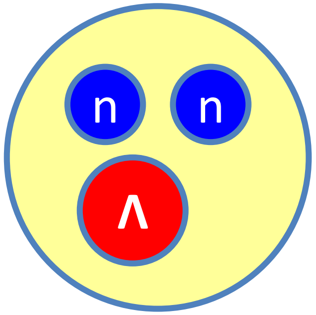
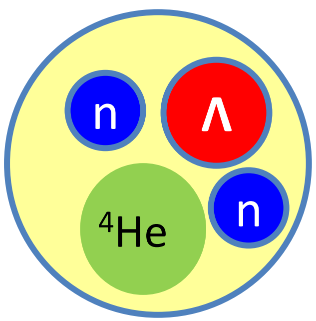
Structure of neutron-rich Λ hypernuclei

E. Hiyama (RIKEN)

Outline



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



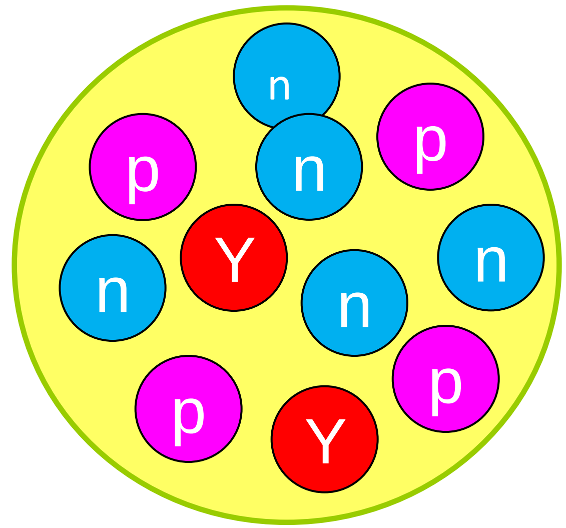
$^{7}_{\Lambda}He$

To study the structure of multi-strangeness systems

Hypernucleus =

Many-body system of

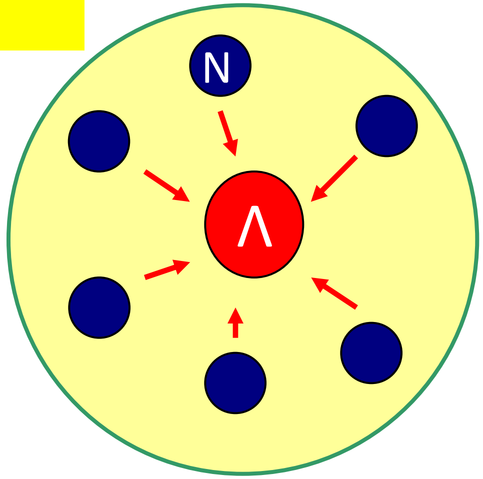
- neutrons,
- protons,
- hyperons



Once the Hamiltonian is determined,
it is possible , using few-body calculation method (Gaussian Expansion Method), to precisely calculate
the structure of many-body systems consisting of
neutrons, protons and hyperons.
As a result, we can predict new phenomena
such as we have never imagined before.

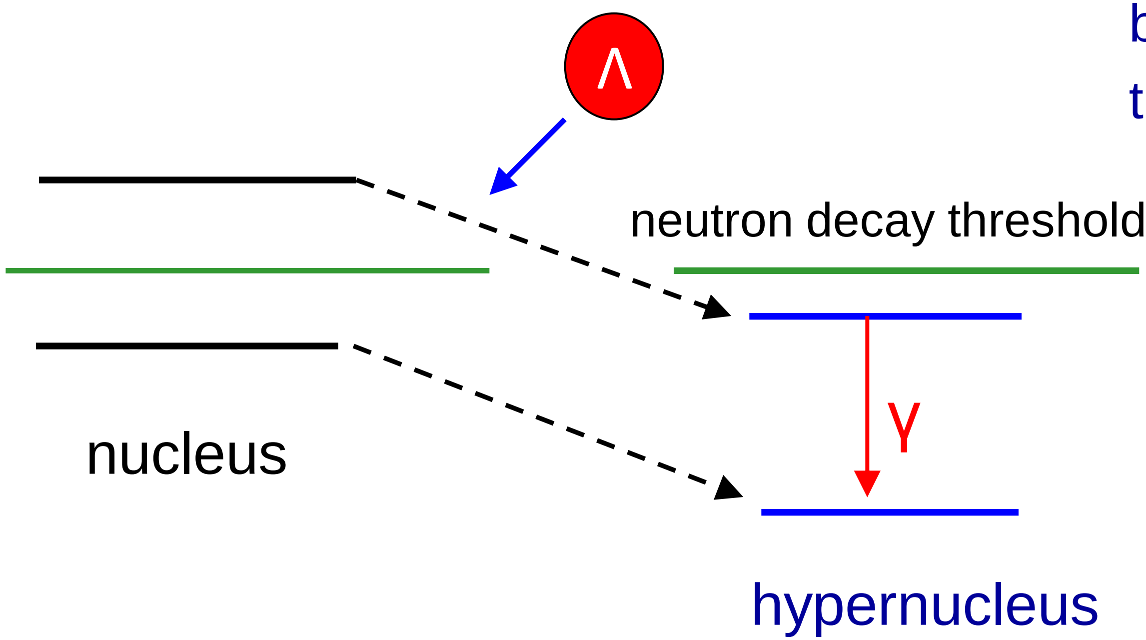
No Pauli principle
Between N and Λ

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



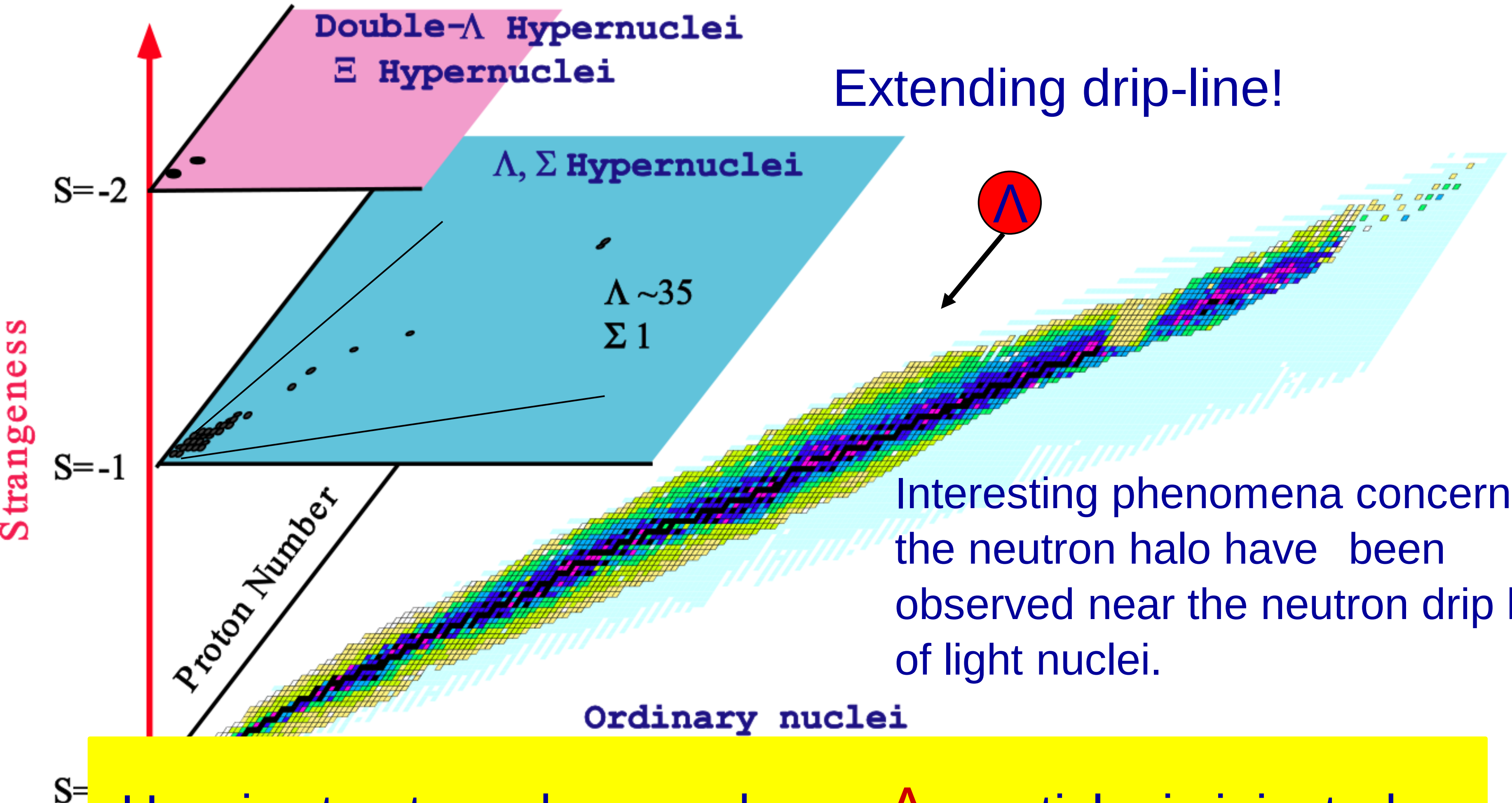
Hypernucleus

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



Nuclear chart with strangeness

Multi-strangeness system
such as Neutron star



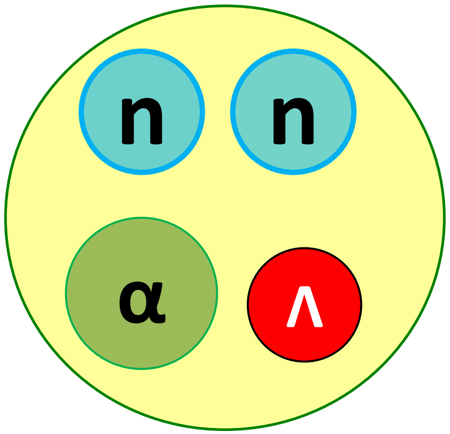
Extending drip-line!

Interesting phenomena concerning the neutron halo have been observed near the neutron drip line of light nuclei.

How is structure change when a Λ particle is injected into neutron-rich nuclei ?

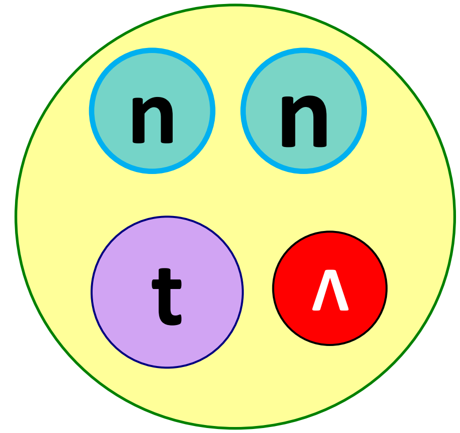
Question : How is structure change when a Λ particle is injected into neutron-rich nuclei?

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

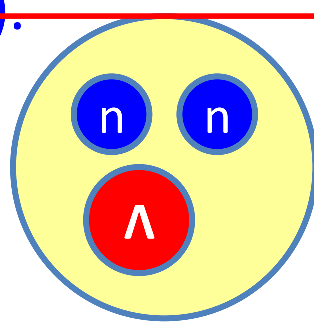


Observed at JLAB, Phys. Rev. Lett. **110**, 12502 (2013).

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

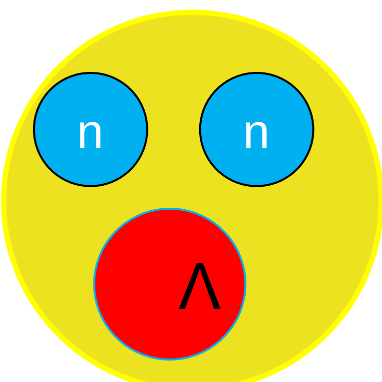


Observed by FINUDA group, Phys. Rev. Lett. **108**, 042051 (2012).



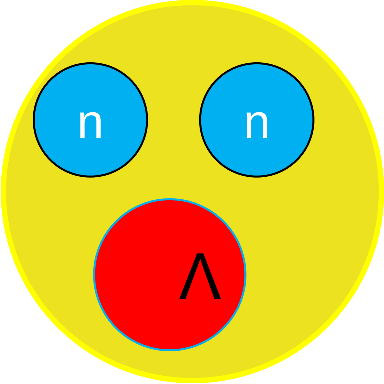
$^{3}_{\Lambda}$n

C. Rappold et al., HypHI collaboration Phys. Rev. C 88, 041001 (R) (2013) three-body calculation of ${}^{3}_{\Lambda}n$



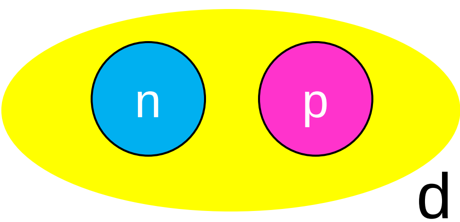
E. Hiyama, S. Ohnishi,
B.F. Gibson, and T. A. Rijken,
PRC89, 061302(R) (2014).

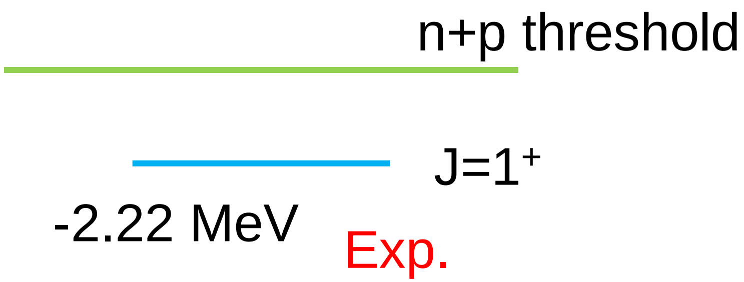
What is interesting to study nnΛ system?



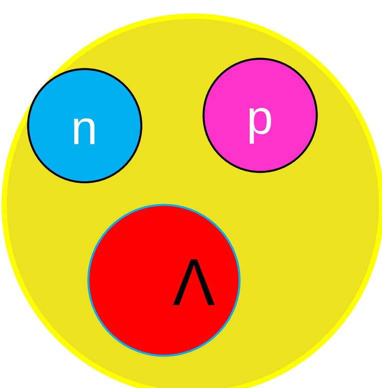
S=0

The lightest nucleus to have a bound state is deuteron.



