JLab (e,e'K^{+})

-1.00 1^{+}

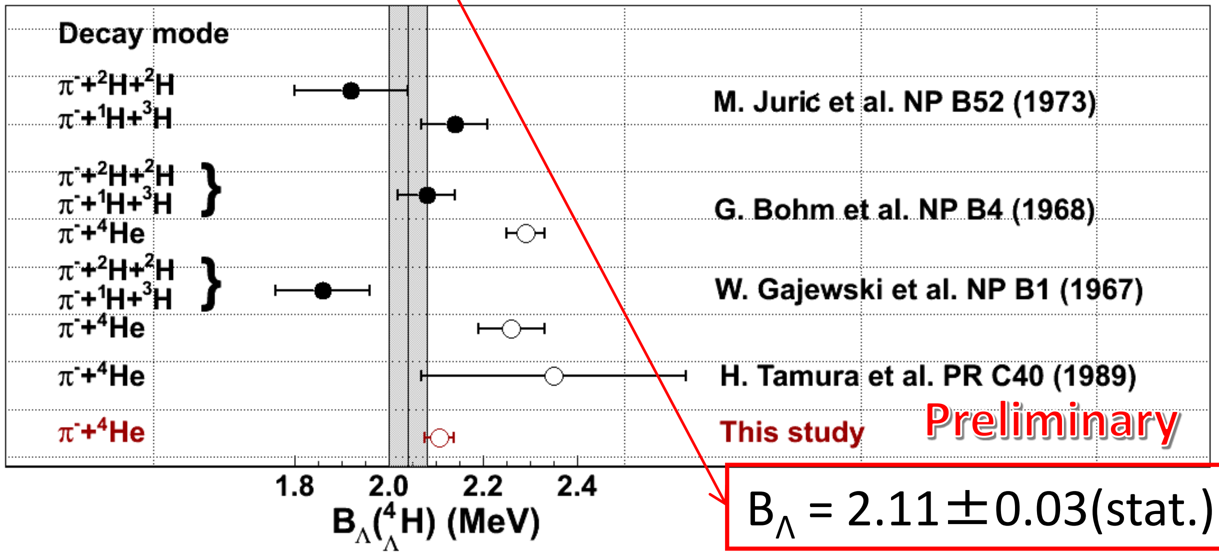
-2.04 0^{+}

J-PARC E13

-1.24 1^{+}

-2.39 0^{+}

ΔB_{Λ}=0.28 MeV!
still we have CSB effect.



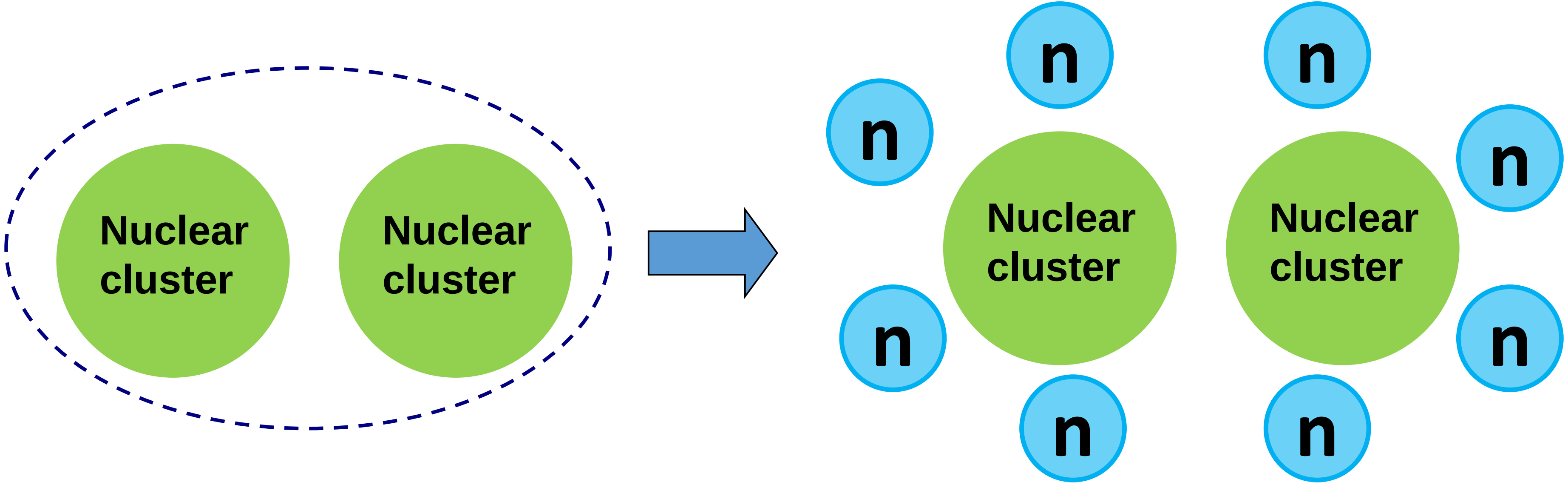
B_{Λ} = 2.11±0.03(stat.)±0.09(syst.)

Why is it interesting to study neutron-rich Λ hypernucleus such as ${}^{7}_{\Lambda}\mathrm{He}$?

Second of major goals in hypernuclear physics

To study the structure of multi-strange systems

In neutron-rich and proton-rich nuclei,

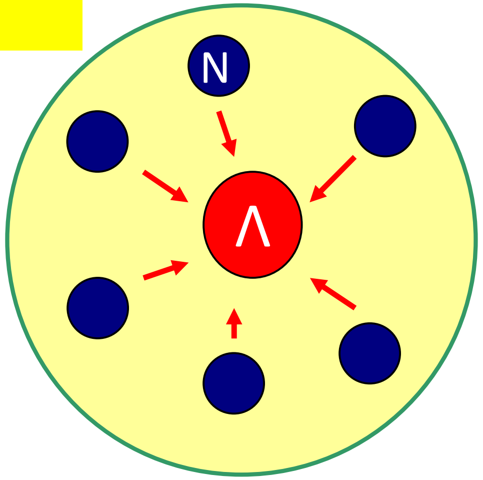


When some neutrons or protons are added to clustering nuclei, additional neutrons are located outside the clustering nuclei due to the Pauli blocking effect.

