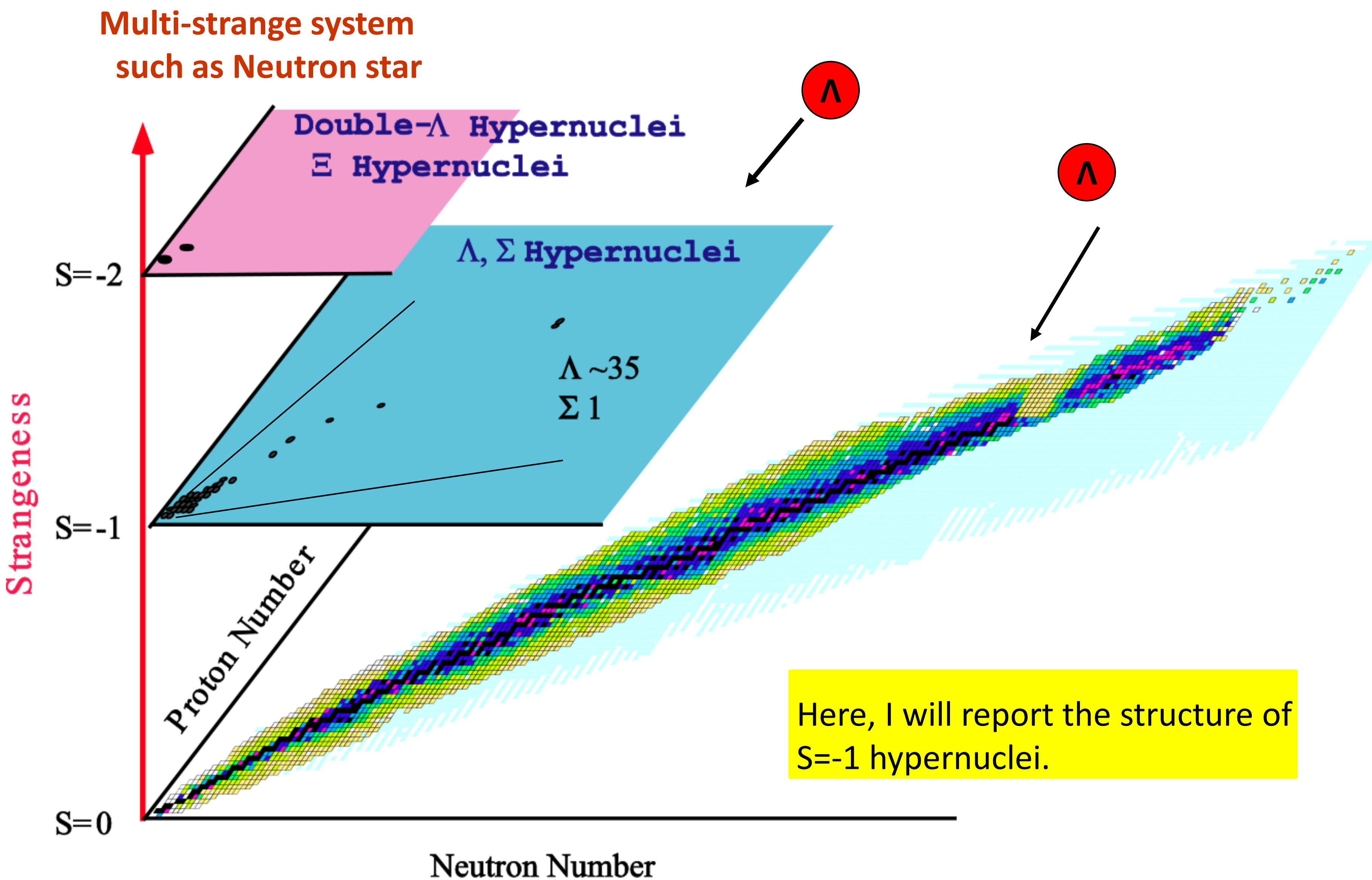
Structure of neutron-rich Λ hypernuclei

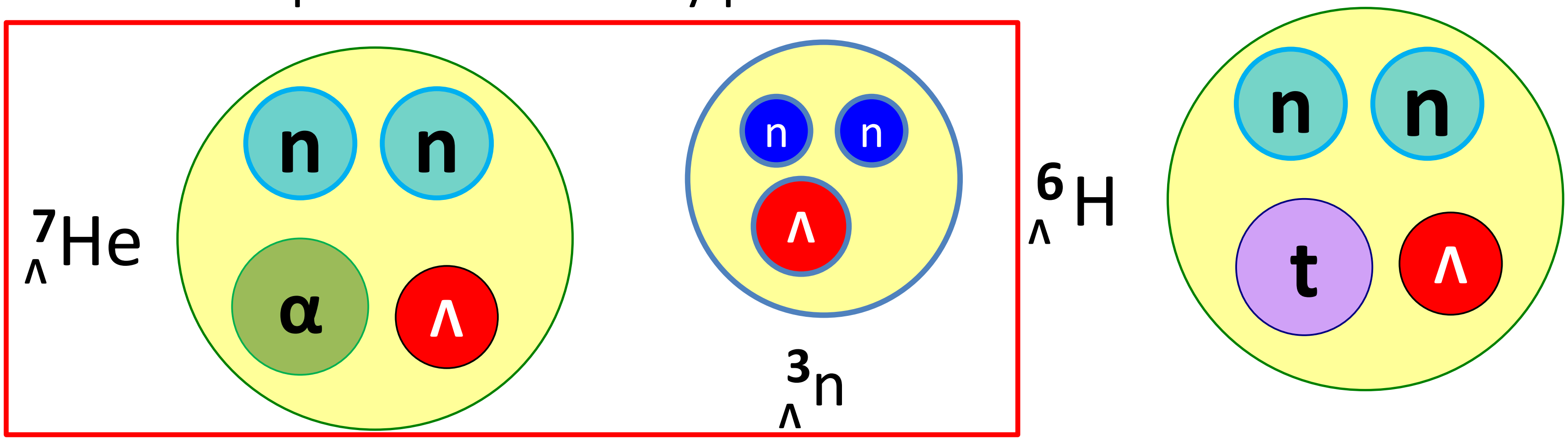
E. Hiyama (RIKEN)

Nuclear chart with strangeness



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.



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

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

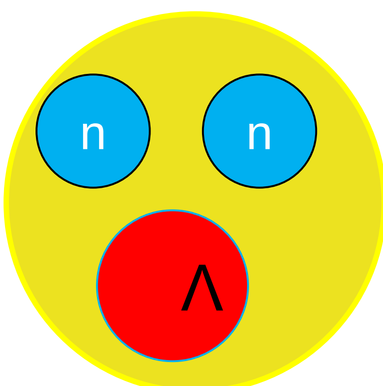