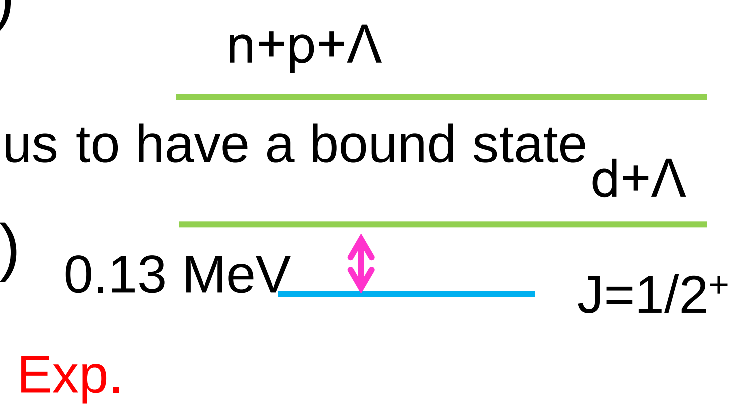


S=-1 (Λ hypernucear sector)



Lightest hypernucleus to have a bound state

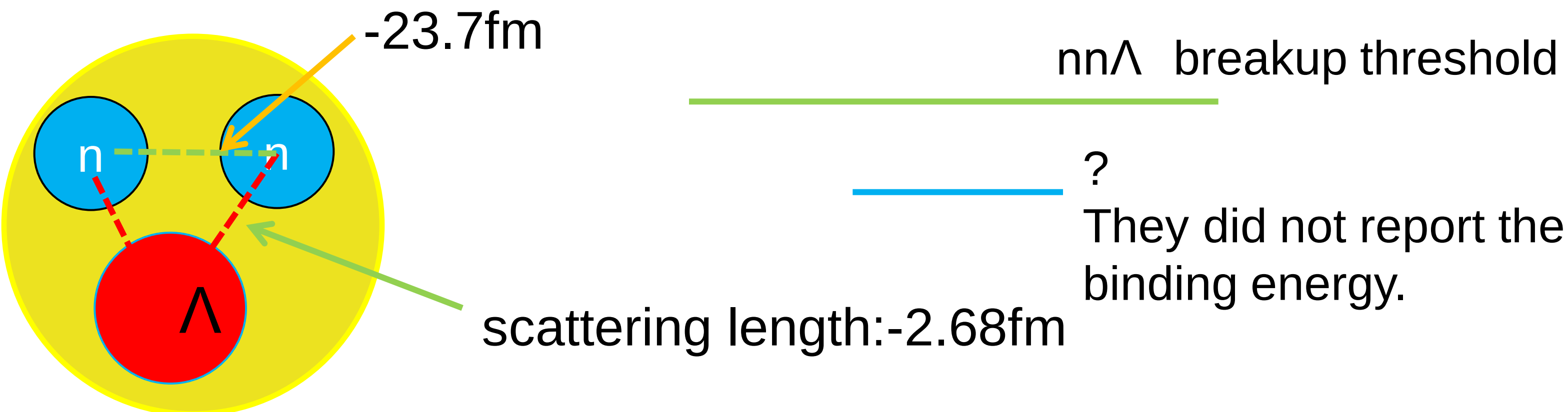
$^{3}_{\Lambda}H$ (hyper-triton)



PHYSICAL REVIEW C 88, 041001(R) (2013)

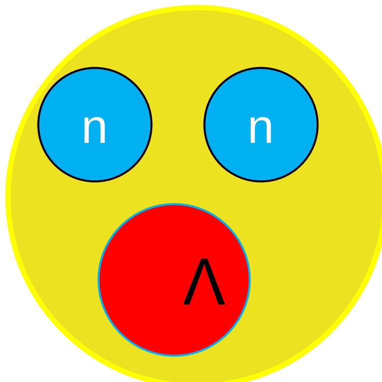
Search for evidence of $^{3}_{\Lambda}n$ by observing $d + \pi^-$ and $t + \pi^-$ final states in the reaction of $^{6}\text{Li} + {}^{12}\text{C}$ at 2A GeV

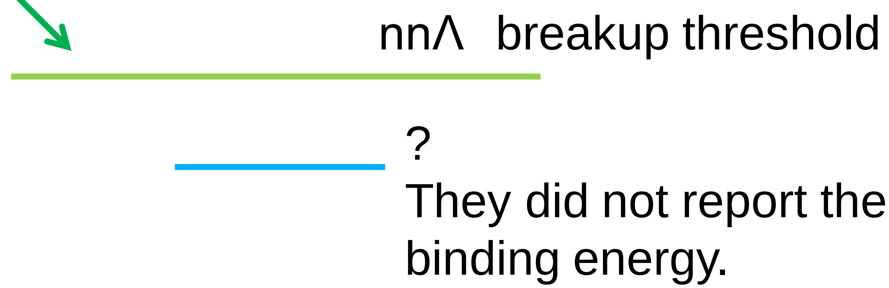
C. Rappold,[1,2,*] E. Kim,[1,3] T. R. Saito,[1,4,5,†] O. Bertini,[1,4] S. Bianchin,[1] V. Bozkurt,[1,6] M. Kavatsyuk,[7] Y. Ma,[1,4] F. Maas,[1,4,5] S. Minami,[1] D. Nakajima,[1,8] B. Özel-Tashenov,[1] K. Yoshida,[1,5,9] P. Achenbach,[4] S. Ajimura,[10] T. Aumann,[1,11] C. Ayerbe Gayoso,[4] H. C. Bhang,[3] C. Caesar,[1,11] S. Erturk,[6] T. Fukuda,[12] B. Göküzüm,[1,6] E. Guliev,[7] J. Hoffmann,[1] G. Ickert,[1] Z. S. Ketenci,[6] D. Khaneft,[1,4] M. Kim,[3] S. Kim,[3] K. Koch,[1] N. Kurz,[1] A. Le Fèvre,[1,13] Y. Mizoi,[12] L. Nungesser,[4] W. Ott,[1] J. Pochodzalla,[4] A. Sakaguchi,[9] C. J. Schmidt,[1] M. Sekimoto,[14] H. Simon,[1] T. Takahashi,[14] G. J. Tambave,[7] H. Tamura,[15] W. Trautmann,[1] S. Voltz,[1] and C. J. Yoon[3]
(HypHI Collaboration)



Observation of nnΛ system (2013)
Lightest hypernucleus to have a bound state
Any two-body systems are unbound.=>nnΛ system is bound.
Lightest Borromean system.

Theoretical important issue:
Do we have bound state for nnΛ system?
If we have a bound state for this system, how much is binding energy?



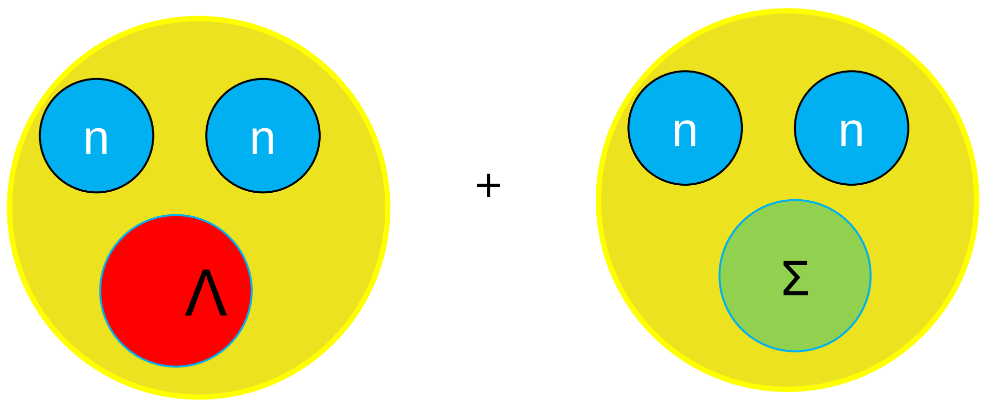


NN interaction : to reproduce the observed binding energies of ^{3}H and ^{3}He

NN: AV8 potential
We do not include 3-body force for nuclear sector.

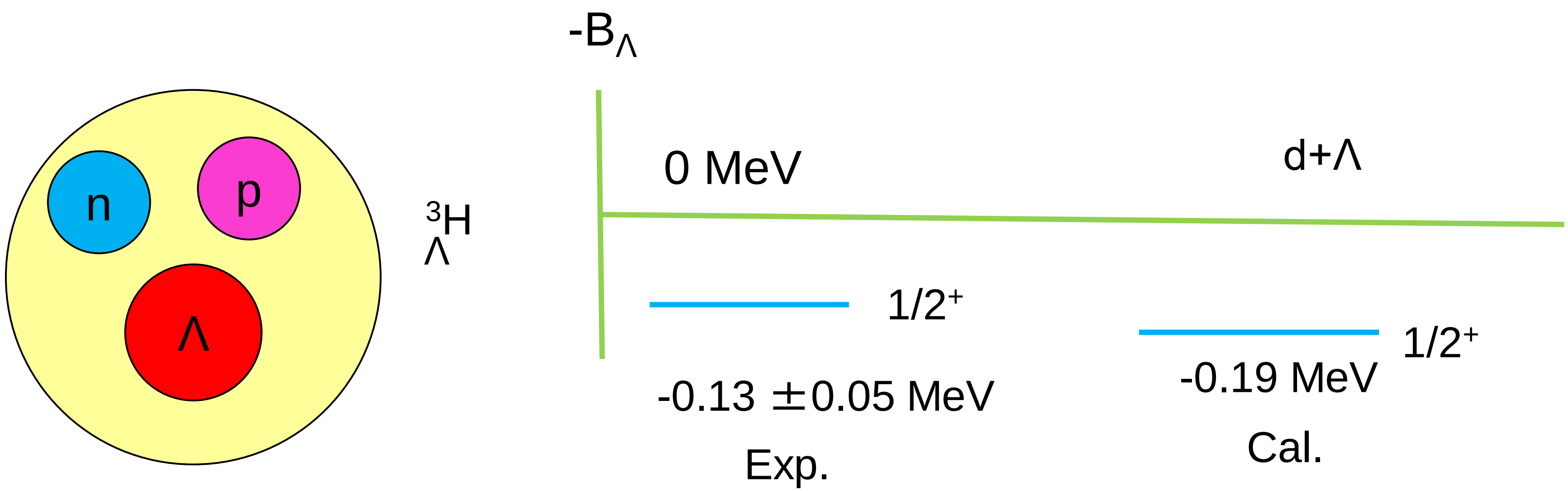
How about YN interaction?

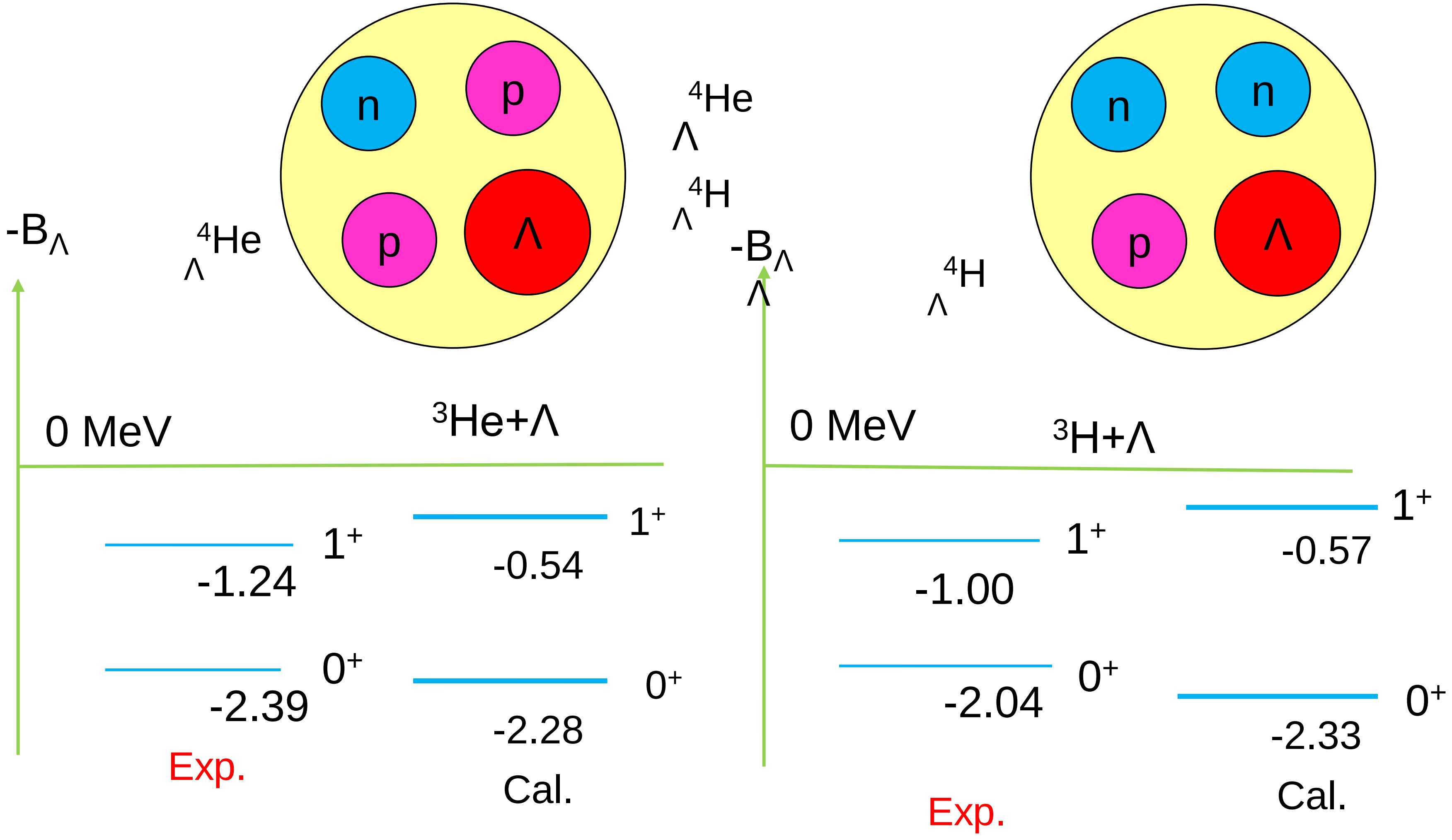
To take into account of Λ particle to be converted into Σ particle, we should perform below calculation using realistic hyperon(Y)-nucleon(N) interaction.



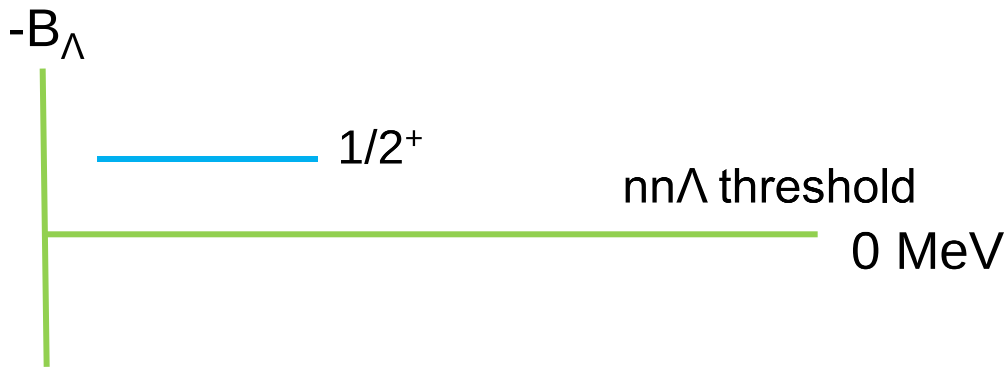
YN interaction: Nijmegen soft core '97f potential (NSC97f) proposed by Nijmegen group

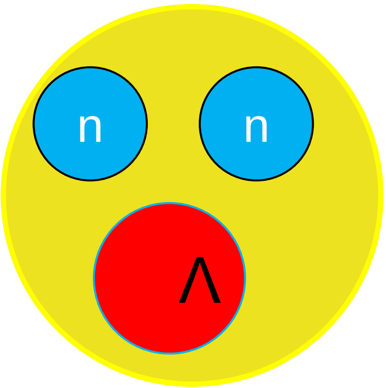
reproduce the observed binding energies of ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$ and ${}^{4}_{\Lambda}He$


n
p
Λ
$^{3}_{\Lambda}H$
$-B_{\Lambda}$
0 MeV
d+Λ
$1/2^{+}$
$1/2^{+}$
-0.13 ±0.05 MeV
-0.19 MeV
Exp.
Cal.



What is binding energy of nnΛ?





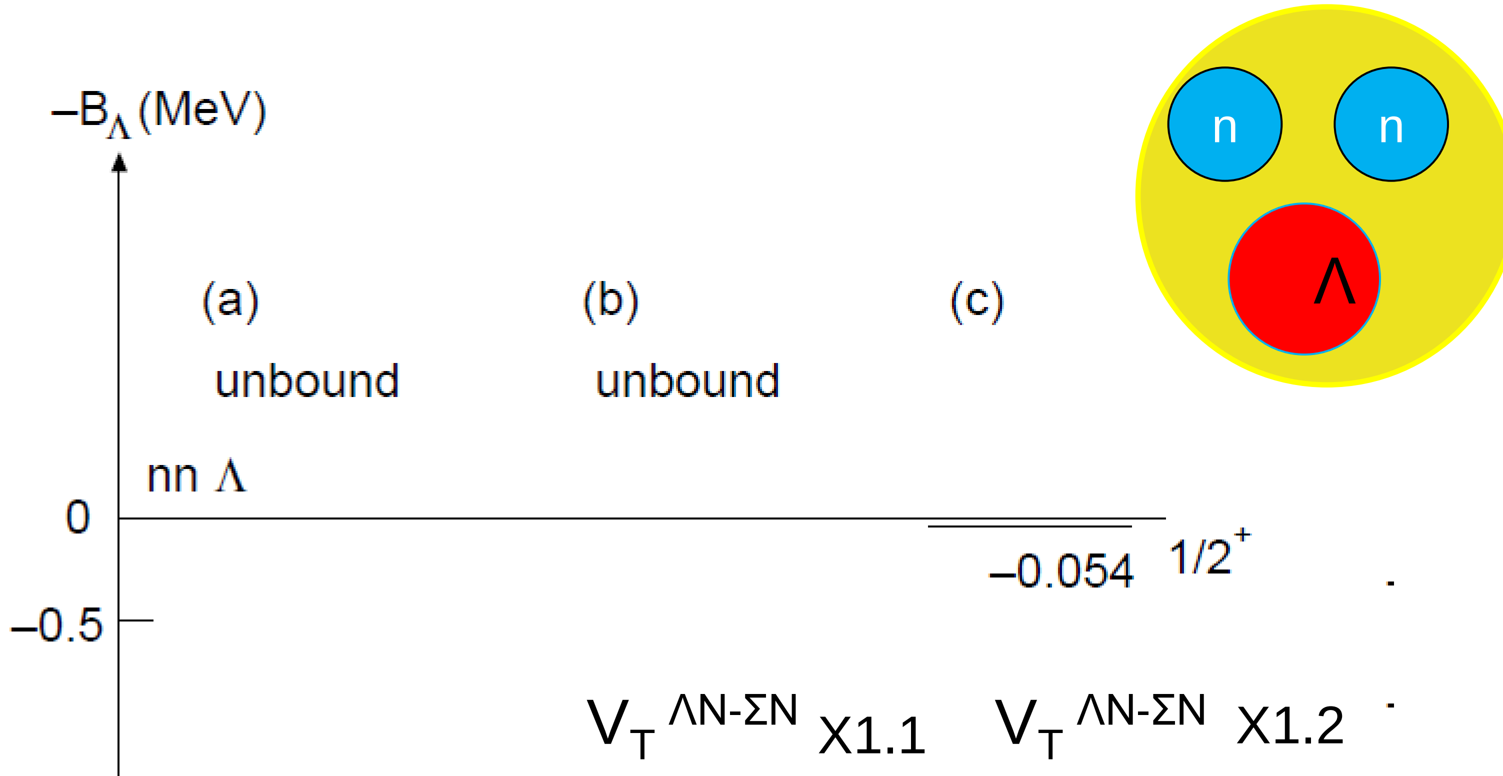
We have no bound state in nnΛ system.
This is inconsistent with the data.