As a result, we have neutron/proton halo structure in these nuclei. There are many interesting phenomena in this field as you know.

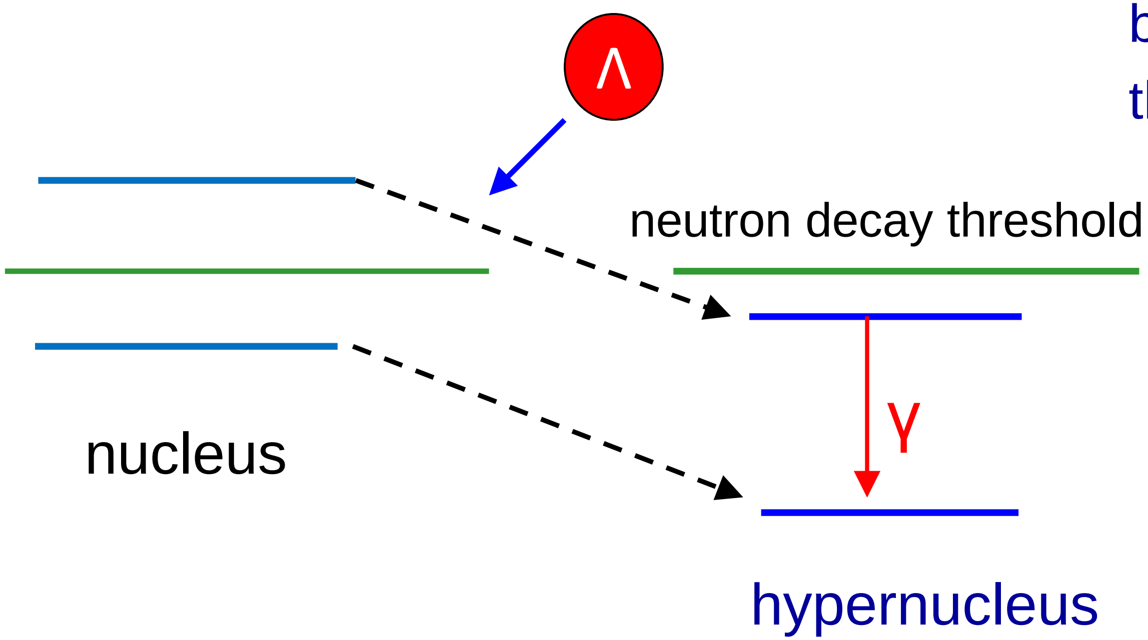
No Pauli principle
Between N and Λ

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



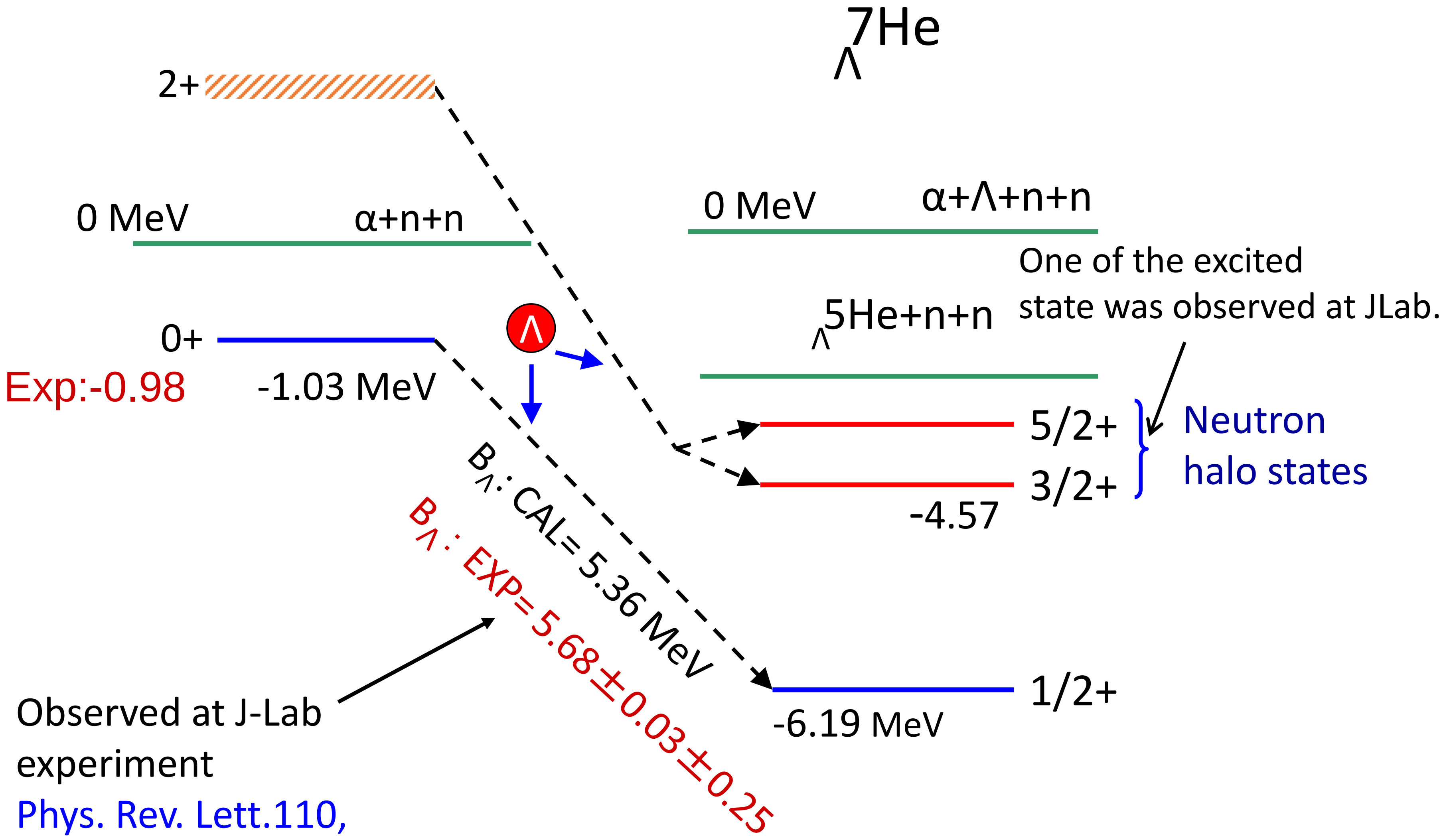
Hypernucleus

Due to the attraction of Λ N interaction, the resultant hypernucleus will become more stable against the neutron decay.