FINUDA collaboration & A. Gal,
Phys. Rev. Lett. **108**,
042051 (2012).

Observation of Neutron-rich Λ-hypernuclei

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

Section 2

three-body calculation of ${}^{3}_{\Lambda}n$



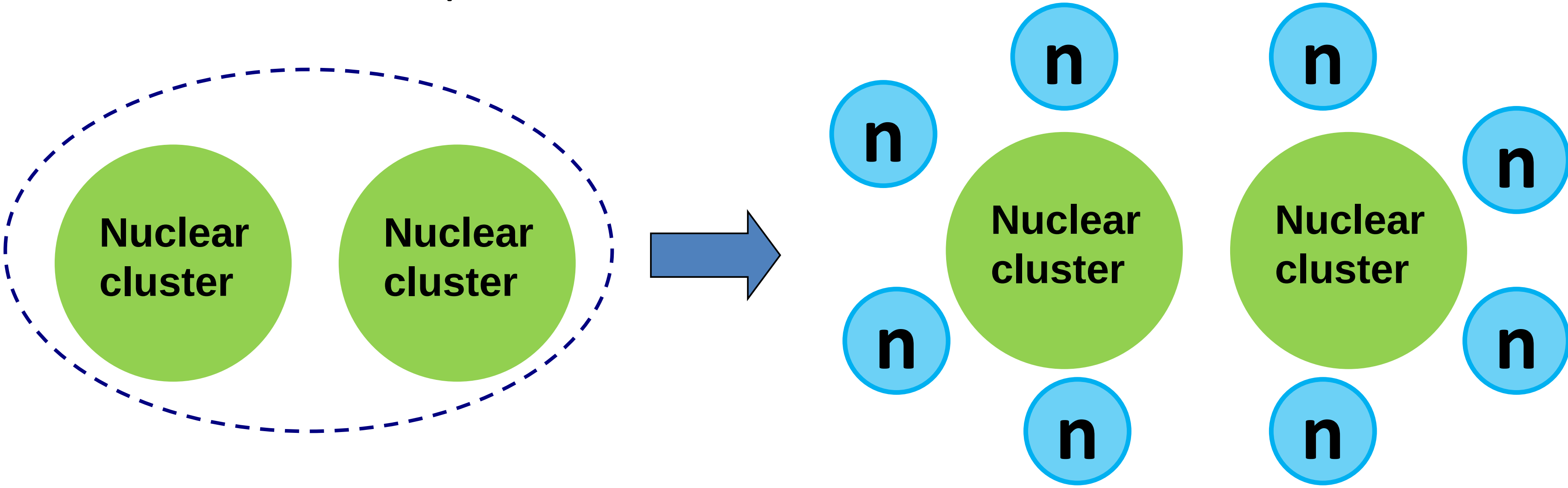
E. Hiyama, S. Ohnishi,
B.F. Gibson, and T. A. Rijken,
PRC89, 061302(R) (2014).