Now, we have a question.

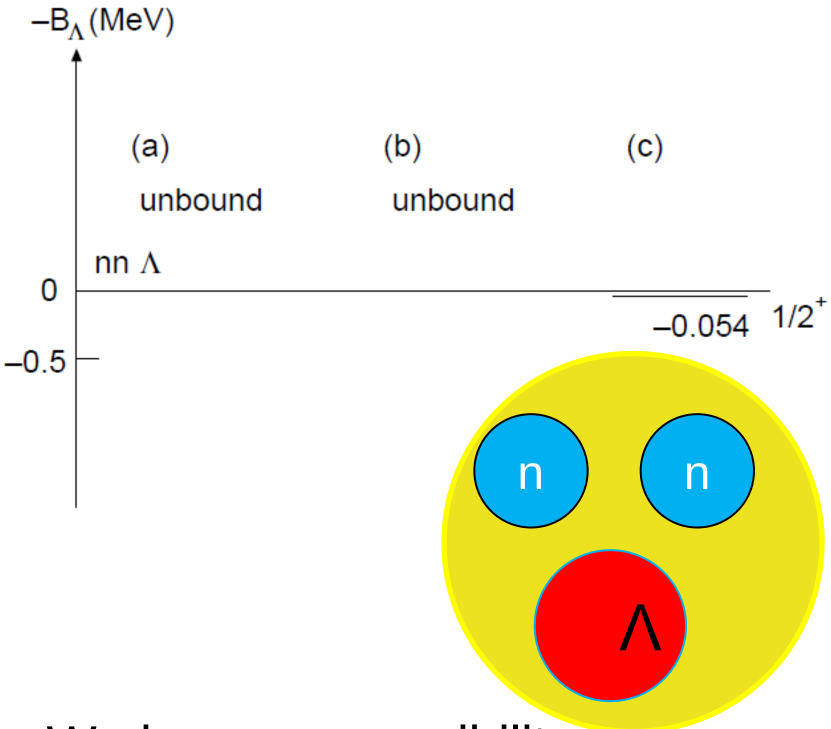
Do we have a possibility to have a bound state in nnΛ system tuning strength of YN potential ?

It should be noted to maintain consistency with the binding energies of $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$ and $^{4}_{\Lambda}He$.

$V_T^{\Lambda N-\Sigma N}$ X1.1, 1.2



When we have a bound state in nnΛ system, what are binding energies of ${}^{3}_{\Lambda}H$ and A=4 hypernuclei?



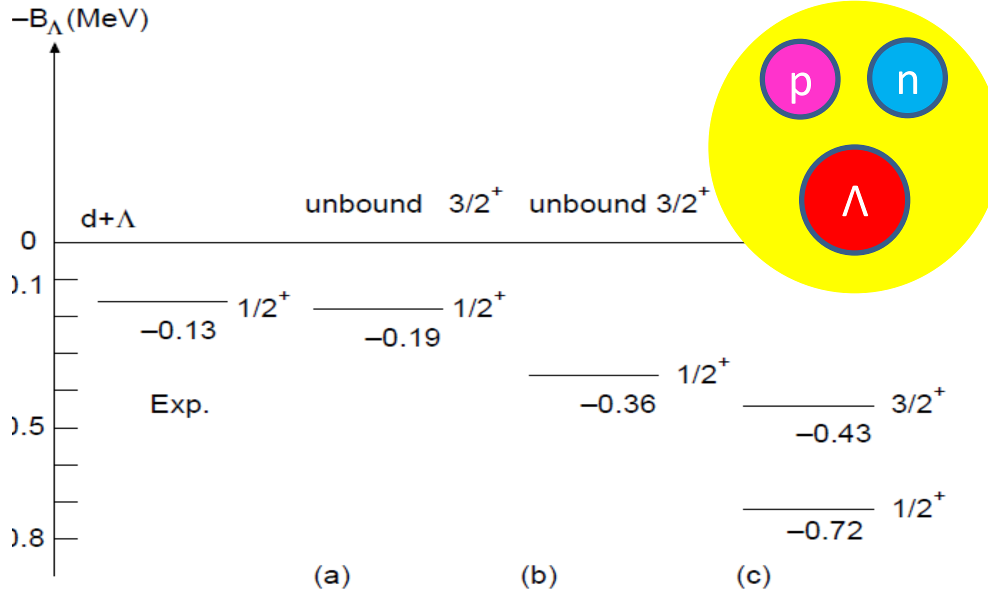
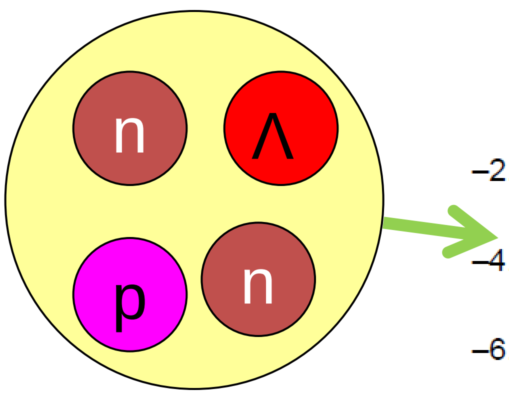
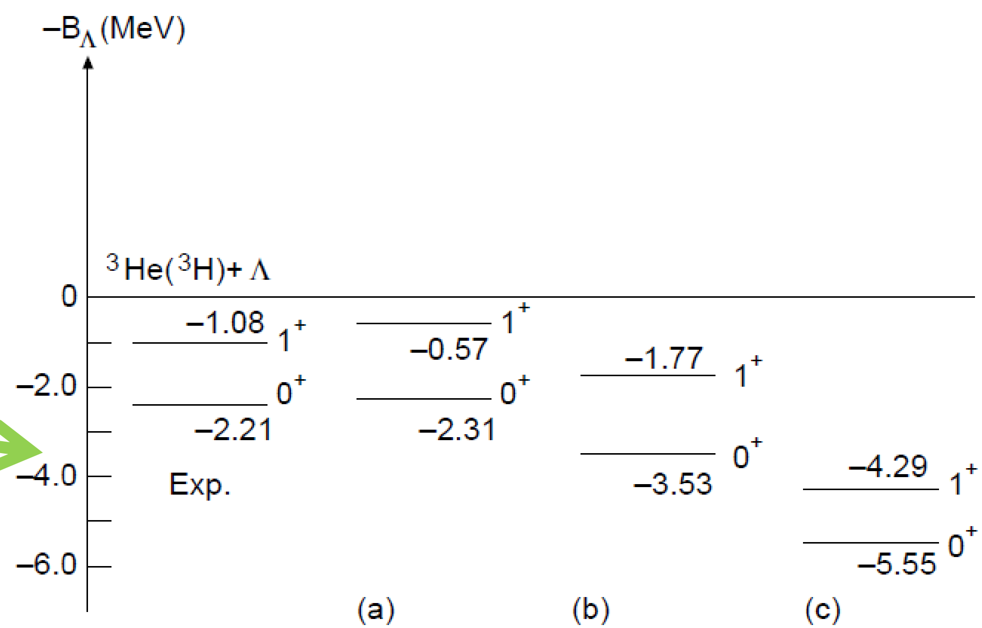


FIG. 3: Calculated Λ-separation energy for $^3_\Lambda$H with (a) $^3V^T_{N\Lambda-N\Sigma}$ × 1.00, (b) $^3V^T_{N\Lambda-N\Sigma}$ × 1.10, and (c) $^3V^T_{N\Lambda-N\Sigma}$ ×

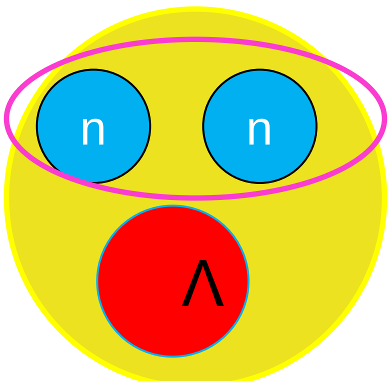
We have no possibility to have a bound state in nnΛ system.





Question: If we tune $^1S_0$ state of nn interaction,
Do we have a possibility to have a bound state in nnΛ?
In this case, the binding energies of ^{3}H and ^{3}He reproduce the observed data?

Some authors pointed out to have dineutron bound state in nn system. Ex. H. Witala and W. Gloeckle, Phys. Rev. C85, 064003 (2012).



T=1, $^1S_0$ state
I multiply component of $^1S_0$ state by 1.13 and 1.35. What is the binding energies of nnΛ ?

PHYSICAL REVIEW C **85**, 064003 (2012)

Di-neutron and the three-nucleon continuum observables

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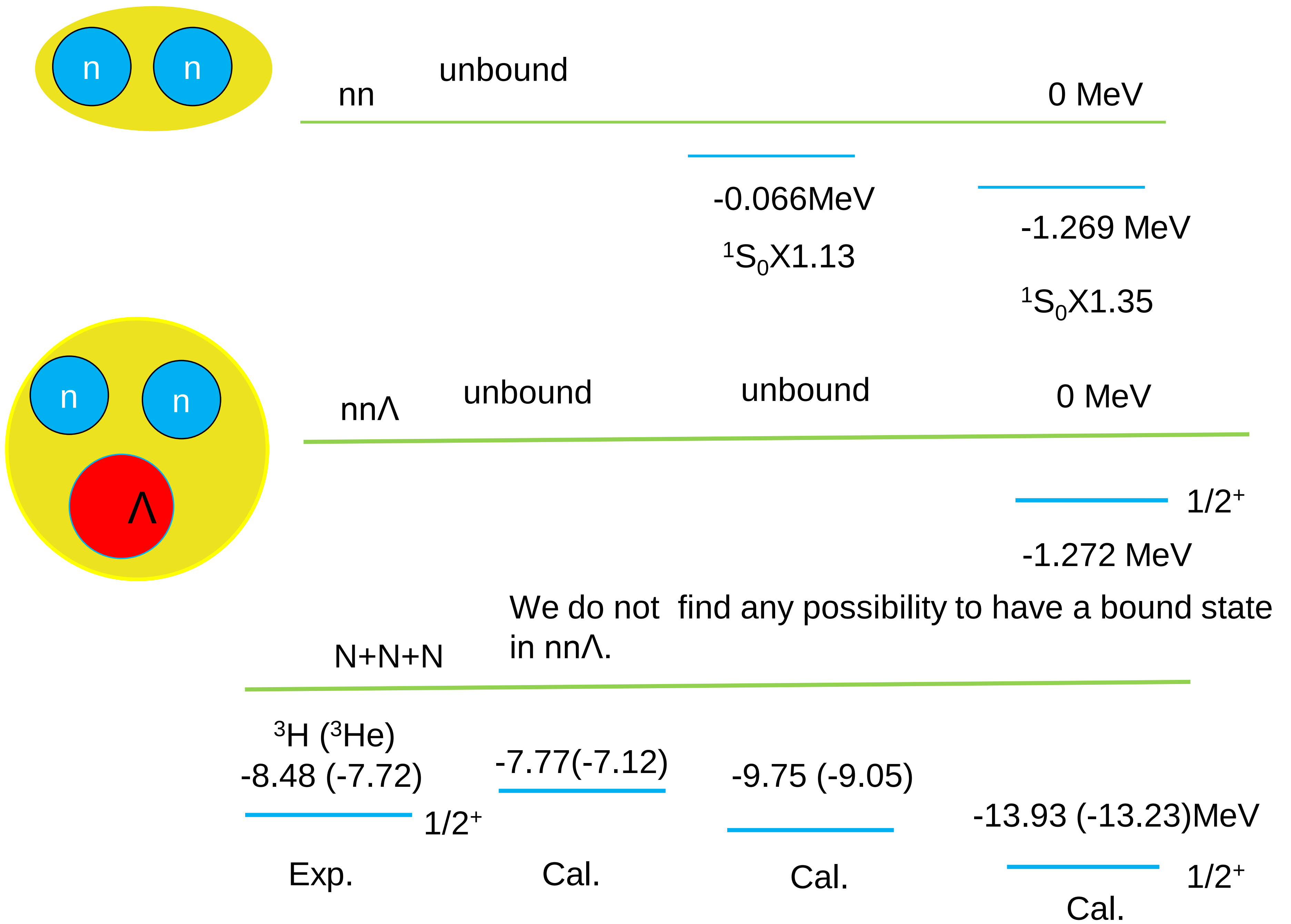
(Received 24 April 2012; published 25 June 2012)

We investigate how strongly a hypothetical $^1S_0$ bound state of two neutrons would affect observables in neutron-deuteron reactions. To that aim we extend our momentum-space scheme of solving the three-nucleon Faddeev equations and incorporate in addition to the deuteron also a $^1S_0$ di-neutron bound state. We discuss effects induced by a di-neutron on the angular distributions of the neutron-deuteron elastic scattering and deuteron breakup cross sections. A comparison to the available data for the neutron-deuteron total cross section and elastic scattering angular distributions cannot decisively exclude the possibility that two neutrons can form a $^1S_0$ bound state. However, strong modifications of the final-state-interaction peaks in the neutron-deuteron breakup reaction seem to disallow the existence of a di-neutron.



n
n
nn
unbound
0 MeV
-0.066MeV
$^1S_0$X1.13
-1.269 MeV
$^1S_0$X1.35
n
n
Λ
nnΛ
unbound
unbound
0 MeV
$1/2^+$
-1.272 MeV
We do not find any possibility to have a bound state in nnΛ.
N+N+N
^{3}H (^{3}He)
-8.48 (-7.72)
$1/2^+$
-7.77(-7.12)
-9.75 (-9.05)
-13.93 (-13.23)MeV
$1/2^+$
Exp.
Cal.
Cal.
Cal.

Summary of nnΛ system:

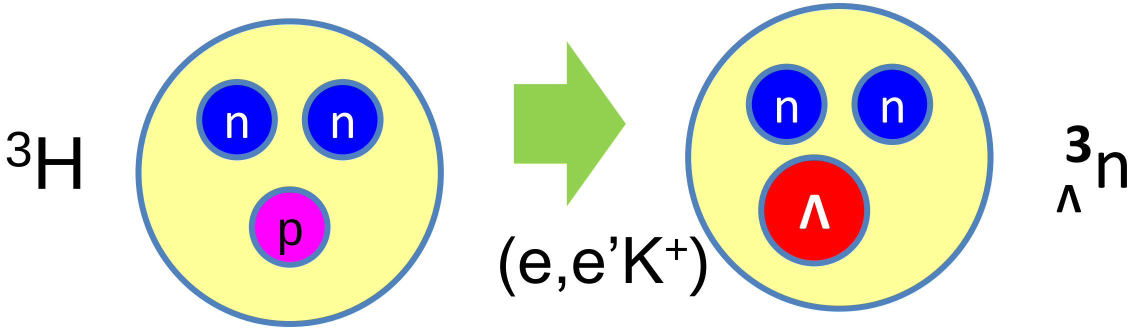
Motivated by the reported observation of data suggesting a bound state nnΛ, we have calculated the binding energy of this hyperucleus taking into account ΛN-ΣN explicitly. We did not find any possibility to have a bound state in this system.