CAL: E. Hiyama et al., PRC 53, 2075 (1996), PRC 80, 054321 (2009)

6He Another interesting issue is to study the excited states of $^{7}_{\Lambda}$He.



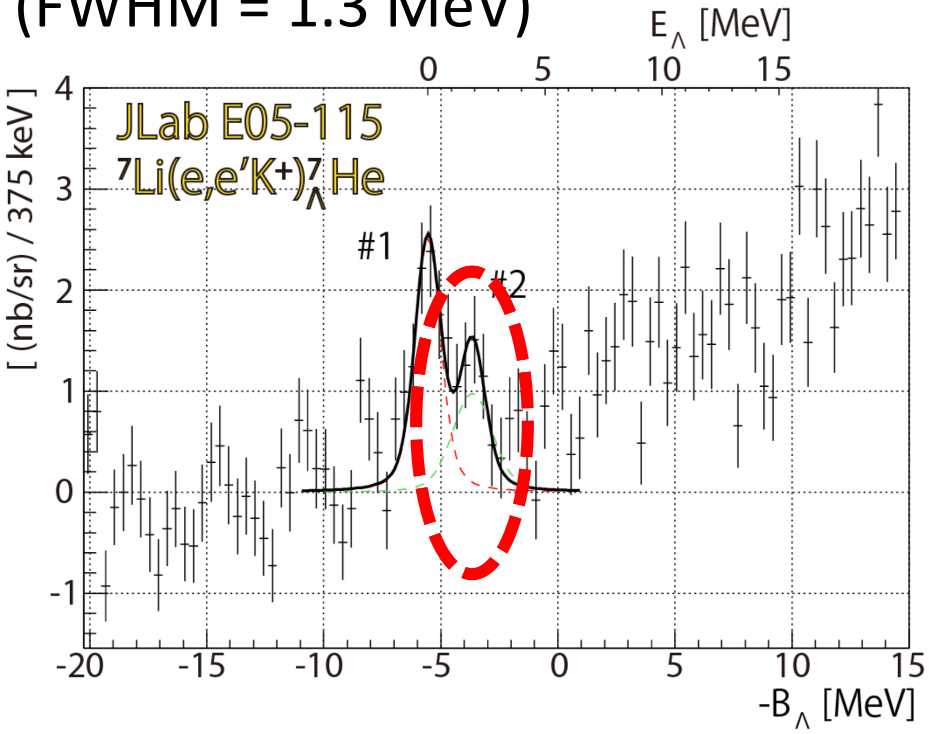
One of the excited state was observed at JLab.

Neutron halo states

Observed at J-Lab experiment
Phys. Rev. Lett.110, 012502 (2013).

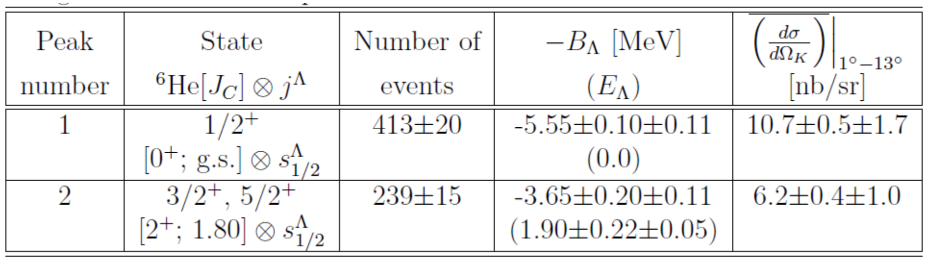
$^{7}Li(e,e'K^{+})^{7}_{\Lambda}He$

(FWHM = 1.3 MeV)



At present, due to poor statics,
It is difficult to have the third peak.
Theoretically, is it possible to
have new state?
Let's consider it.