Why is it interesting to study neutron-rich Λ hypernucleus such as nnΛ?

One of major goals in hypernuclear physics

To study the structure of multi-strange systems

In neutron-rich and proton-rich nuclei,

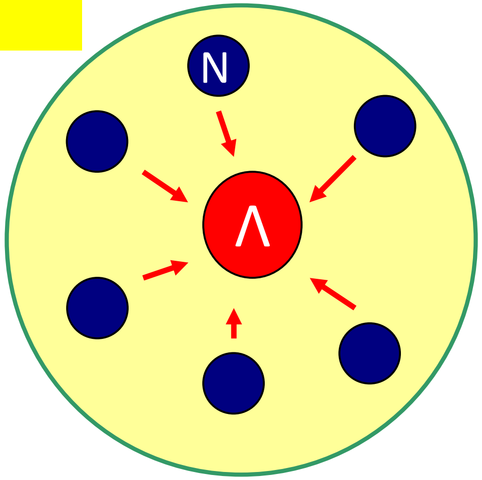


When some neutrons or protons are added to clustering nuclei, additional neutrons are located outside the clustering nuclei due to the Pauli blocking effect.

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

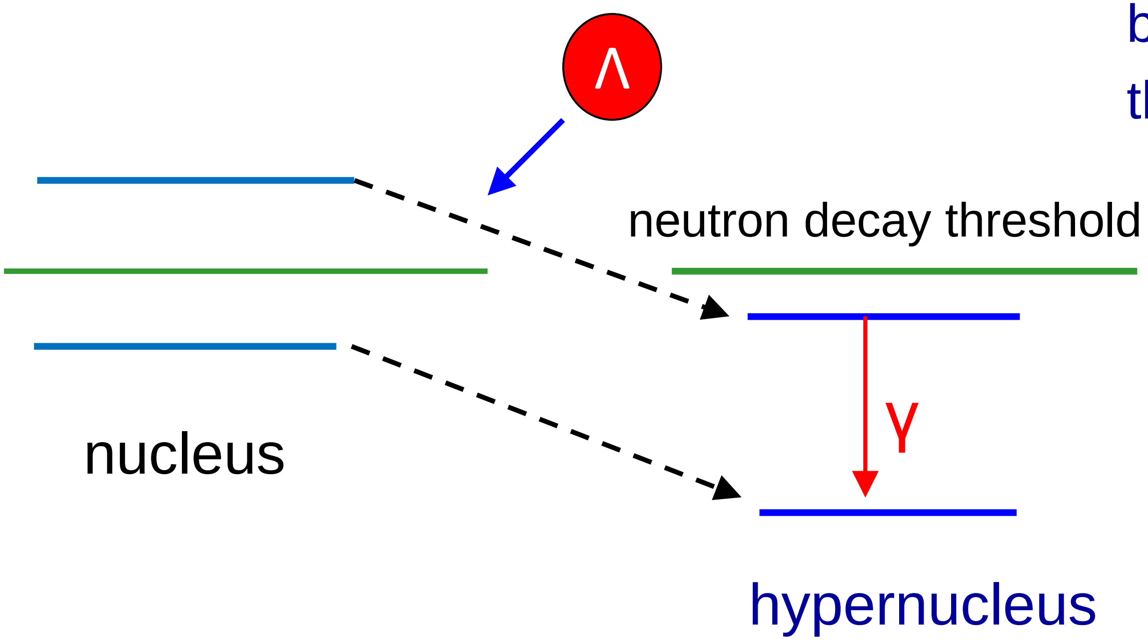
No Pauli principle
Between N and Λ

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