‘Nonexistence of a Λnn bound state’
H. Garcilazo and A. Valcarce,
Phys. Rev. C 89, 057001 (2014).
They did not find any bound state in nnΛ system.

However, the experimentally they reported evidence for a bound state. As long as we believe the data, we should consider additional missing elements in the present calculation. But, I have no idea. Experimentally, they did not report any binding energy.

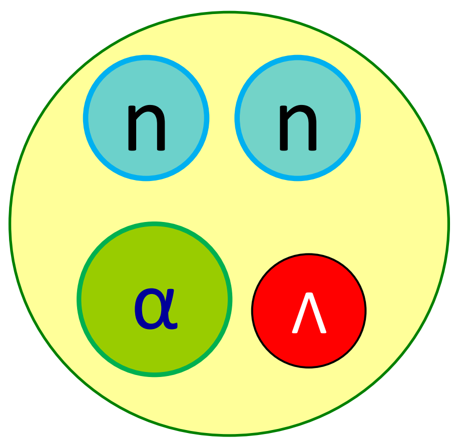
Summary of nnΛ system:

It might be good idea to
perform search experiment of nnΛ system at Jlab to conclude whether or not the system exists as bound state experimentally.

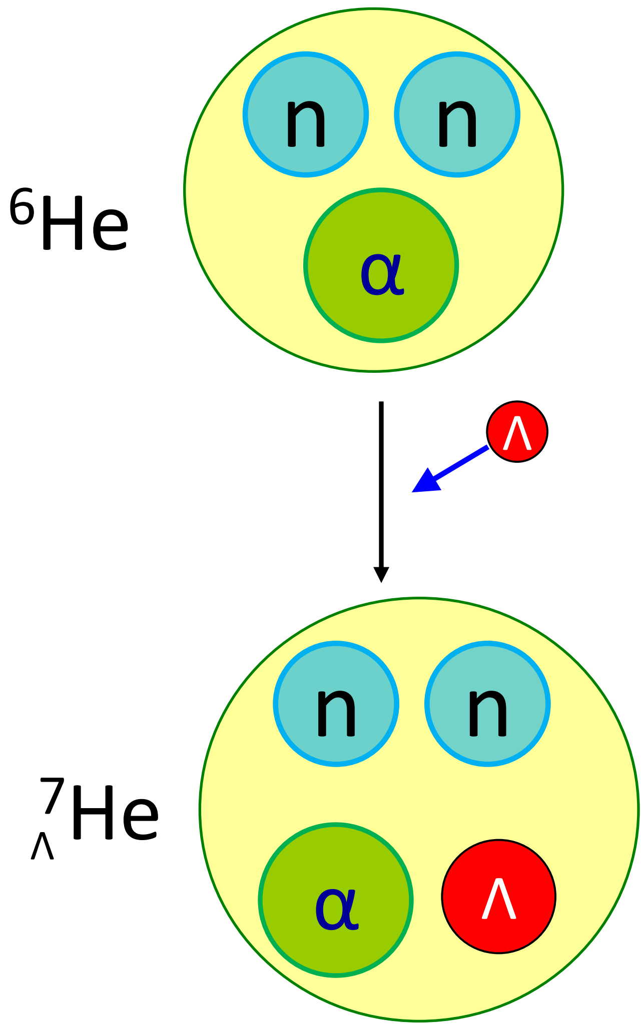


Or I hope to perform search experiment at GSI again in the Future.

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



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

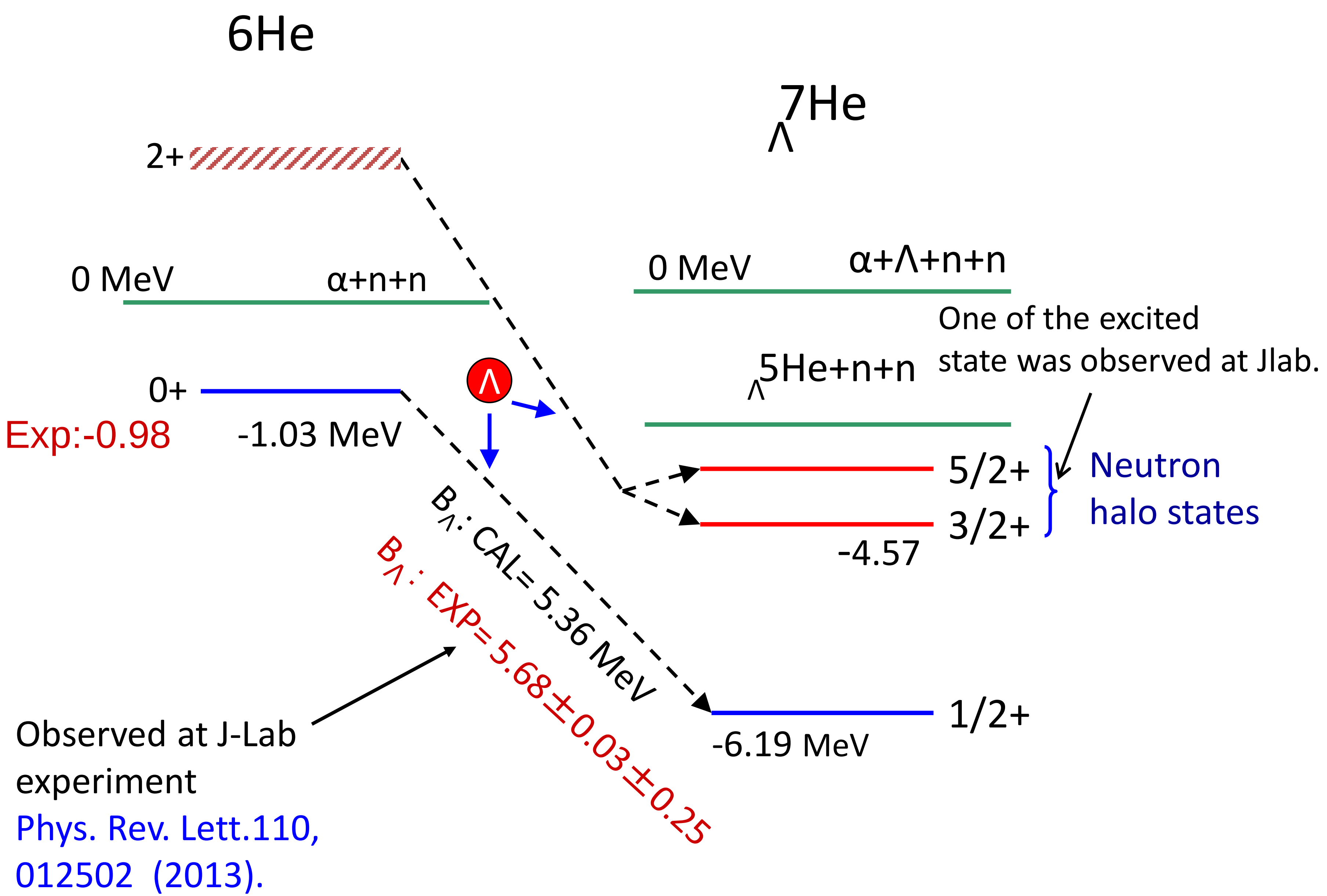


^{6}He : One of the lightest
n-rich nuclei

$^{7}_{\Lambda}$He: One of the lightest
n-rich hypernuclei

Observed at JLAB,
Phys. Rev. Lett. 110, 12502 (2013).

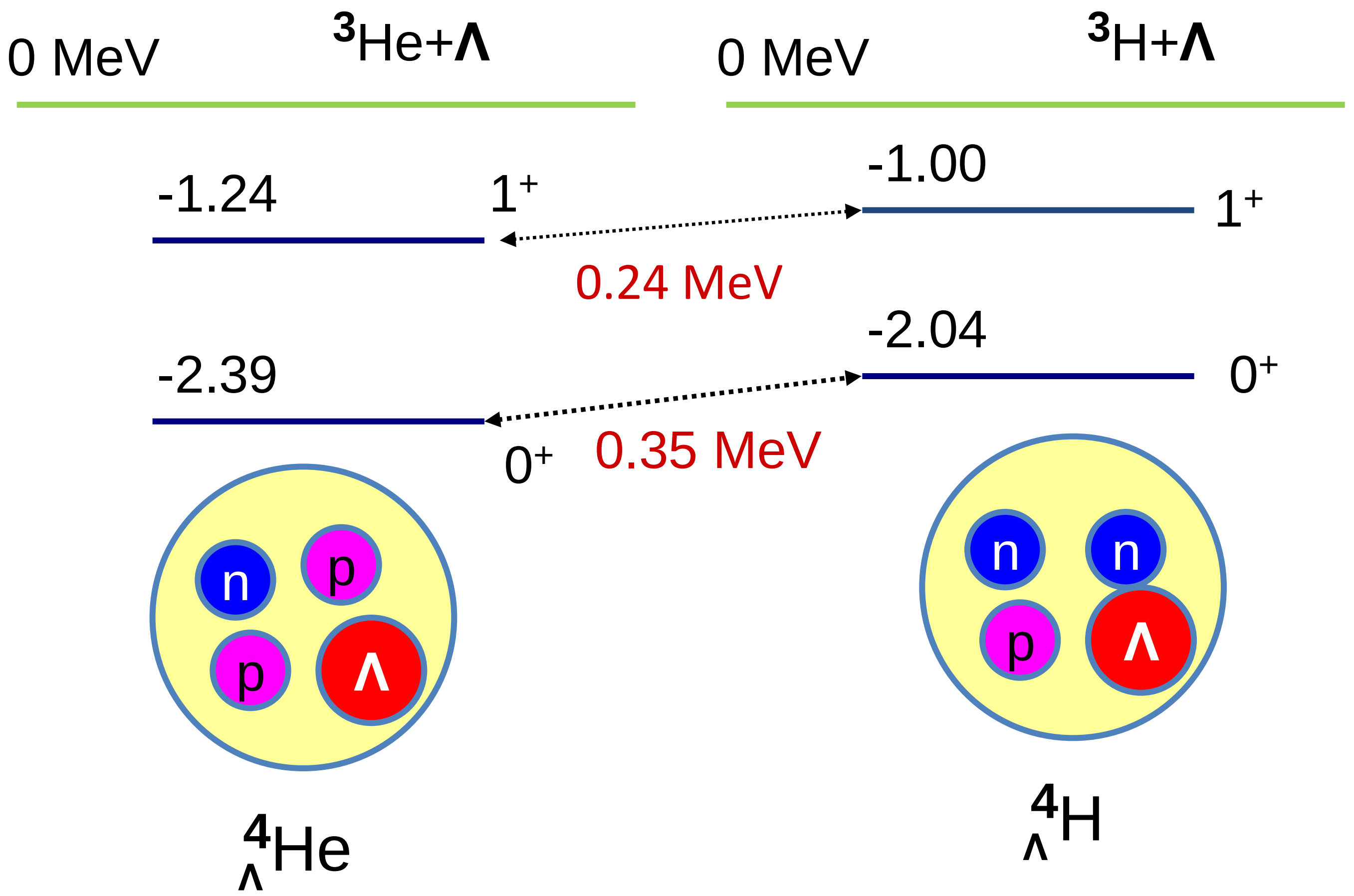
CAL: E. Hiyama et al., PRC 53, 2075 (1996), PRC 80, 054321 (2009)

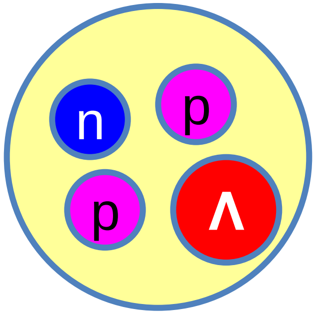


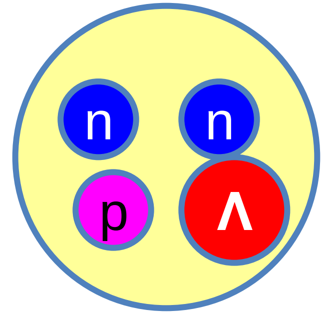
The ground state of $^{7}_{\Lambda}He$ is important to study of CSB interaction between Λn and Λp.

In S= -1 sector

Exp.





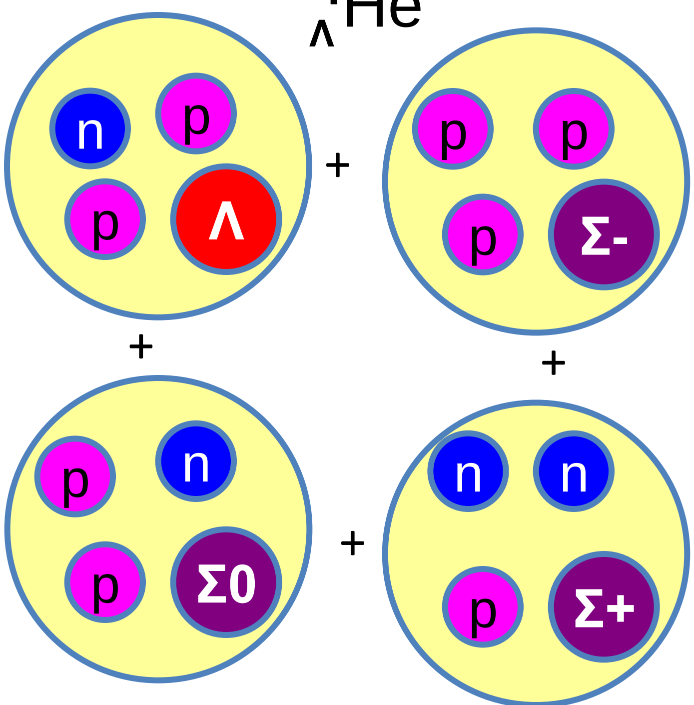


${}^{4}_{\Lambda}He$

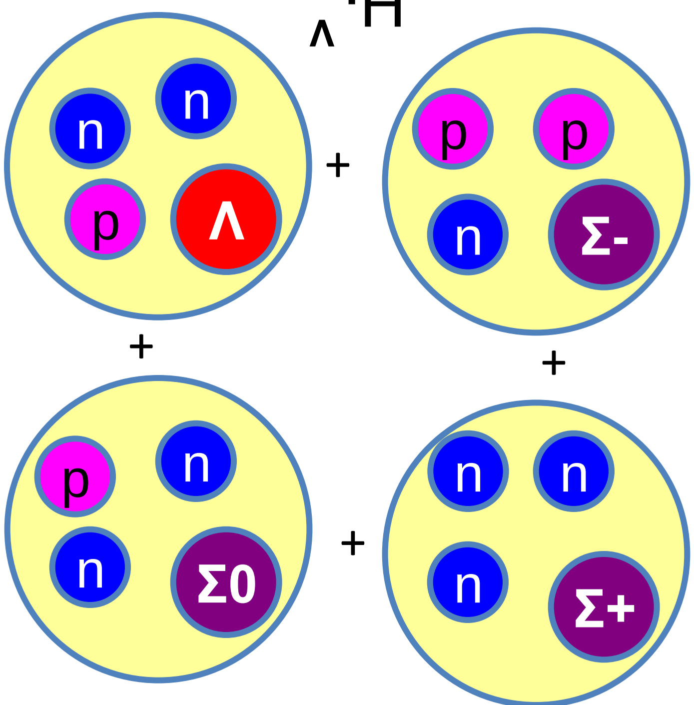
${}^{4}_{\Lambda}H$

However, Λ particle has no charge.