Fitting results

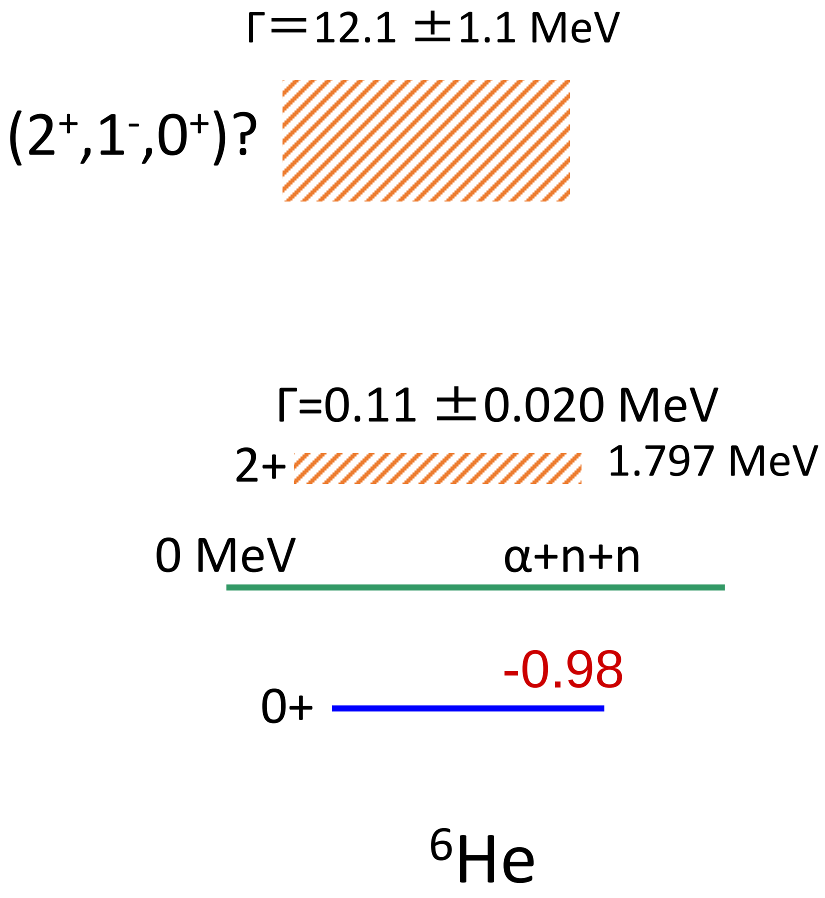


Peak number	State $^{6}He[J_C] \otimes j^{\Lambda}$	Number of events	$-B_{\Lambda}$ [MeV] (E_{Λ})	$\left(\frac{d\sigma}{d\Omega_K}\right)\Big\|_{1^\circ-13^\circ}$ [nb/sr]
1	$1/2^{+}$ $[0^{+};\ g.s.] \otimes s^{\Lambda}_{1/2}$	413±20	-5.55±0.10±0.11 (0.0)	10.7±0.5±1.7
2	$3/2^{+},\ 5/2^{+}$ $[2^{+};\ 1.80] \otimes s^{\Lambda}_{1/2}$	239±15	-3.65±0.20±0.11 (1.90±0.22±0.05)	6.2±0.4±1.0

Good agreement with my prediction

Question: In ${}^{7}_{\Lambda}$He, do we have any other new states?
If so, what is spin and parity?

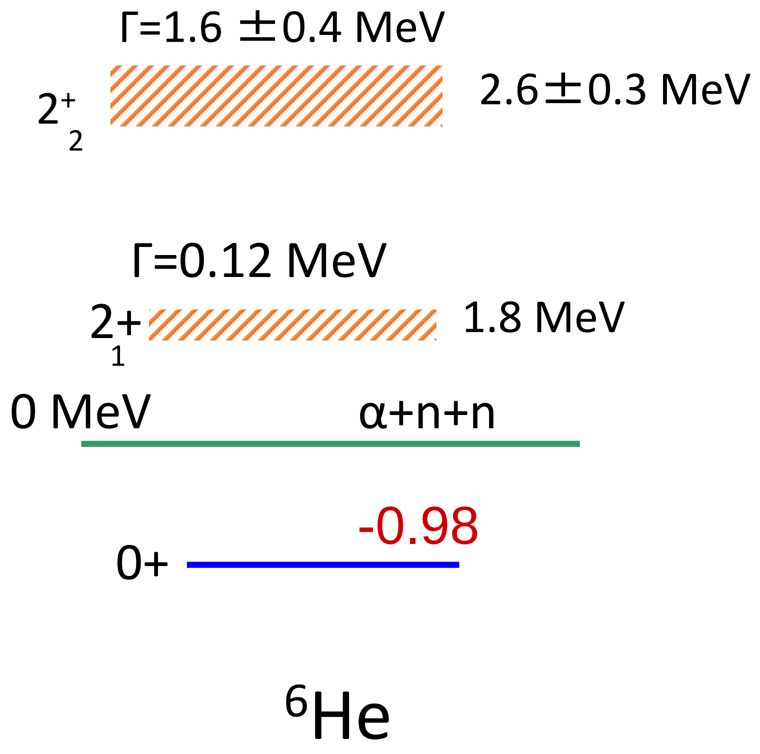
First, let us discuss about energy spectra of ^{6}He core nucleus.



Exp.

Data in 2002

Core nucleus

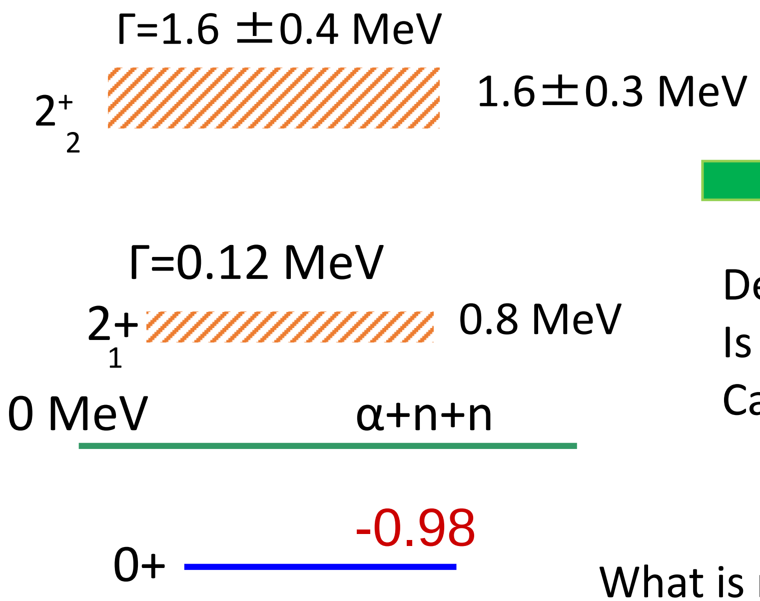


Exp.

Data in 2012

X. Mougeot et al., Phys. Lett. B 718 (2012) 441. p(^{8}He, t)^{6}He

How about theoretical result?



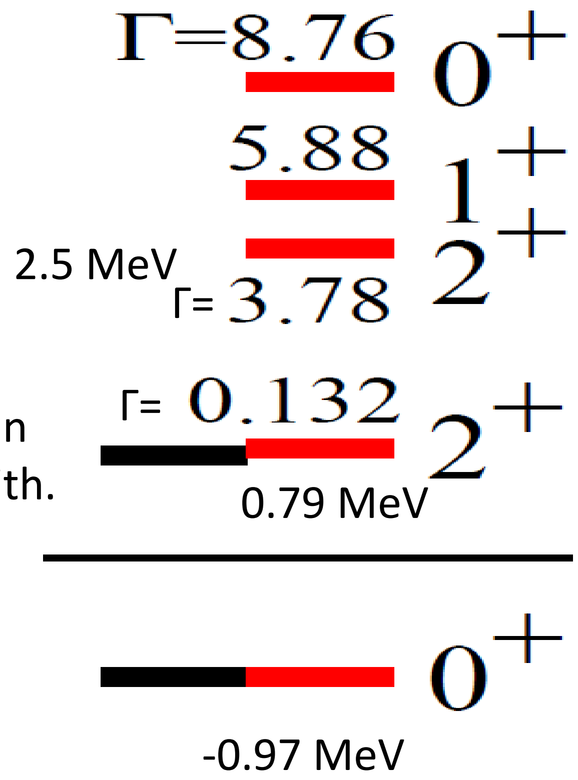
^{6}He

Exp.