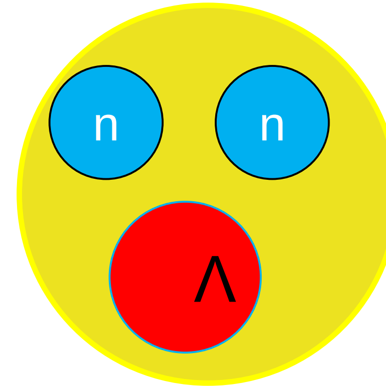


Hypernucleus

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

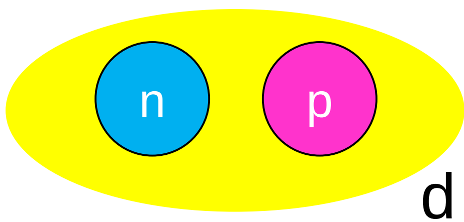


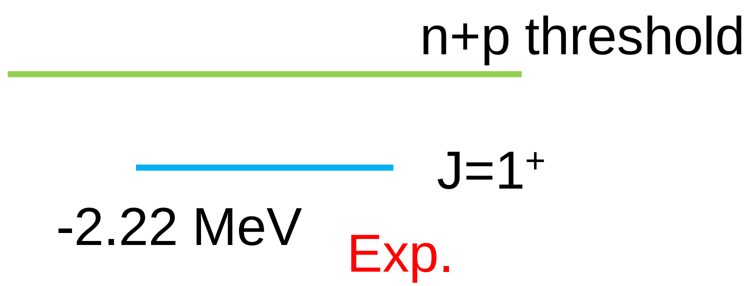
What is interesting to study nnΛ system?



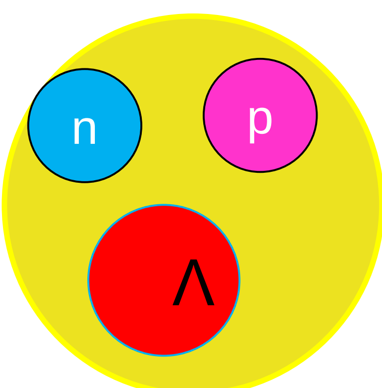
S=0

The lightest nucleus to have a bound state is deuteron.



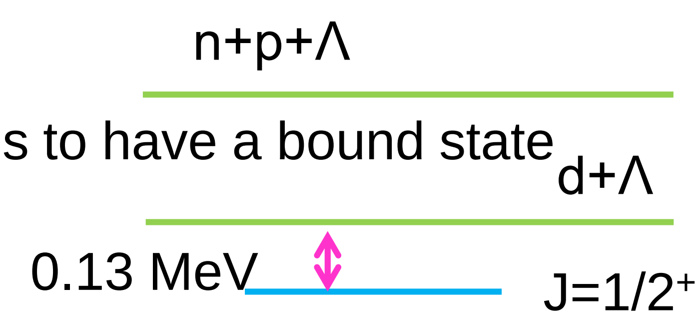


S=-1 (Λ hypernucear sector)



Lightest hypernucleus to have a bound state

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

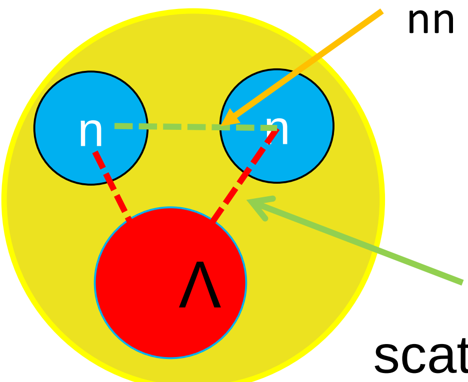


Exp.