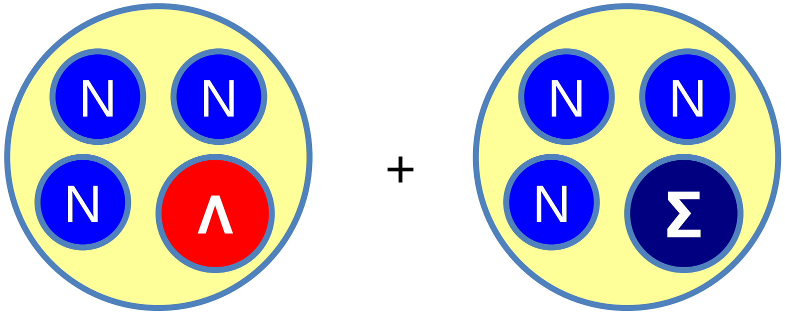
${}^{4}_{\Lambda}He$



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



In order to explain the energy difference, 0.35 MeV,



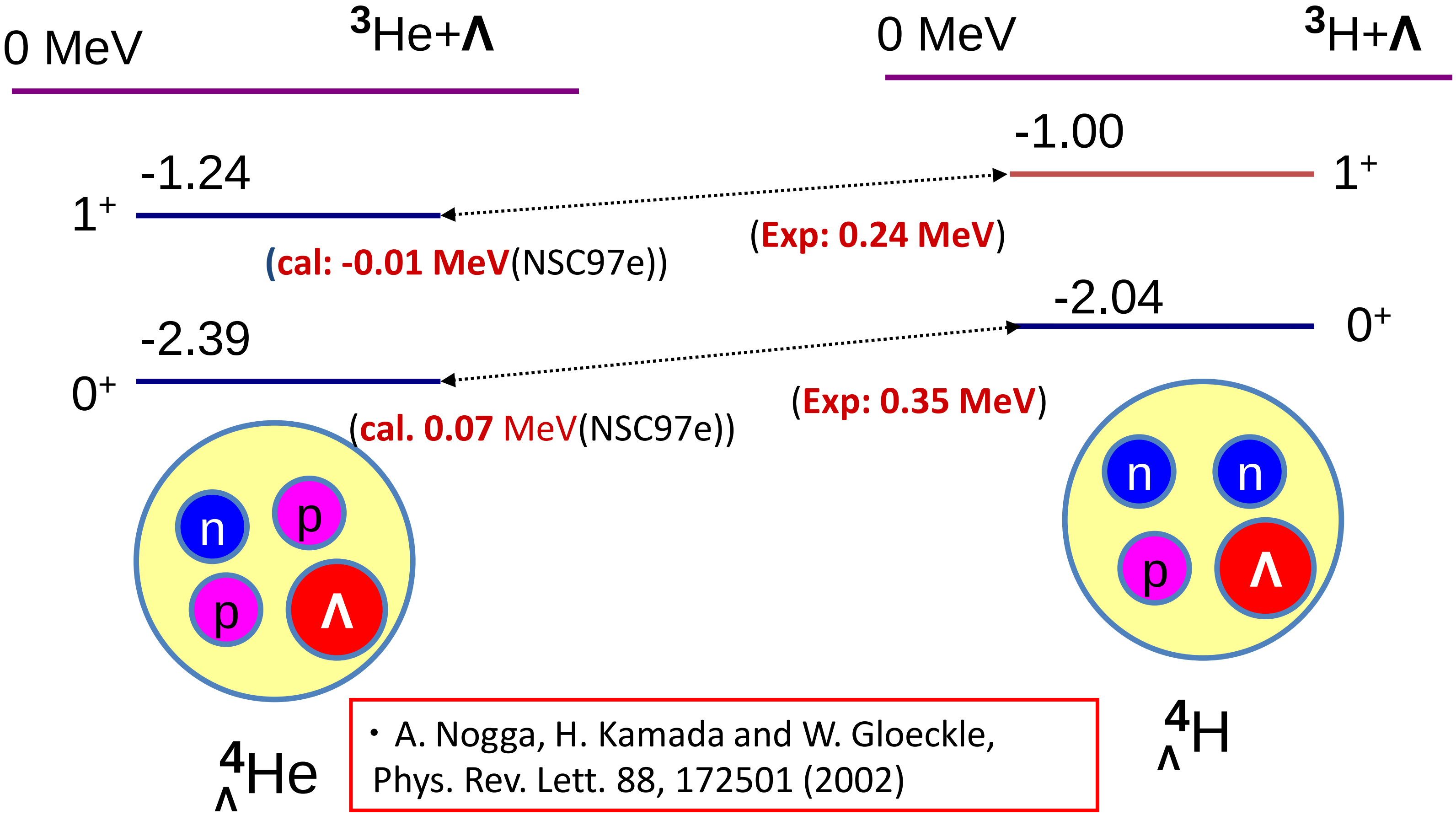
(3N+**Λ**)　　　　(3N+**Σ**)

- 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)

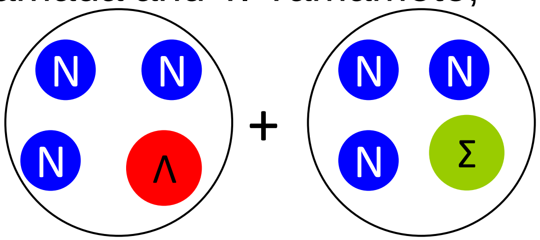
- H. Nemura. Y. Akaishi and Y. Suzuki, Phys. Rev. Lett.89, 142504 (2002).

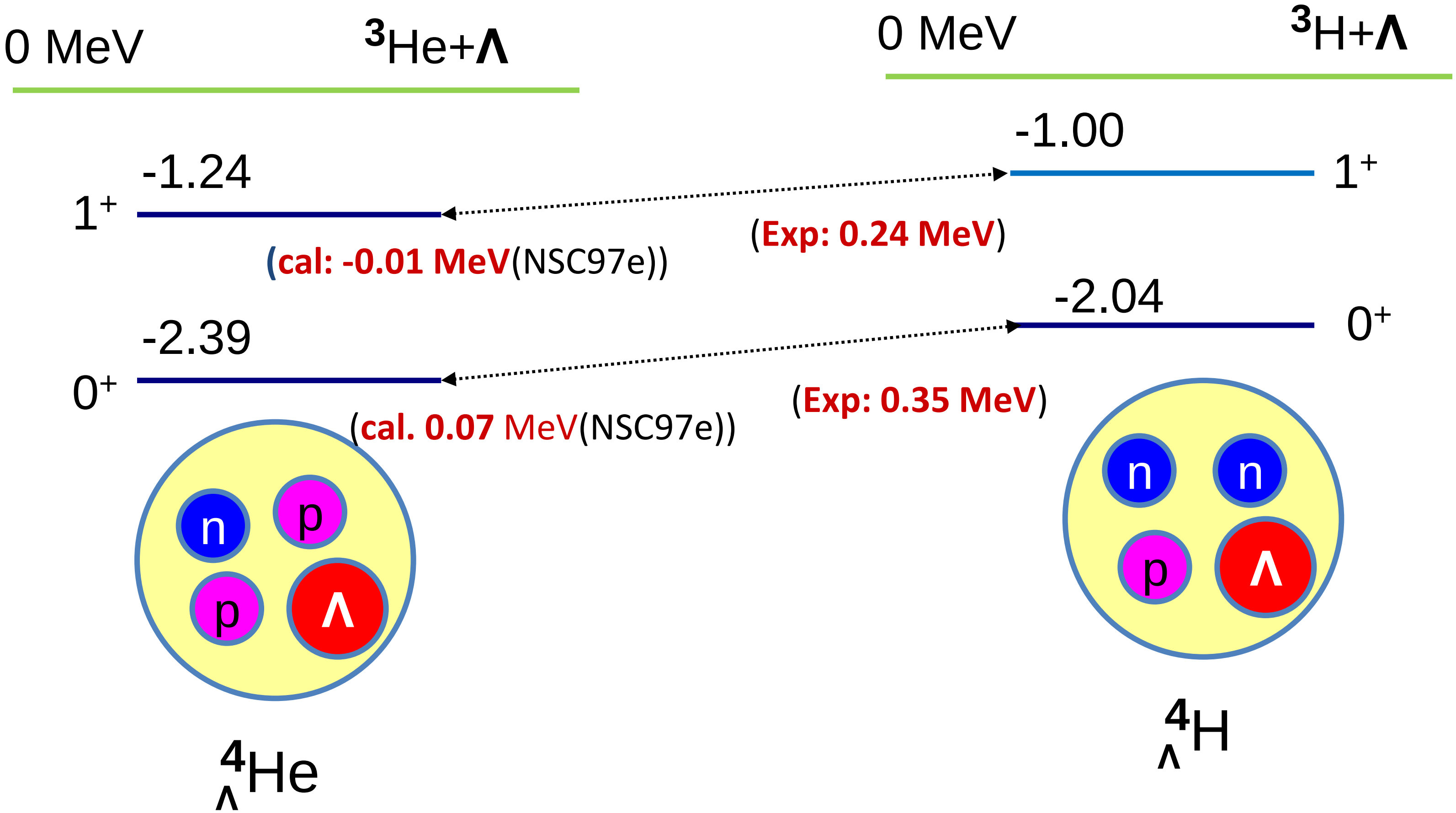
Coulomb potentials between charged particles (p, $\Sigma^{\pm}$) are included.



- 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).





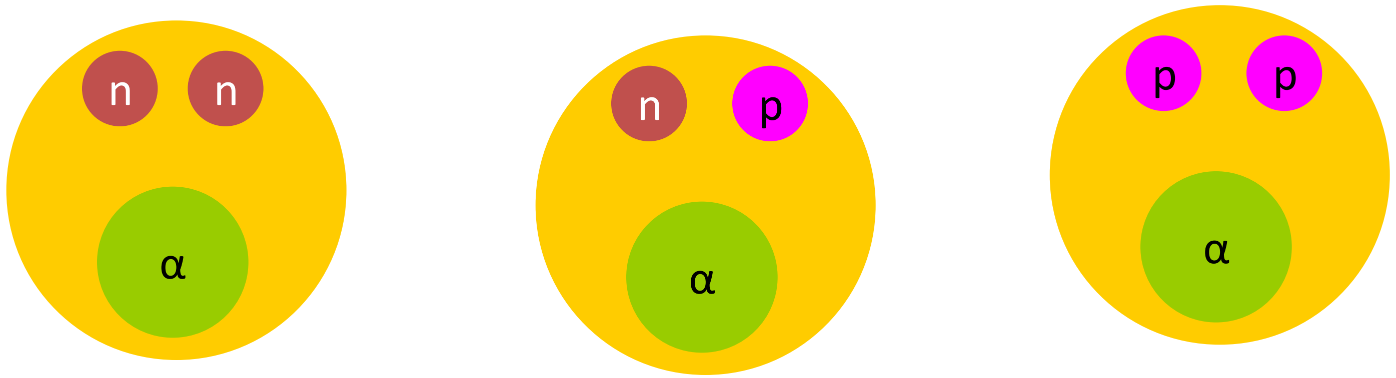
There exist NO YN interaction to reproduce the data.

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

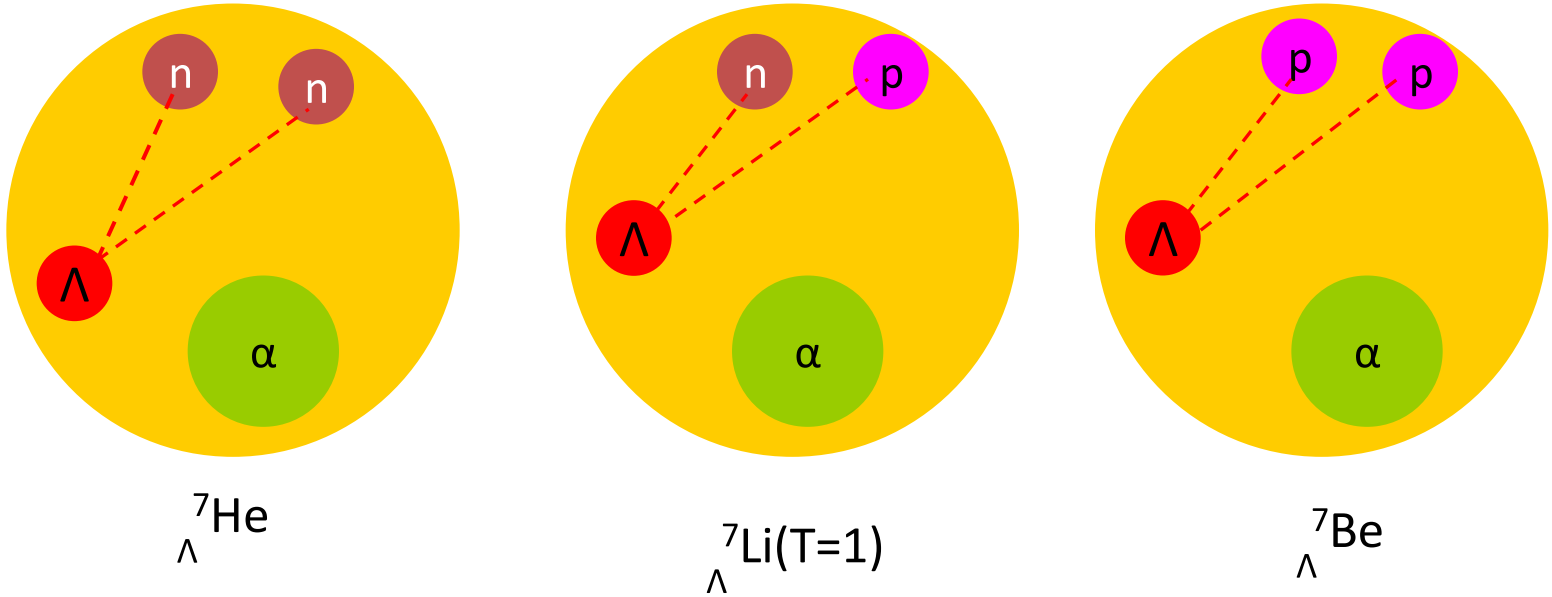
It is interesting to investigate the charge symmetry breaking effect in p-shell Λ hypernuclei as well as s-shell Λ hypernuclei.

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

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

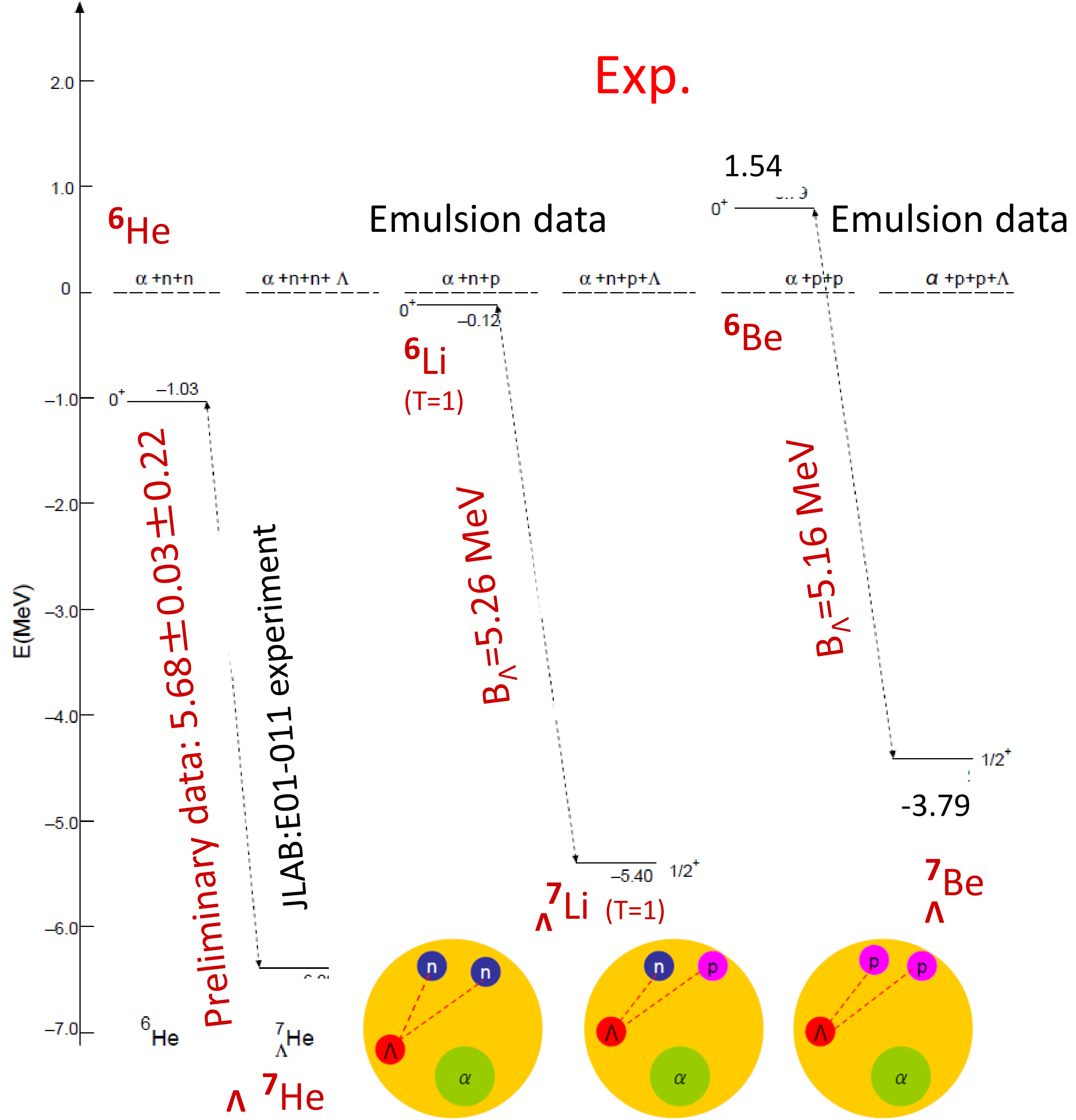


^{6}He ^{6}Li(T=1) ^{6}Be



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.