Data in 2012
X. Mougeot et al., Phys. Lett. B 718 (2012) 441. p(^{8}He, t)^{6}He

Decay with
Is smaller than
Calculated with.

What is my result?

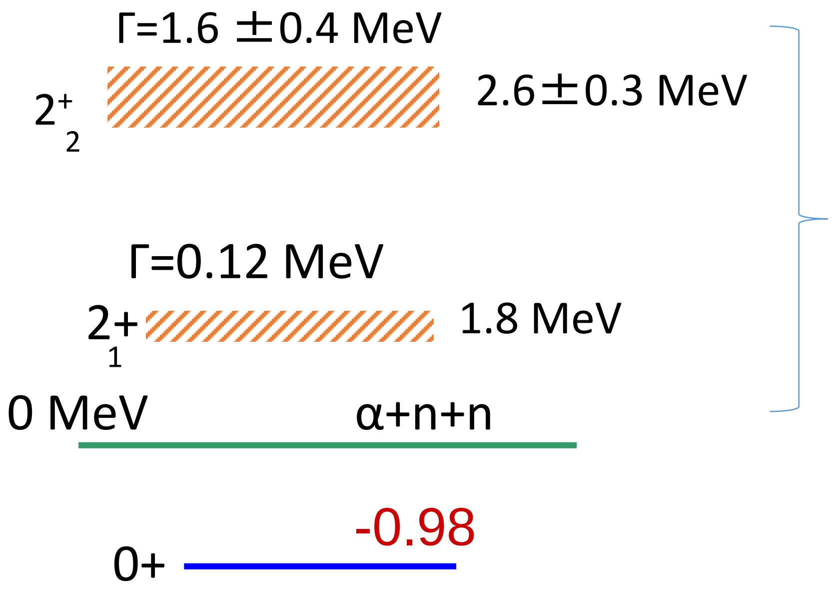


theory

Myo et al., PRC 84, 064306 (2011).

^{6}He

Question: What are theoretical results?



Γ=1.6 ±0.4 MeV

2^+_2 2.6±0.3 MeV

Γ=0.12 MeV

2^+_1 1.8 MeV

0 MeV α+n+n

-0.98

0+

^{6}He

Exp.

Data in 2012
X. Mougeot et al., Phys. Lett. B 718 (2012) 441. p(^{8}He, t)^{6}He

These are resonant states.

I should obtain energy position and decay width.

To do so, I use complex scaling method which is one of powerful method to get resonant states.

The Hamiltonian for ^{6}He is written as

$$H = T + V_{NN} + + \sum_{i=1}^{2} \left[V_{\alpha N_i} + V_{\alpha N_i}^{\mathrm{Pauli}} \right] \quad ,$$

and for $^7_\Lambda$He is written as

$$H = T + V_{NN} + V_{\Lambda\alpha} + \sum_{i=1}^{2} \left[V_{\Lambda N_i} + V_{\alpha N_i} + V_{\alpha N_i}^{\mathrm{Pauli}} \right] \quad .$$

Complex scaling is defined by the following transformation.

$$U(\theta) f(\boldsymbol{x}) = \exp\left(i \frac{3}{2} \theta \right) f(\exp(i\theta) \boldsymbol{x})$$

$$H(\theta) = U(\theta) H U(\theta)^{-1} ,$$

$$| \Psi_\theta \rangle = U(\theta) | \Psi \rangle .$$

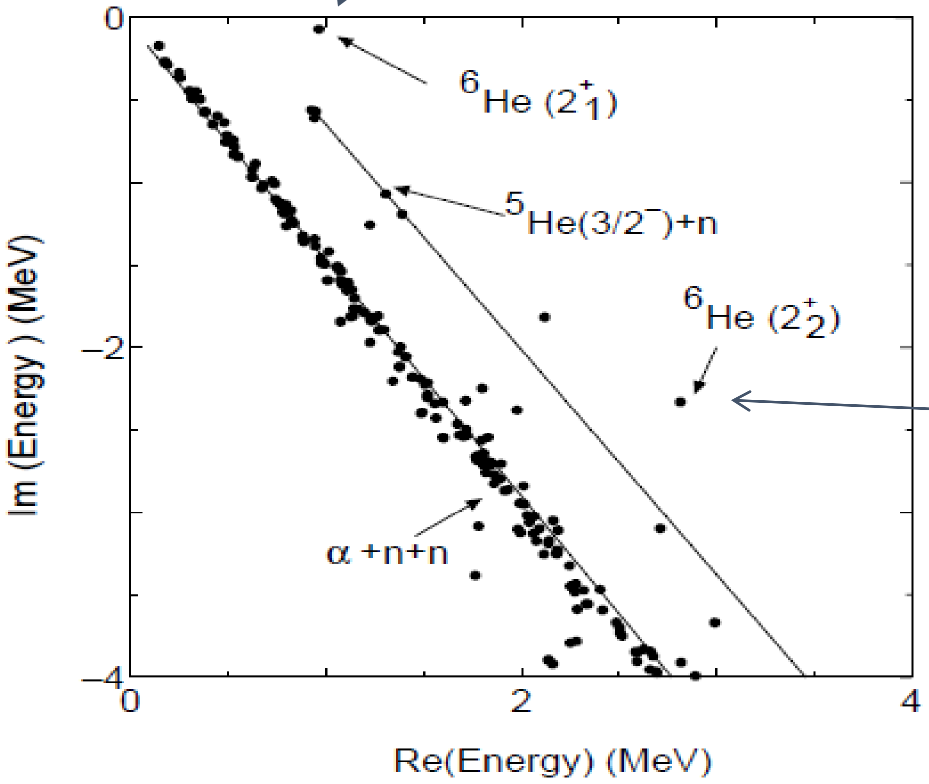
As a result, I should solve this Schroediner equation.