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 $^{6}\mathrm{Li}+{}^{12}\mathrm{C}$ 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)



nn unbound

scattering length:-2.68fm

nnΛ breakup threshold

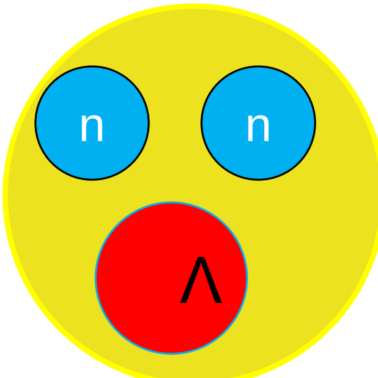
?
They did not report the binding energy.

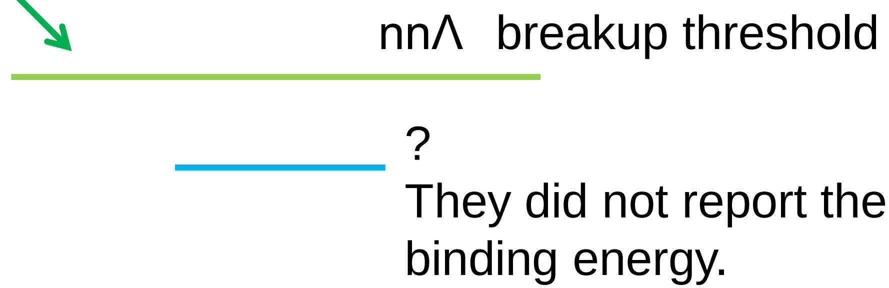
Observation of nnΛ system (2013)
Lightest hypernucleus to have a bound state
Any two-body systems are unbound.=>nnΛ system is bound.
Lightest Borromean system.

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?





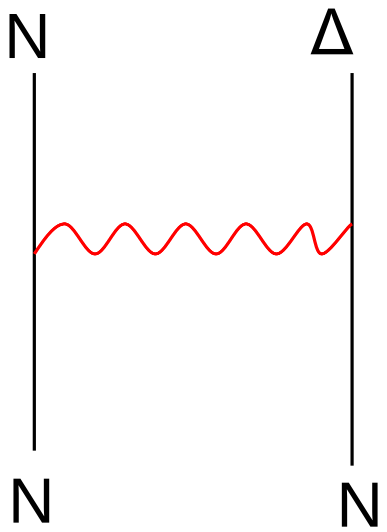
NN interaction : to reproduce the observed binding energies of ^{3}H and ^{3}He

NN: AV8 potential

We do not include 3-body force for nuclear sector.

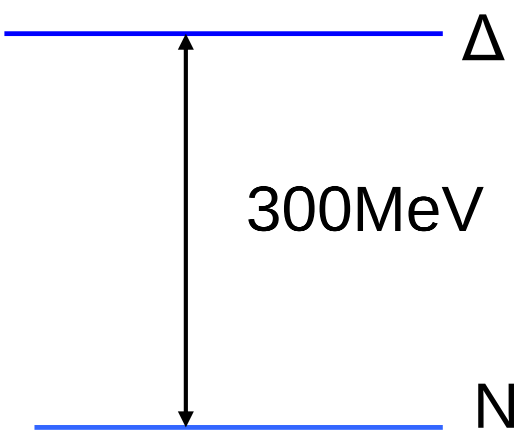
How about YN interaction?

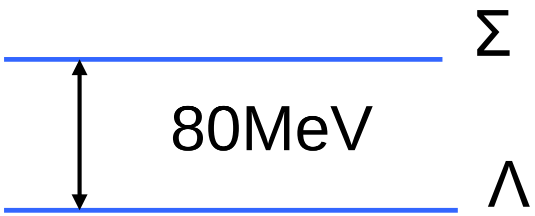
Non-strangeness nuclei

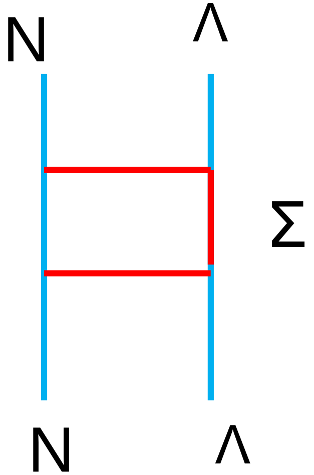


Nucleon can be converted into Δ.
However, since mass difference between nucleon and Δ is large, then probability of Δ in nucleus is not large.