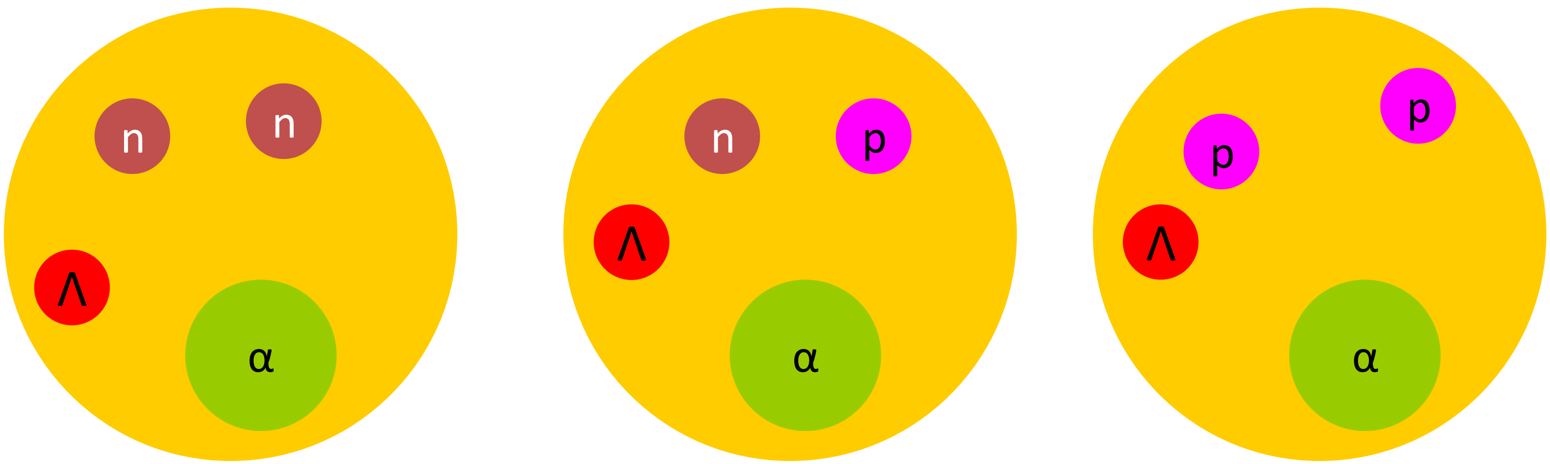


Exp.
Emulsion data
Emulsion data
E(MeV)
2.0
1.0
0
−1.0
−2.0
−3.0
−4.0
−5.0
−6.0
−7.0
6He
α +n+n
α +n+n+ Λ
α +n+p
α +n+p+Λ
α +p+p
α +p+p+Λ
0+
−1.03
0+
−0.12
6Li
(T=1)
1.54
0+
6Be
Preliminary data: 5.68±0.03±0.22
JLAB:E01-011 experiment
B_Λ=5.26 MeV
B_Λ=5.16 MeV
1/2+
-3.79
−5.40
1/2+
Λ7Li (T=1)
Λ7Be
6He
Λ7He
Λ7He
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.



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

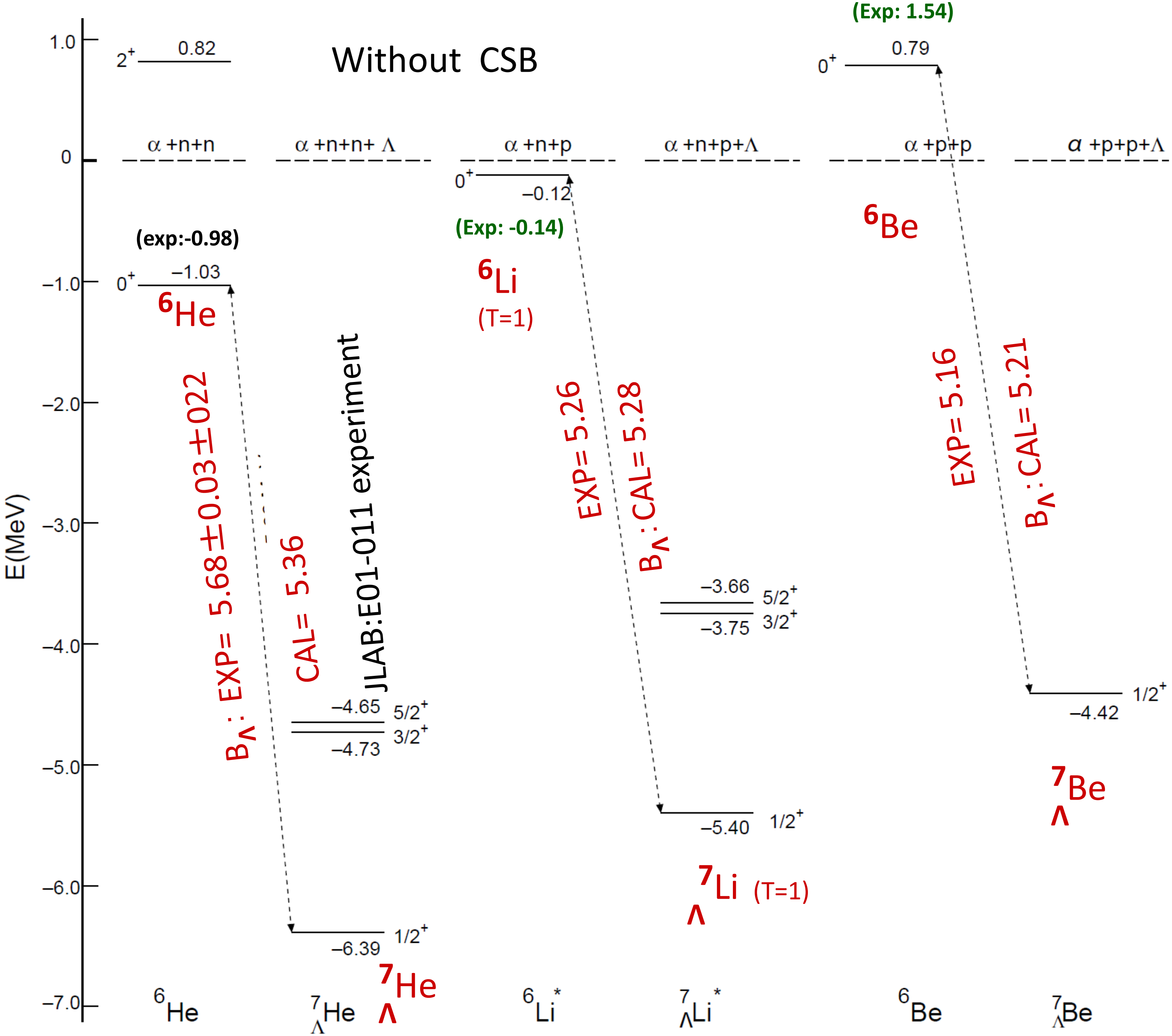
For this purpose, we study structure of A=7 hypernuclei within the framework of α+Λ+N+N 4-body model.

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

Now, it is interesting to see as follows:

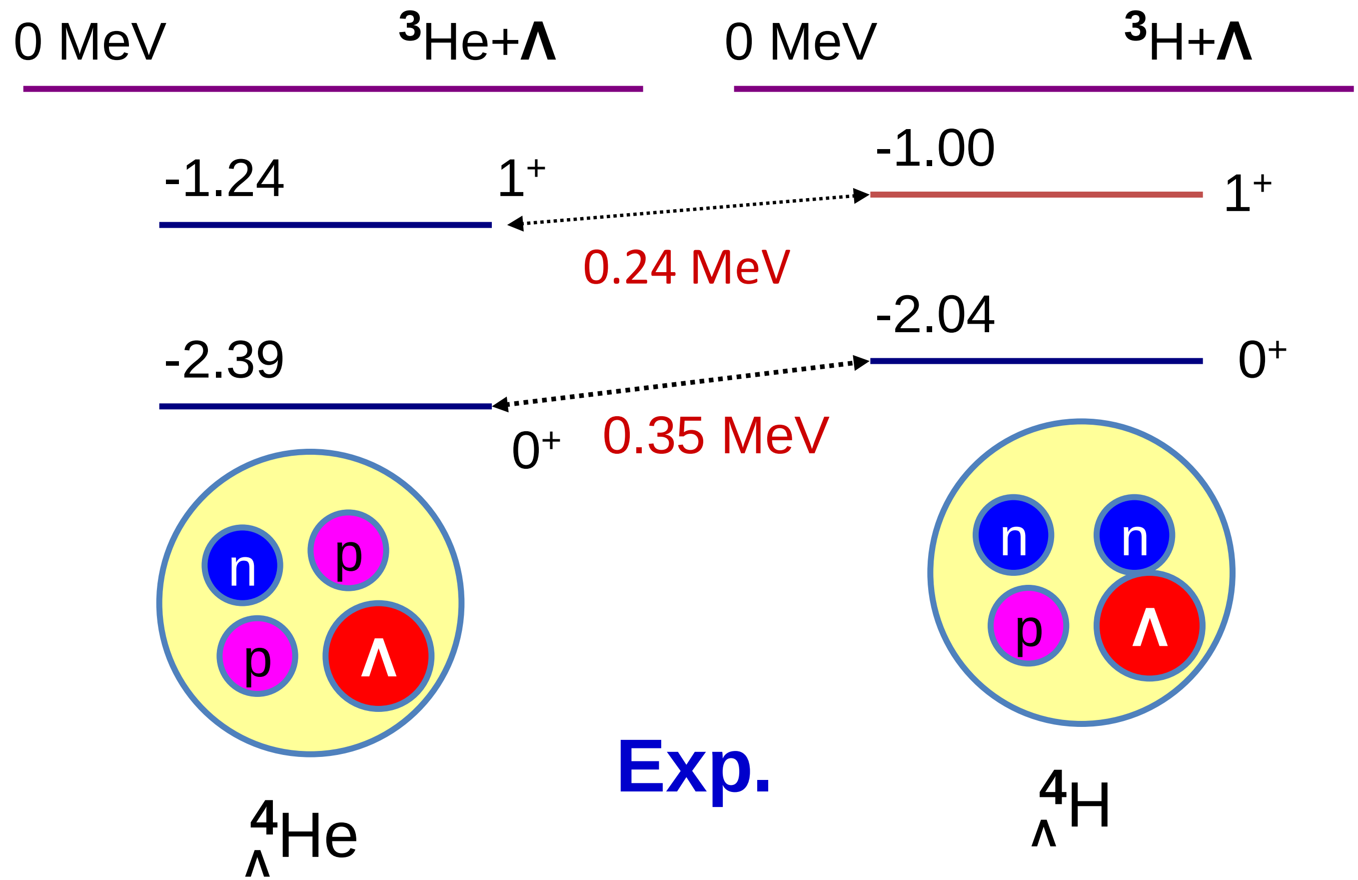
(1)What is the level structure of A=7 hypernuclei
without CSB interaction?

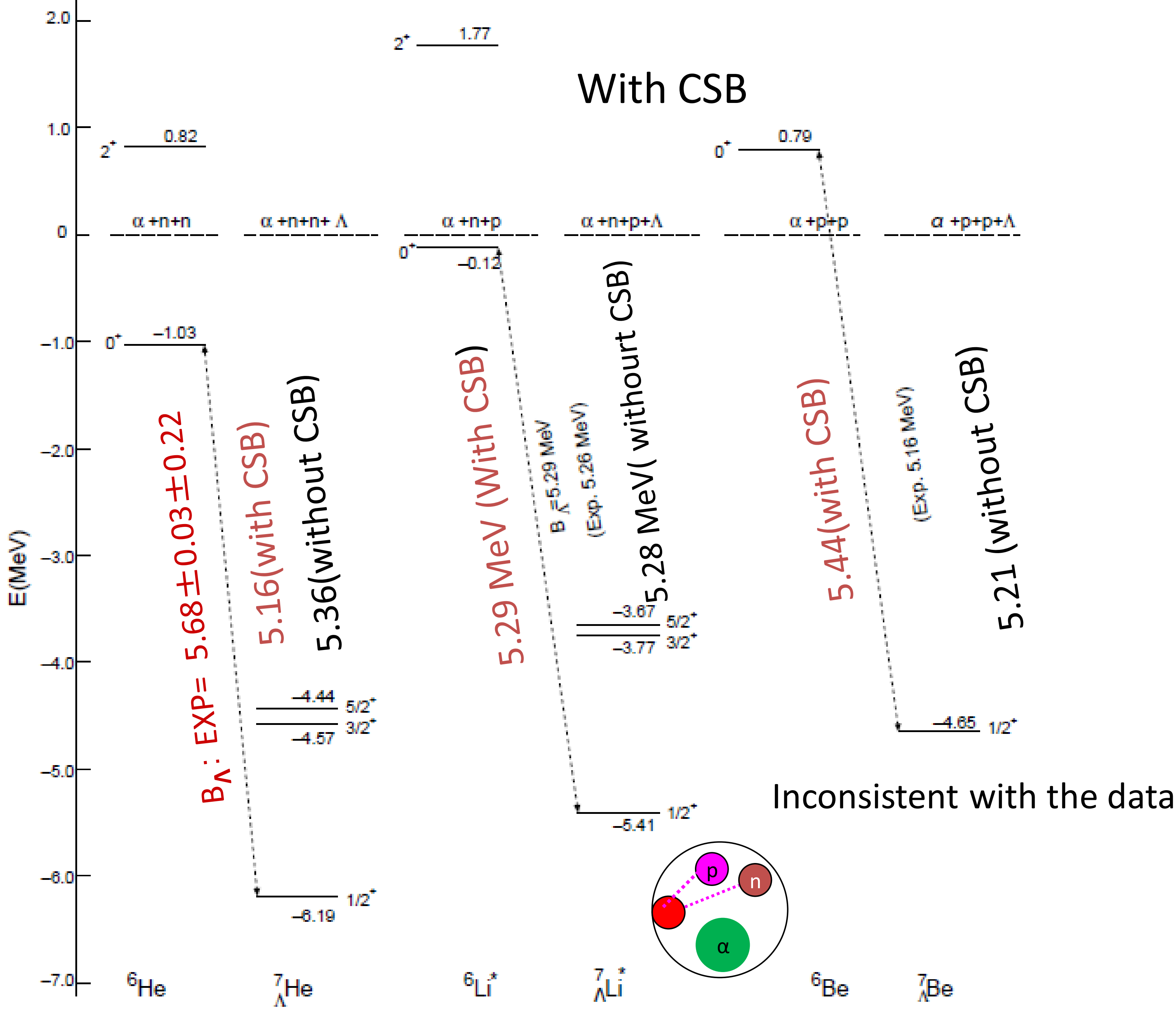
(2) What is the level structure of A=7 hypernuclei
with CSB interaction?