$$H(\theta) | \Psi_\theta \rangle = E(\theta) | \Psi_\theta \rangle$$

$E = E_r + i\Gamma/2$

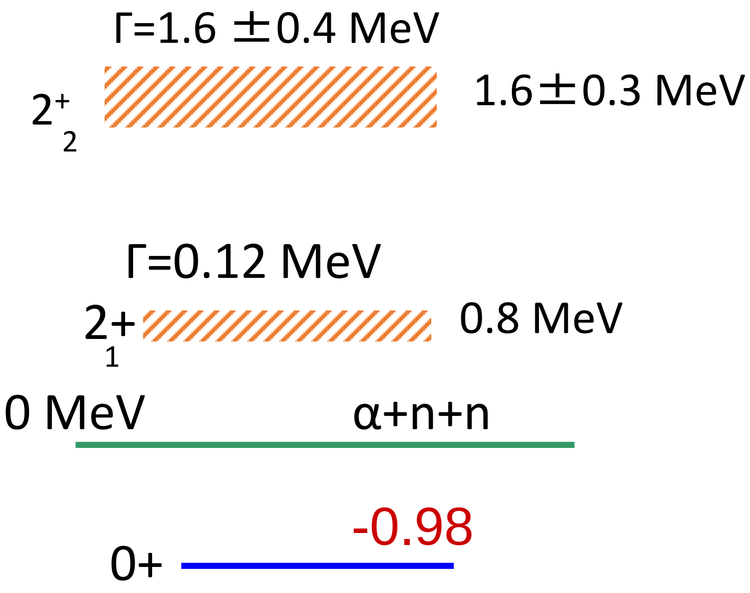
My result

E=0.96 + 0.14 MeV



E=2.81 +4.81 MeV

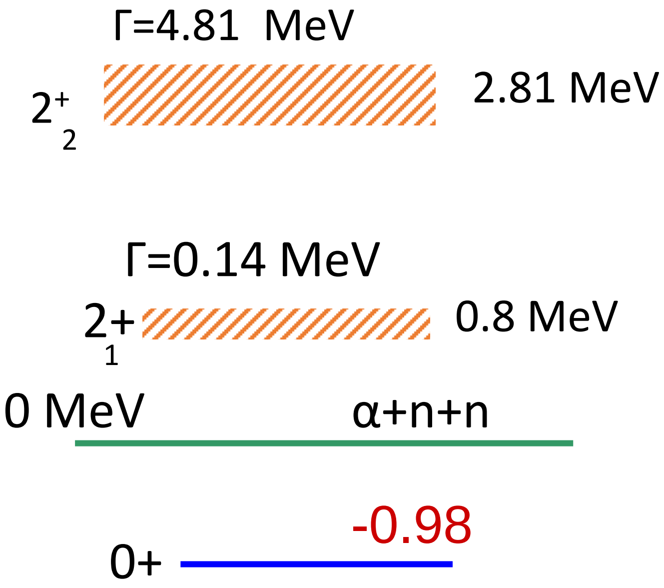
Question: What are theoretical results?



^{6}He

Exp.

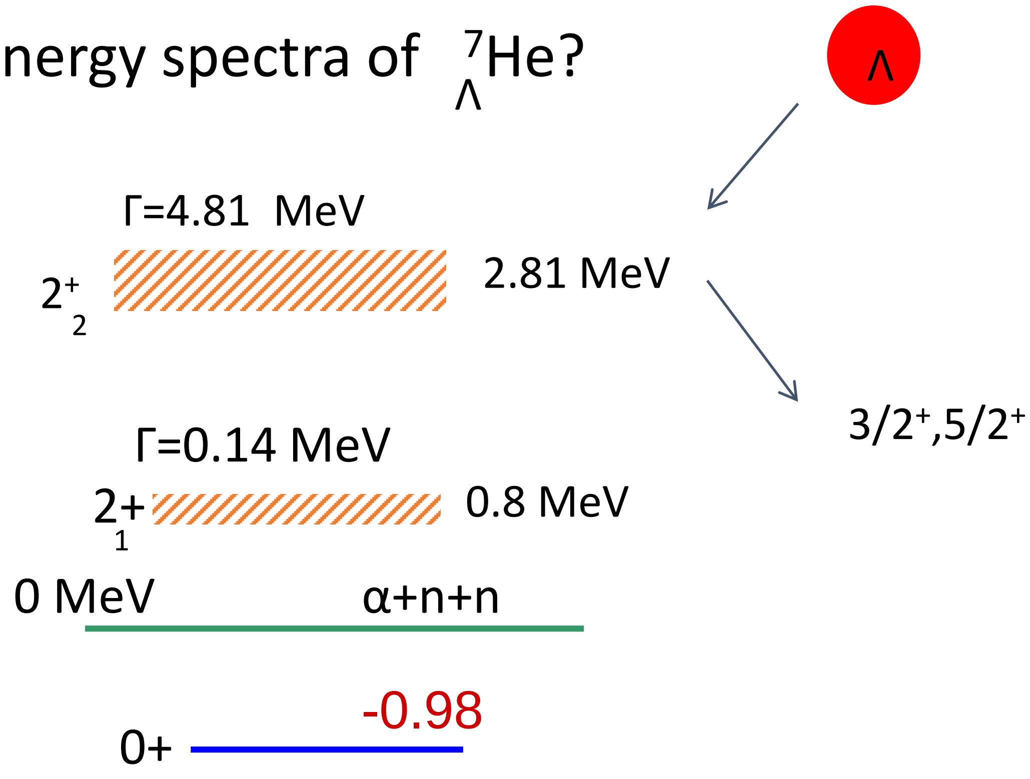
Data in 2012
X. Mougeot et al., Phys. Lett. B 718 (2012) 441. p(^{8}He, t)^{6}He



^{6}He

Cal.

How about energy spectra of $^{7}_{\Lambda}$He?