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

$$V_{\Lambda N}^{\mathrm{CSB}}(r) = -\frac{\tau_z}{2}\left[\frac{1+P_r}{2}\left(v_0^{\mathrm{even,CSB}} + \boldsymbol{\sigma}_\Lambda \cdot \boldsymbol{\sigma}_N v_{\sigma_\Lambda \cdot \sigma_N}^{\mathrm{even,CSB}}\right) e^{-\beta_{\mathrm{even}} r^2} + \frac{1-P_r}{2}\left(v_0^{\mathrm{odd,CSB}} + \boldsymbol{\sigma}_\Lambda \cdot \boldsymbol{\sigma}_N v_{\sigma_\Lambda \cdot \sigma_N}^{\mathrm{odd,CSB}}\right) e^{-\beta_{\mathrm{odd}} r^2}\right], \quad (3.3)$$

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

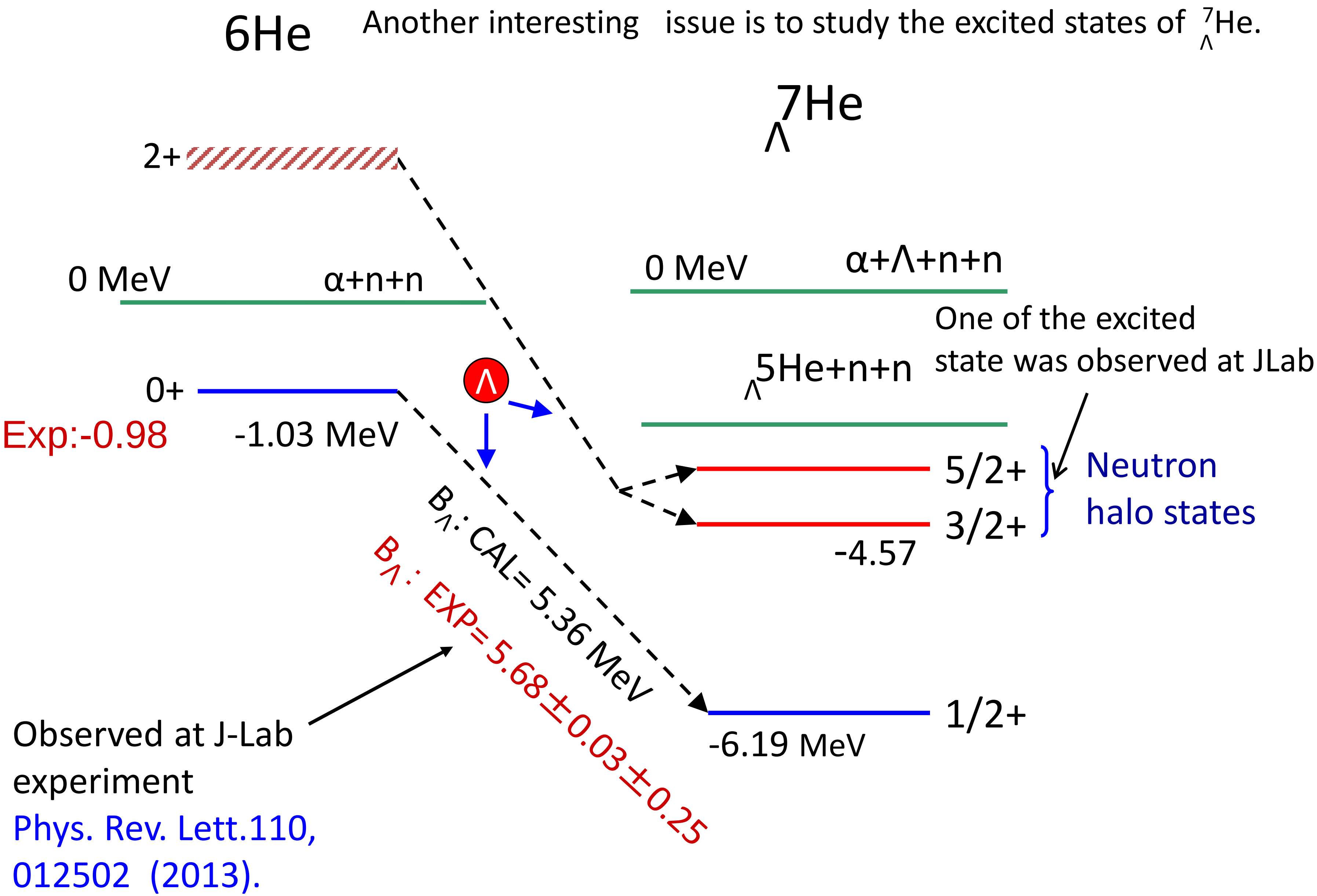




With CSB
E(MeV)
2.0
1.0
0
−1.0
−2.0
−3.0
−4.0
−5.0
−6.0
−7.0
2+ 0.82
α +n+n
0+ −1.03
α +n+n+ Λ
5/2+ −4.44
3/2+ −4.57
1/2+ −6.19
2+ 1.77
α +n+p
0+ −0.12
α +n+p+Λ
5/2+ −3.67
3/2+ −3.77
1/2+ −5.41
0+ 0.79
α +p+p
α +p+p+Λ
1/2+ −4.65
BΛ: EXP= 5.68±0.03±0.22
5.16(with CSB)
5.36(without CSB)
5.29 MeV (With CSB)
BΛ=5.29 MeV
(Exp. 5.26 MeV)
5.28 MeV(withourt CSB)
5.44(with CSB)
(Exp. 5.16 MeV)
5.21 (without CSB)
Inconsistent with the data
p
n
α
6He
7ΛHe
6Li*
7ΛLi*
6Be
7ΛBe

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

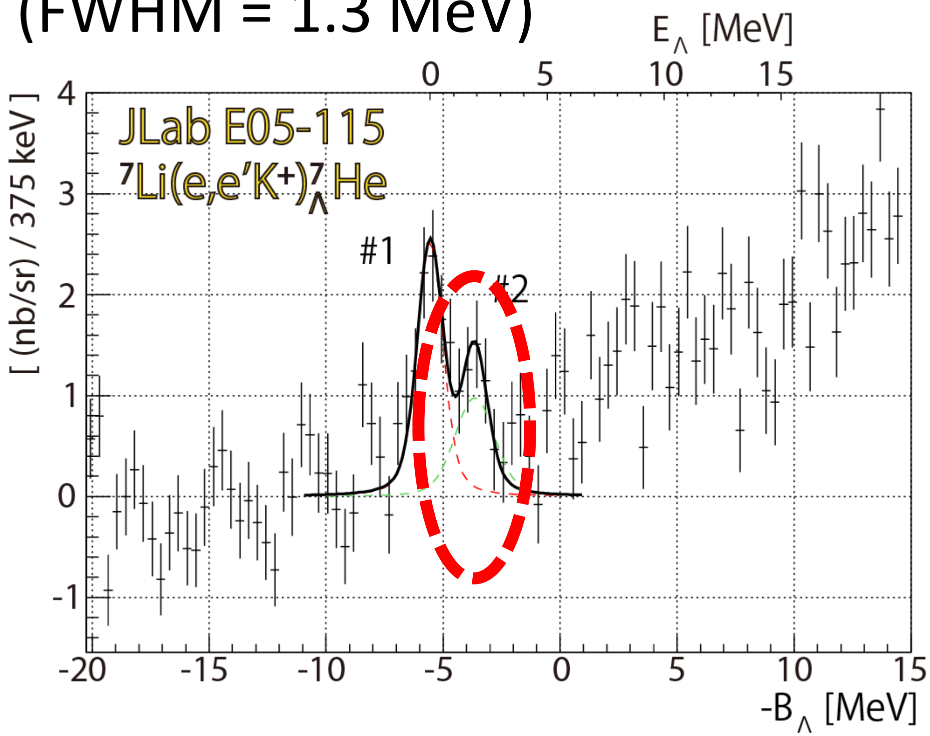
Another interesting issue is to study the excited states of ${}^{7}_{\Lambda}$He.



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

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.

(FWHM = 1.3 MeV)



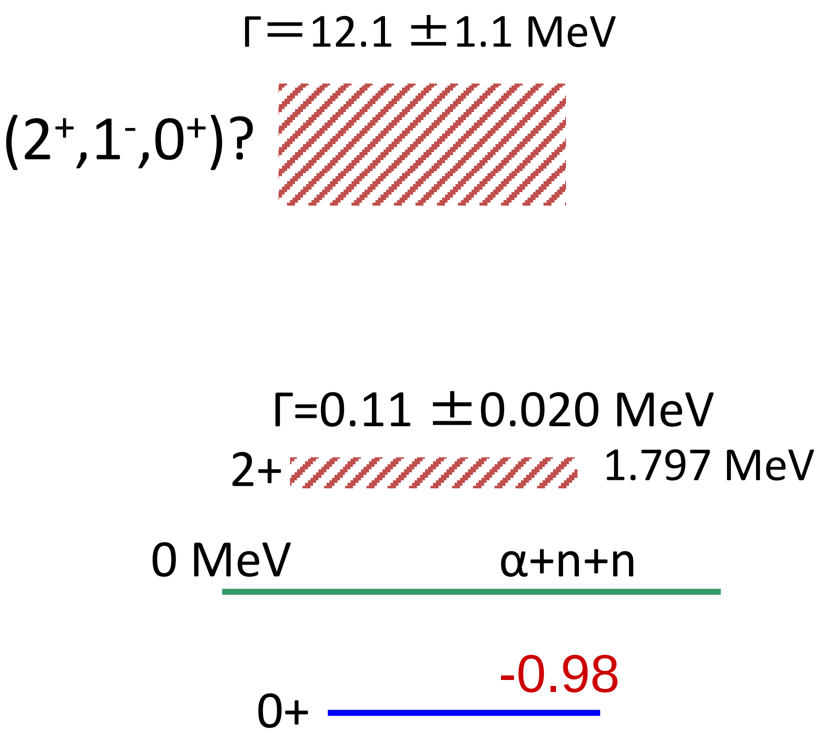
Fitting results

Peak number	State $^{6}He[J_C] \otimes j^{\Lambda}$	Number of events	$-B_{\Lambda}$ [MeV] (E_{Λ})	$\overline{\left(\frac{d\sigma}{d\Omega_K}\right)}\Big\|_{1^\circ-13^\circ}$ [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?

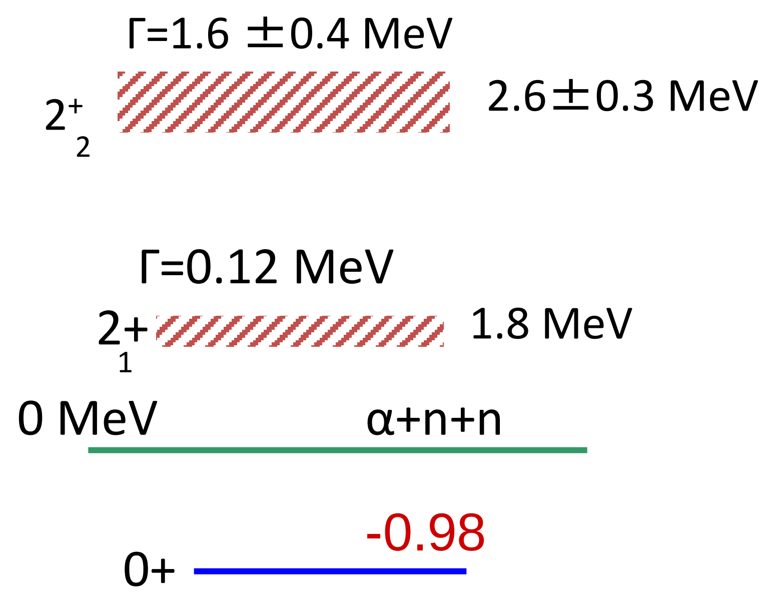
First, let us discuss about energy spectra of ^{6}He core nucleus.



^{6}He

Exp.

Data in 2002



^{6}He

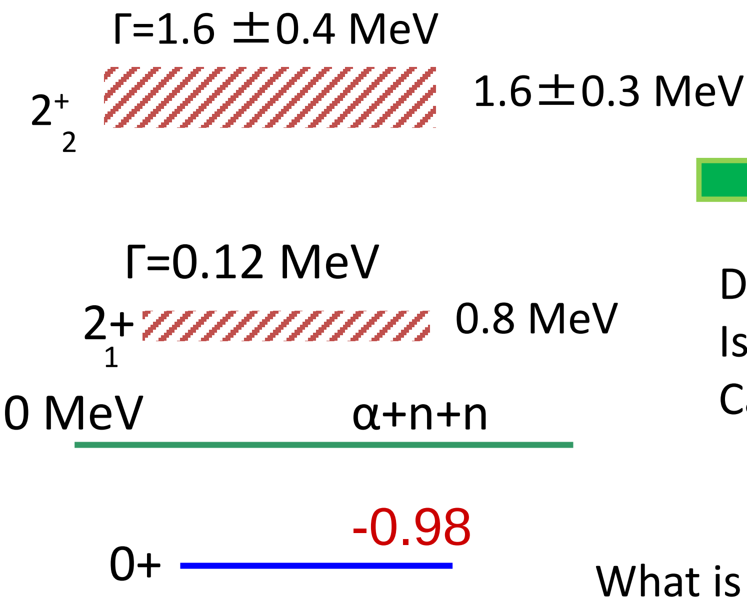
Exp.

Data in 2012

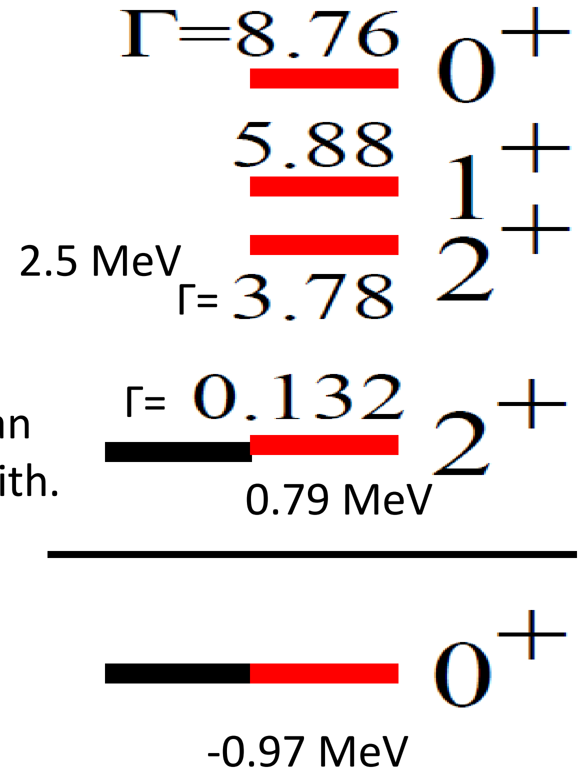
X. Mougeot et al., Phys. Lett. B 718 (2012) 441. p(^{8}He, t)^{6}He

Core nucleus

How about theoretical result?



Decay with
Is smaller than
Calculated with.



What is my result?

^{6}He

theory

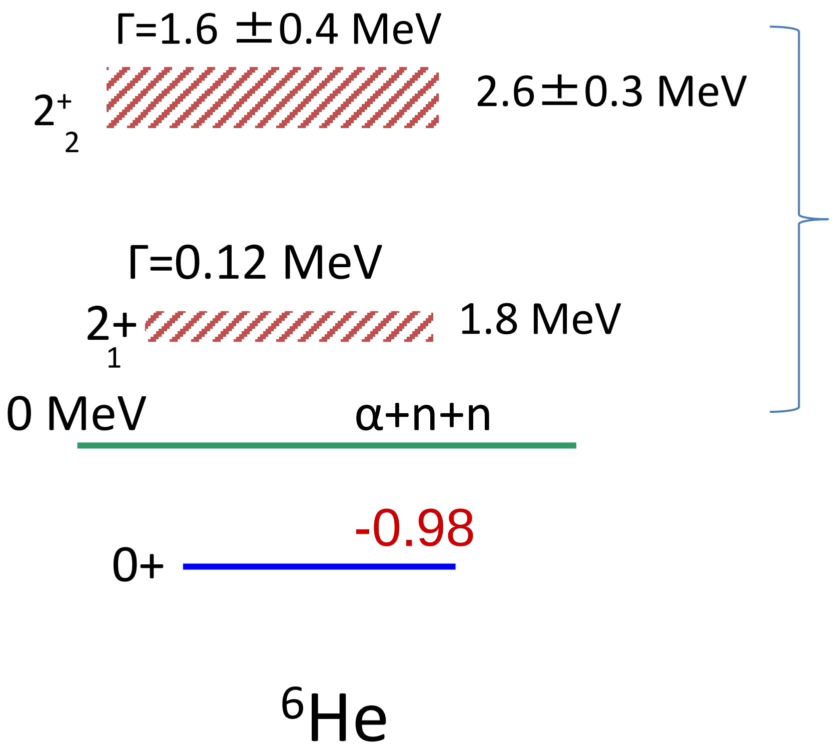
Exp.

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

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

^{6}He

Question: What are theoretical results?



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.

Exp.

Data in 2012

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

The Hamiltonian for ^{6}He is written as

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

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

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

Complex scaling is defined by the following transformation.

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

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

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

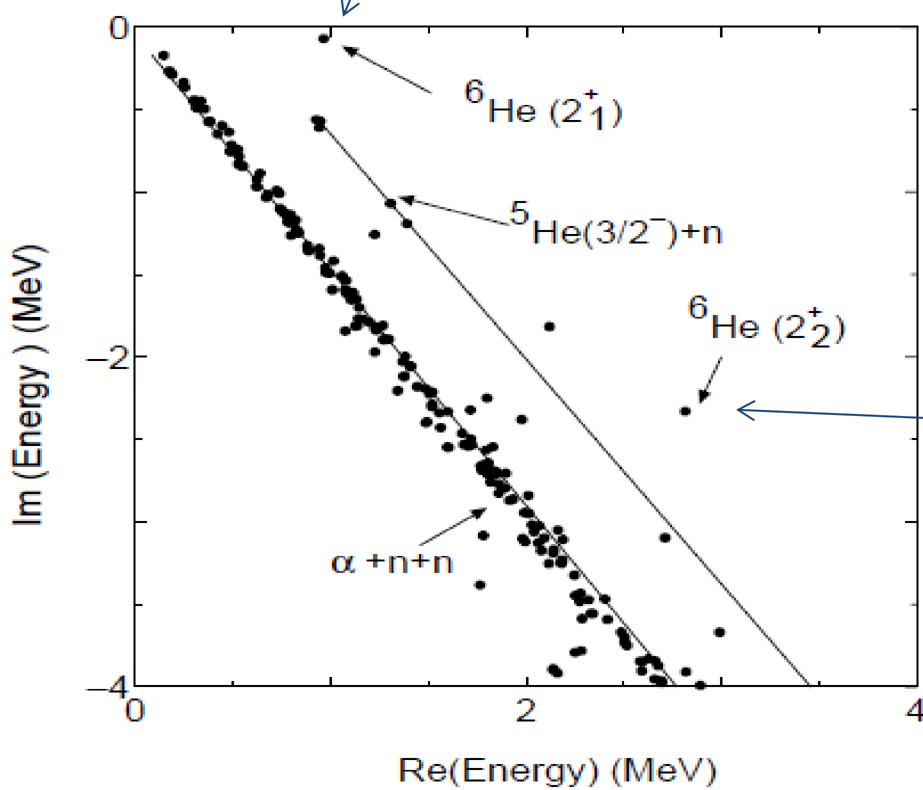
As a result, I should solve this Schroediner equation.

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

$E = E_r + i\Gamma/2$

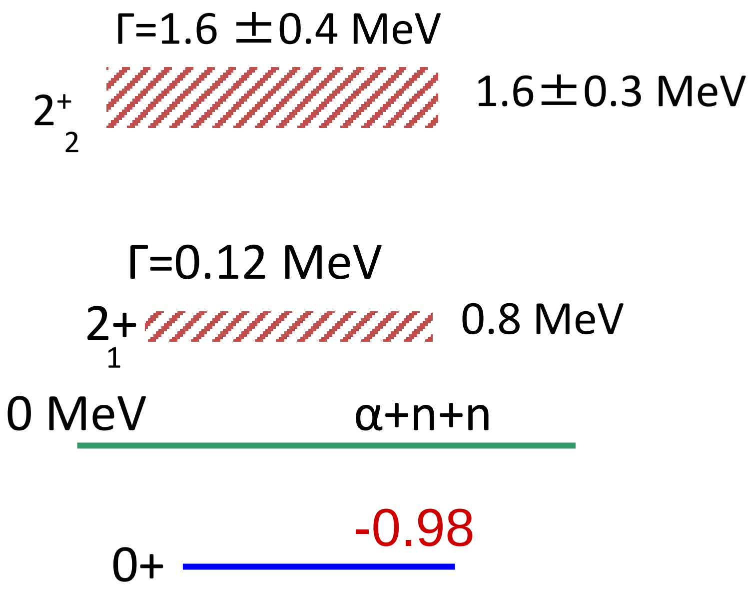
My result

E=0.96 + 0.14 MeV



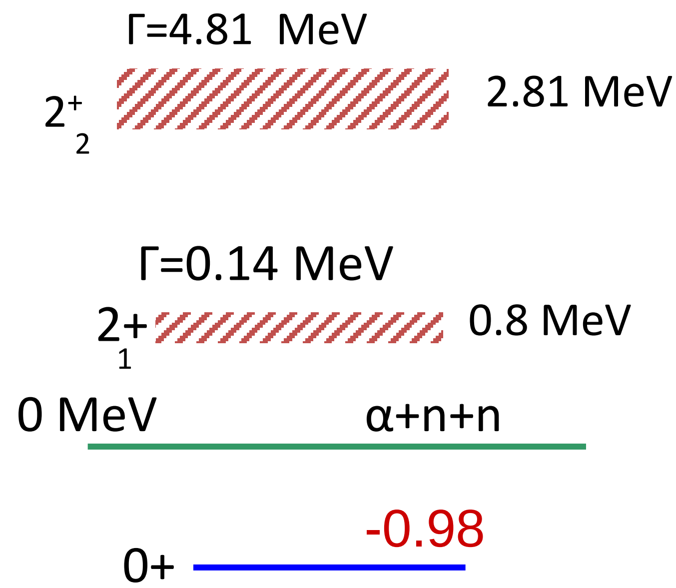
E=2.81 +4.81 MeV

Question: What are theoretical results?



^{6}He

Exp.

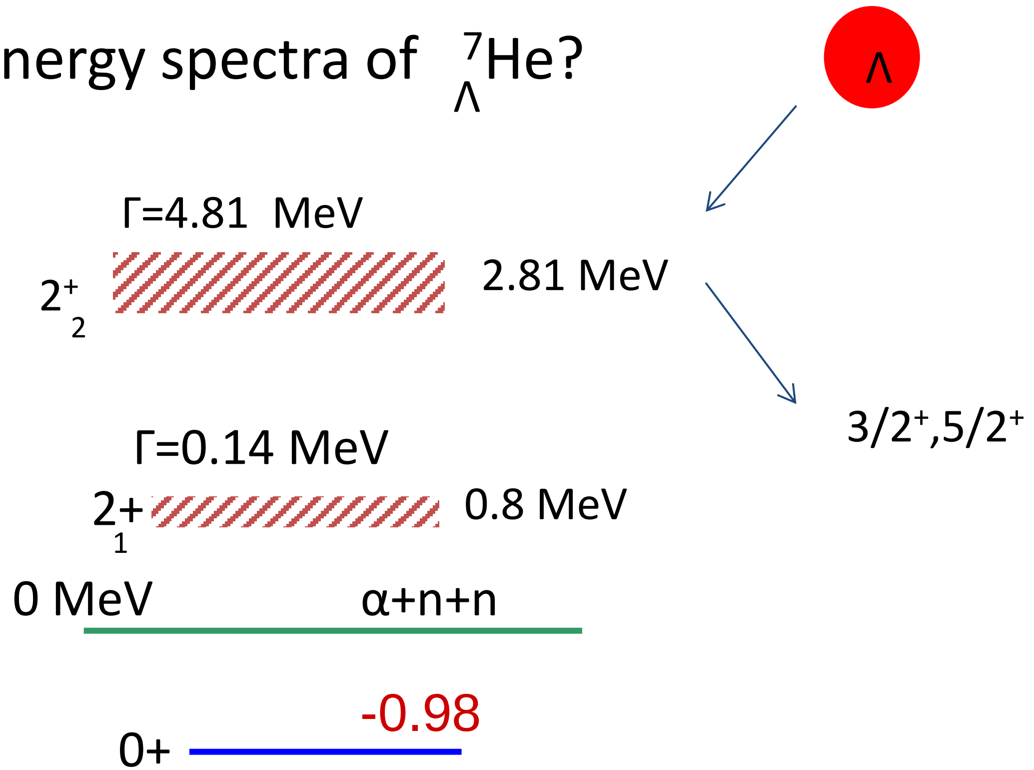


^{6}He

Cal.

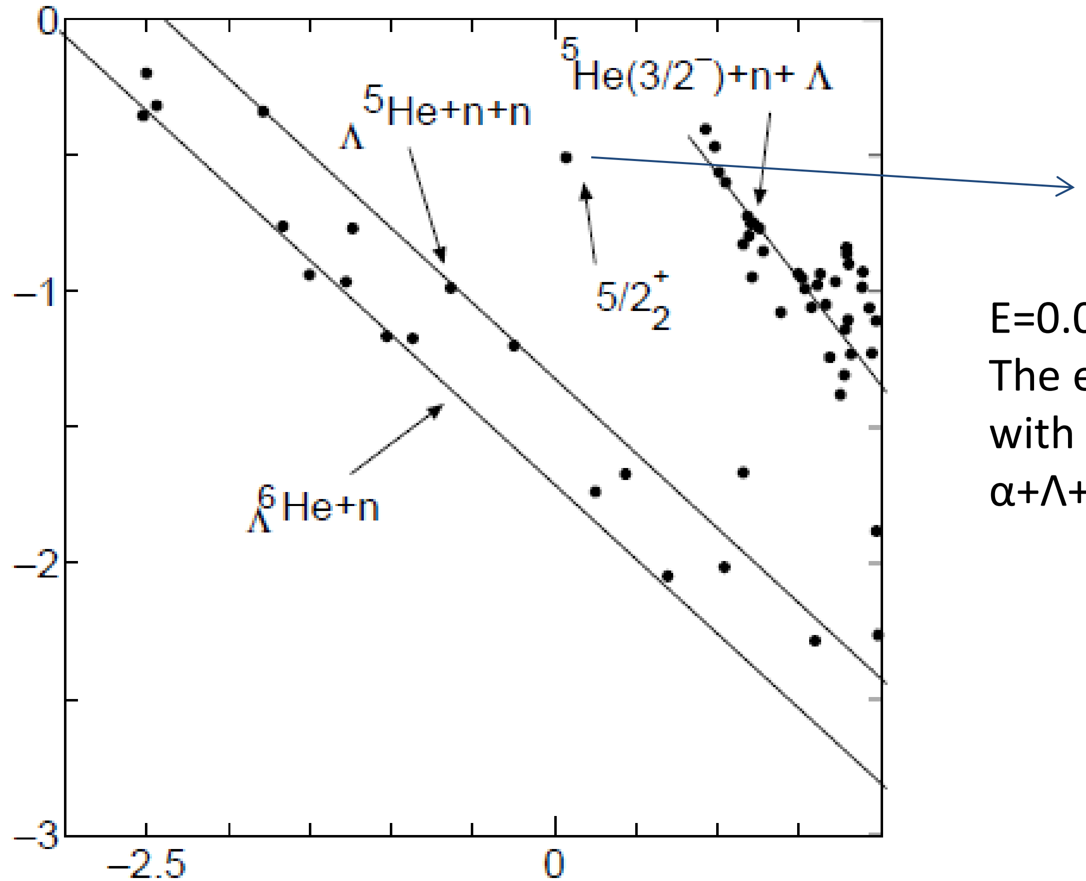
Data in 2012
X. Mougeot et al., Phys. Lett. B 718 (2012) 441. p(^{8}He, t)^{6}He

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

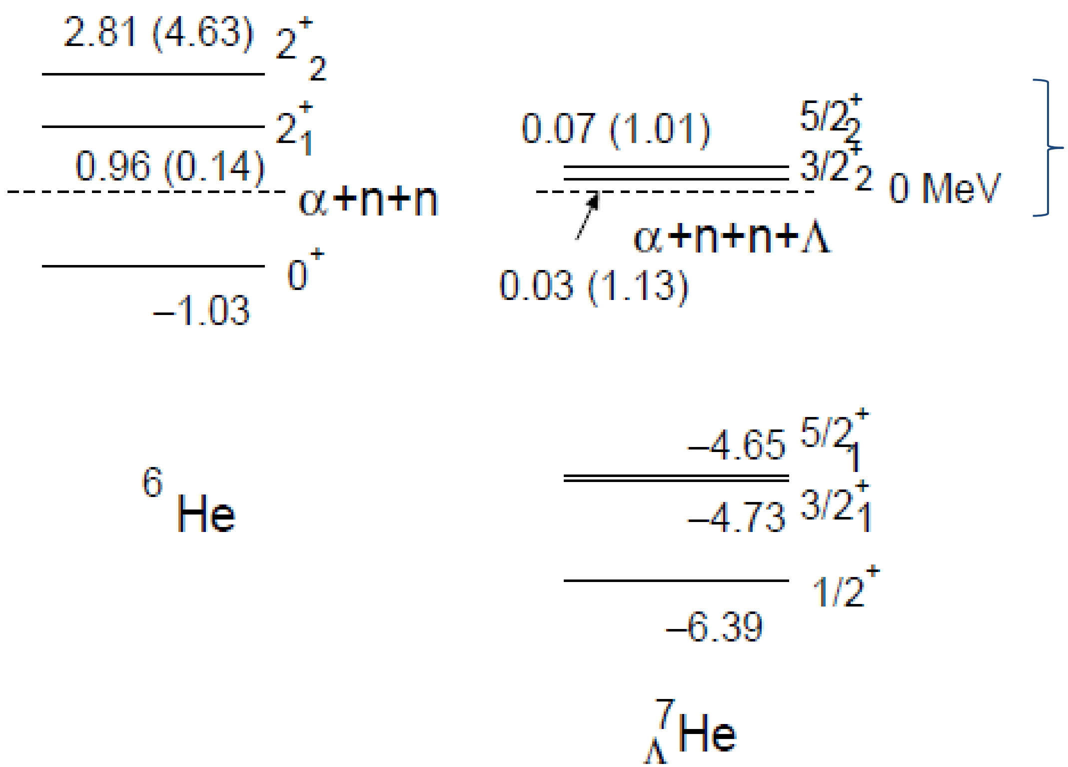


^{6}He

Cal.



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



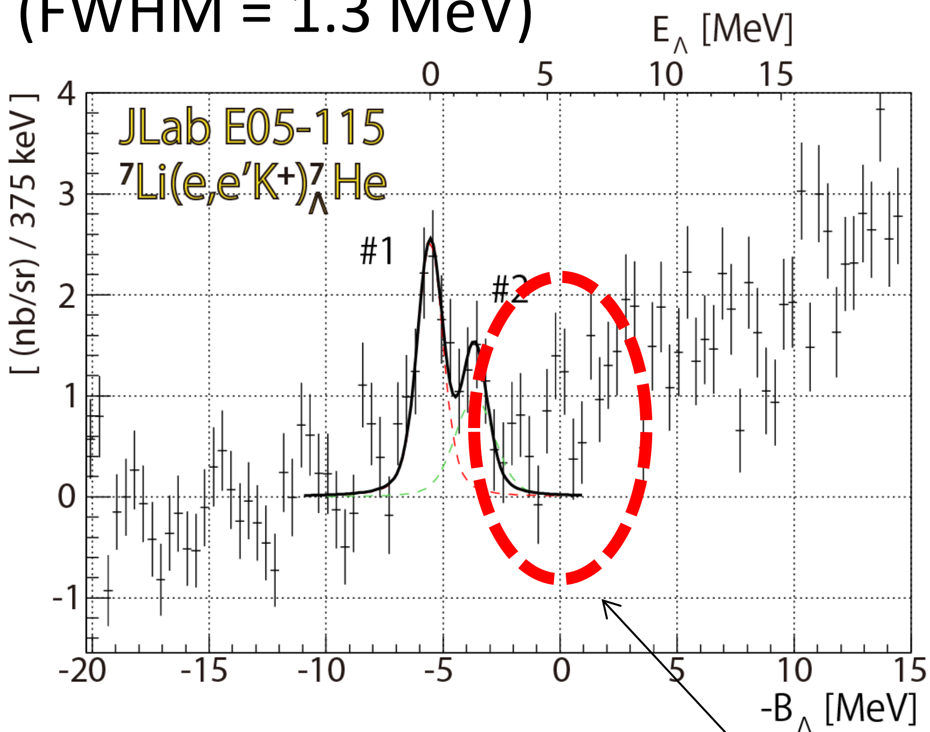
I propose to
The experimentalists to
observe these states.

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

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

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.

(FWHM = 1.3 MeV)



Fitting results

Peak number	State $^{6}He[J_C] \otimes j^{\Lambda}$	Number of events	$-B_{\Lambda}$ [MeV] (E_{Λ})	$\left(\frac{d\sigma}{d\Omega_K}\right)\Big\vert_{1^\circ-13^\circ}$ [nb/sr]
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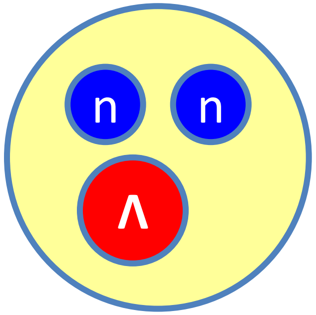
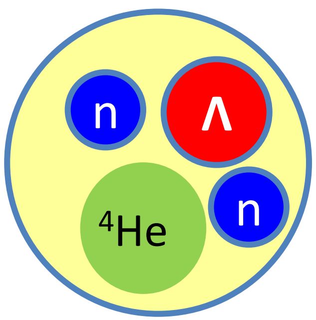
Good agreement with my prediction

Summary



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

(1) Using realistic YN and NN interaction which reproduce data of A=3 and 4 nuclei and hypernuclei, I could not find any possibility to make a bound state in nnΛ. I hope to perform search experiment of nnΛ at JLab.



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

(2) Motivated by observation of second 2^{+} state of ^{6}He, I expect to have the corresponding states in $^{7}_{\Lambda}He$. In the future, I hope to observe these states at JLab. For this purpose, I should calculate reaction cross section with Motoba san's help.