Λ

Γ=4.81 MeV

2^+_2 2.81 MeV

$3/2^+, 5/2^+$

Γ=0.14 MeV

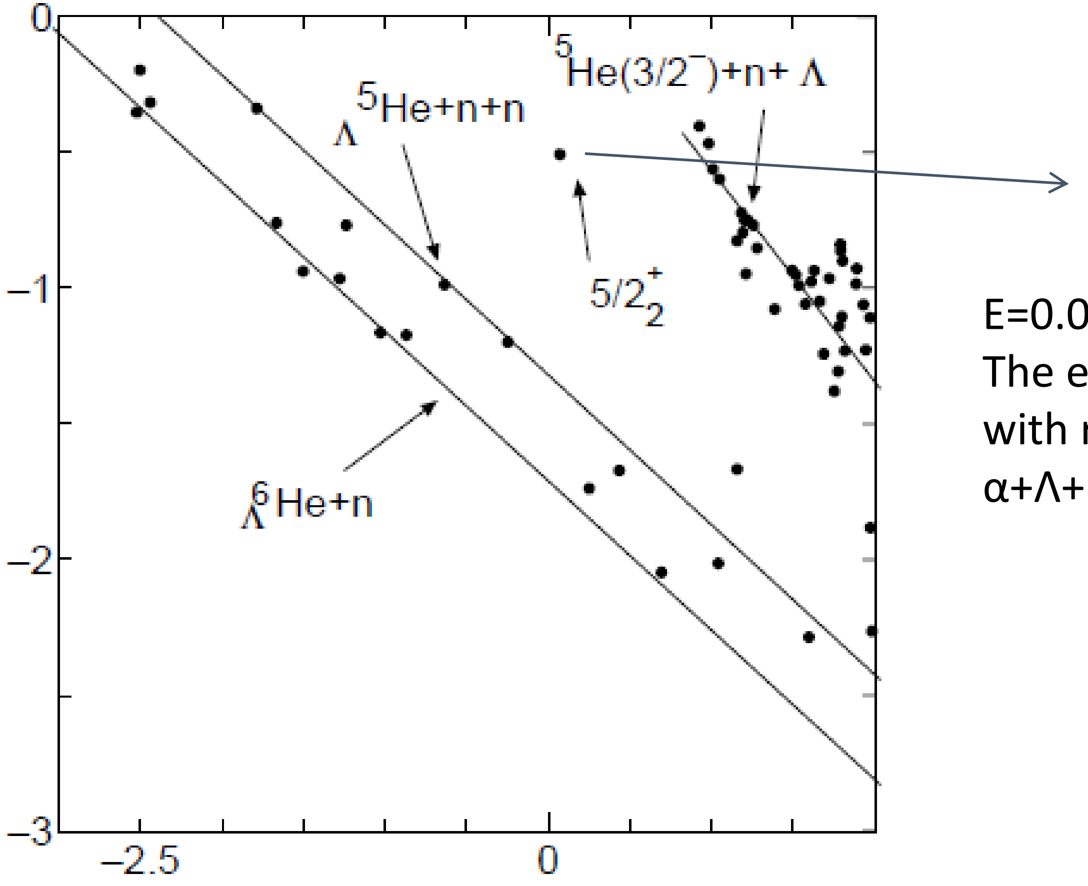
2^+_1 0.8 MeV

0 MeV α+n+n

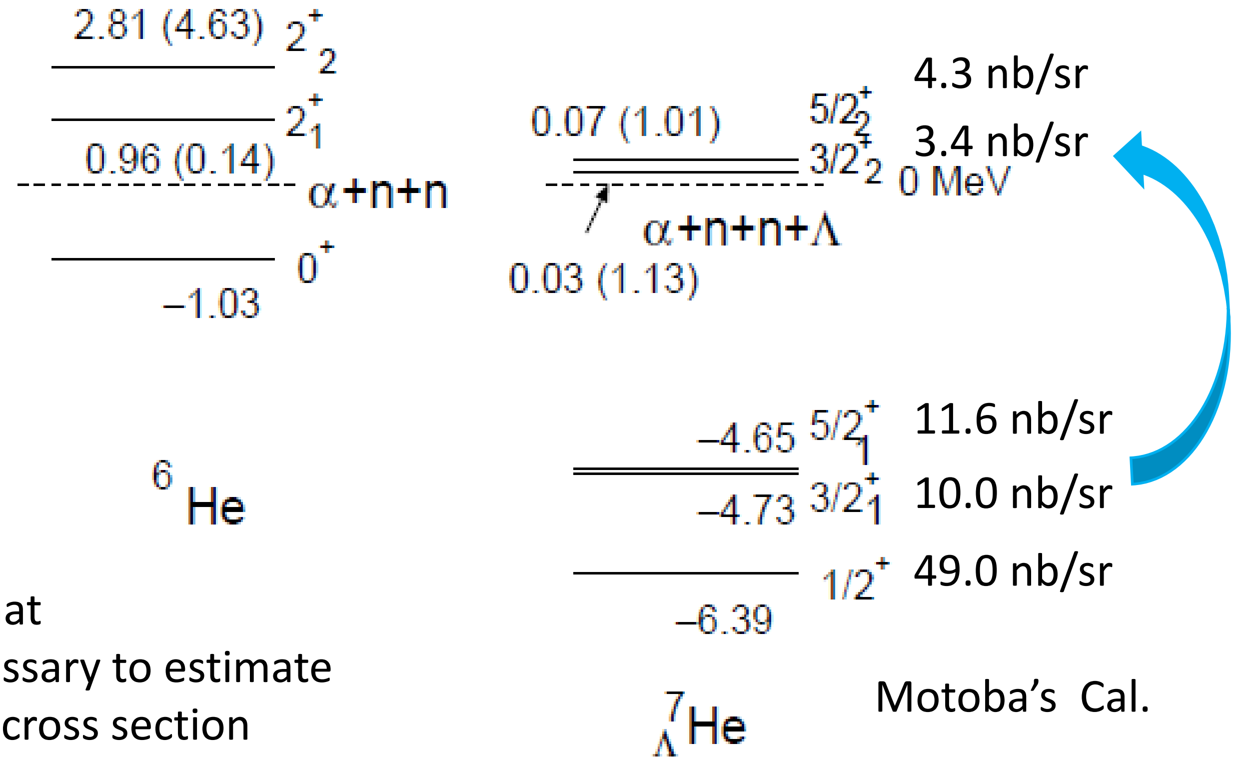
0+ -0.98

^{6}He

Cal.



E=0.07 MeV+1.13 MeV
The energy is measured with respect to α+Λ+n+n threshold.



I propose to experimentalists to observe these states.

40% reduction

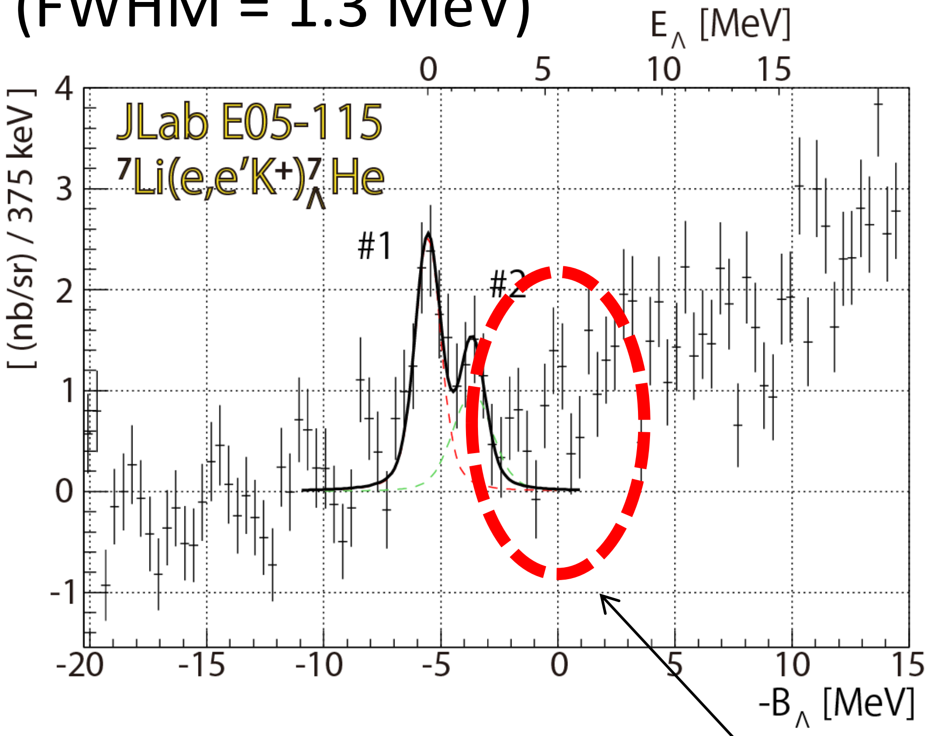
I think that
It is necessary to estimate reaction cross section ^{7}Li (e,e'K$^+$).

Motoba san recently estimated differential cross sections for each state.

At E^{lab}=1.5 GeV and θ=7 deg (E05-115 experimental kimenatics)

^{7}Li(e,e'K^{+})$^{7}_{\Lambda}$He

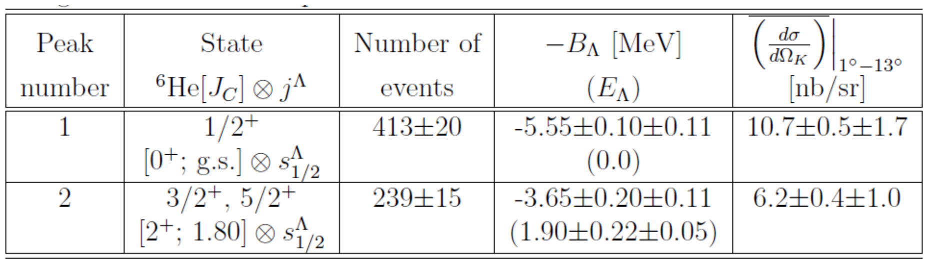
(FWHM = 1.3 MeV)



Third peak???

At present, due to poor statics,
It is difficult to have the third peak.
But, I hope that next experiment
at Jlab will observe the third peak.

Fitting results



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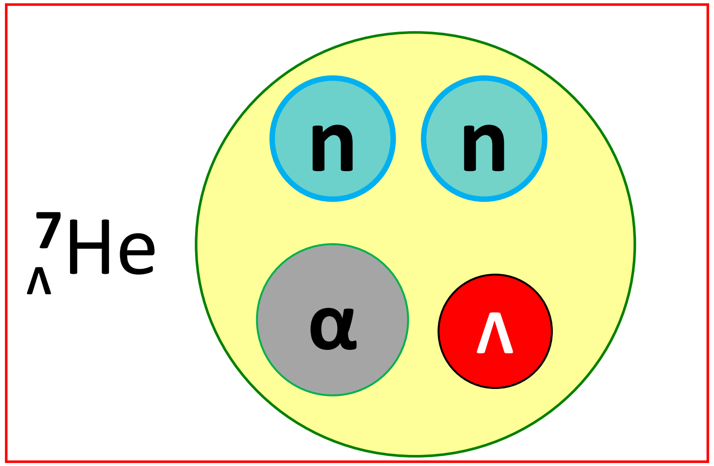
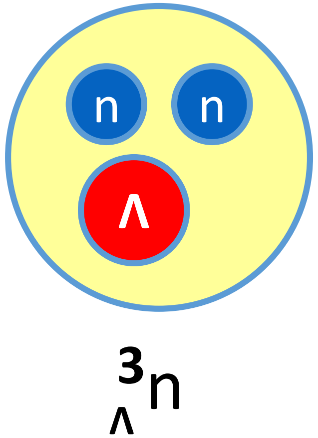
Good agreement with my prediction

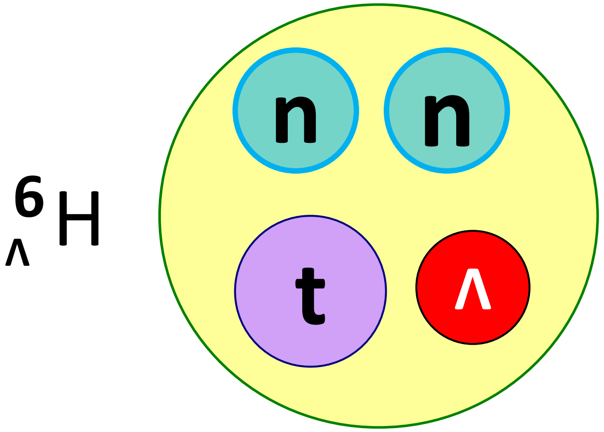
Conclusion



JLAB experiment-E011,
Phys. Rev. Lett. **110**,
12502 (2013).



C. Rappold et al.,
HypHI collaboration
Phys. Rev. C 88,
041001 (R) (2013)



FINUDA collaboration & A. Gal,
Phys. Rev. Lett. **108**,
042051 (2012).

Thank you!