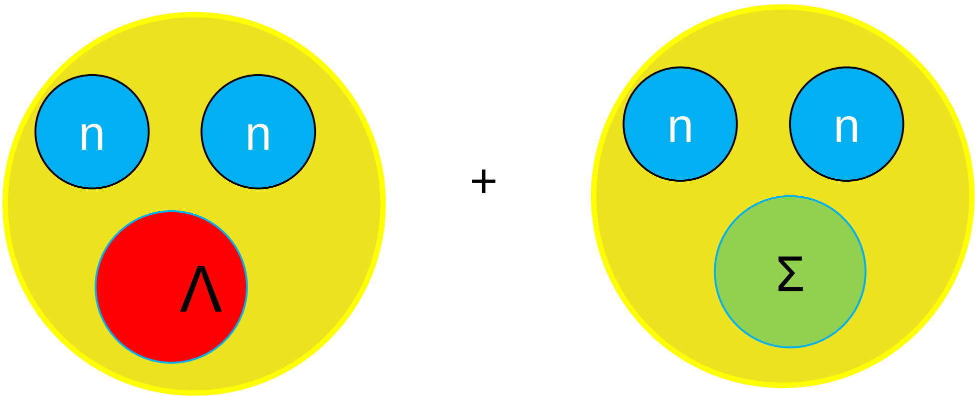
On the other hand, the mass difference between Λ and Σ is much smaller, then Λ can be converted into Σ particle easily.







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

In order to solve few-body problem accurately,

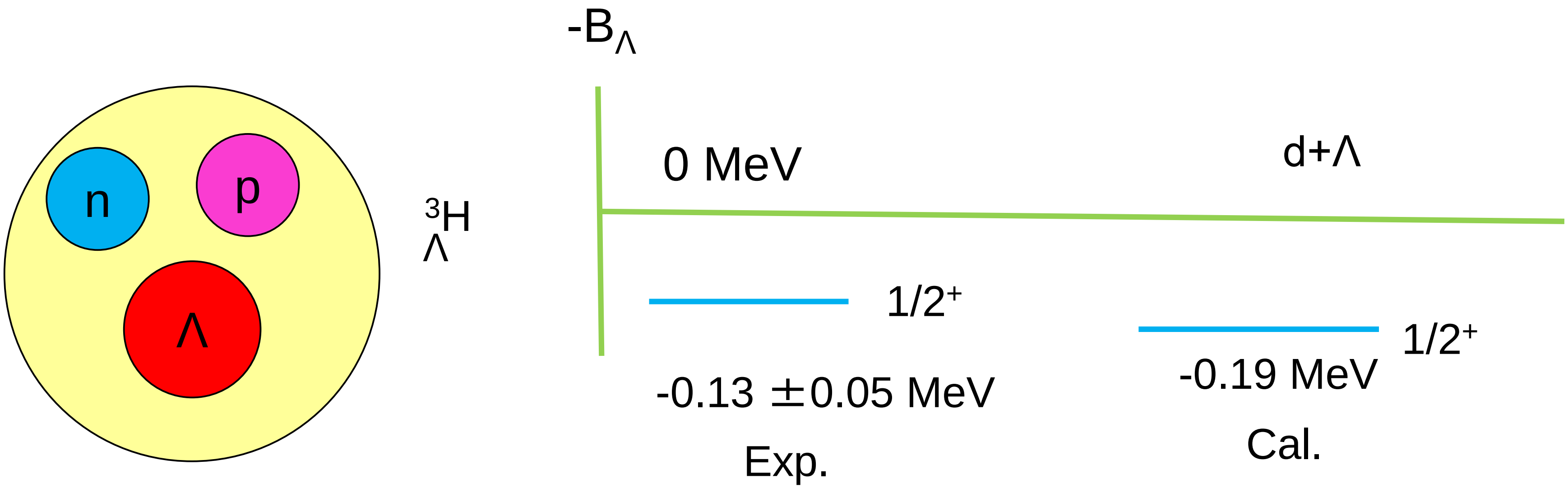
Gaussian Expansion Method (GEM) , since 1987,

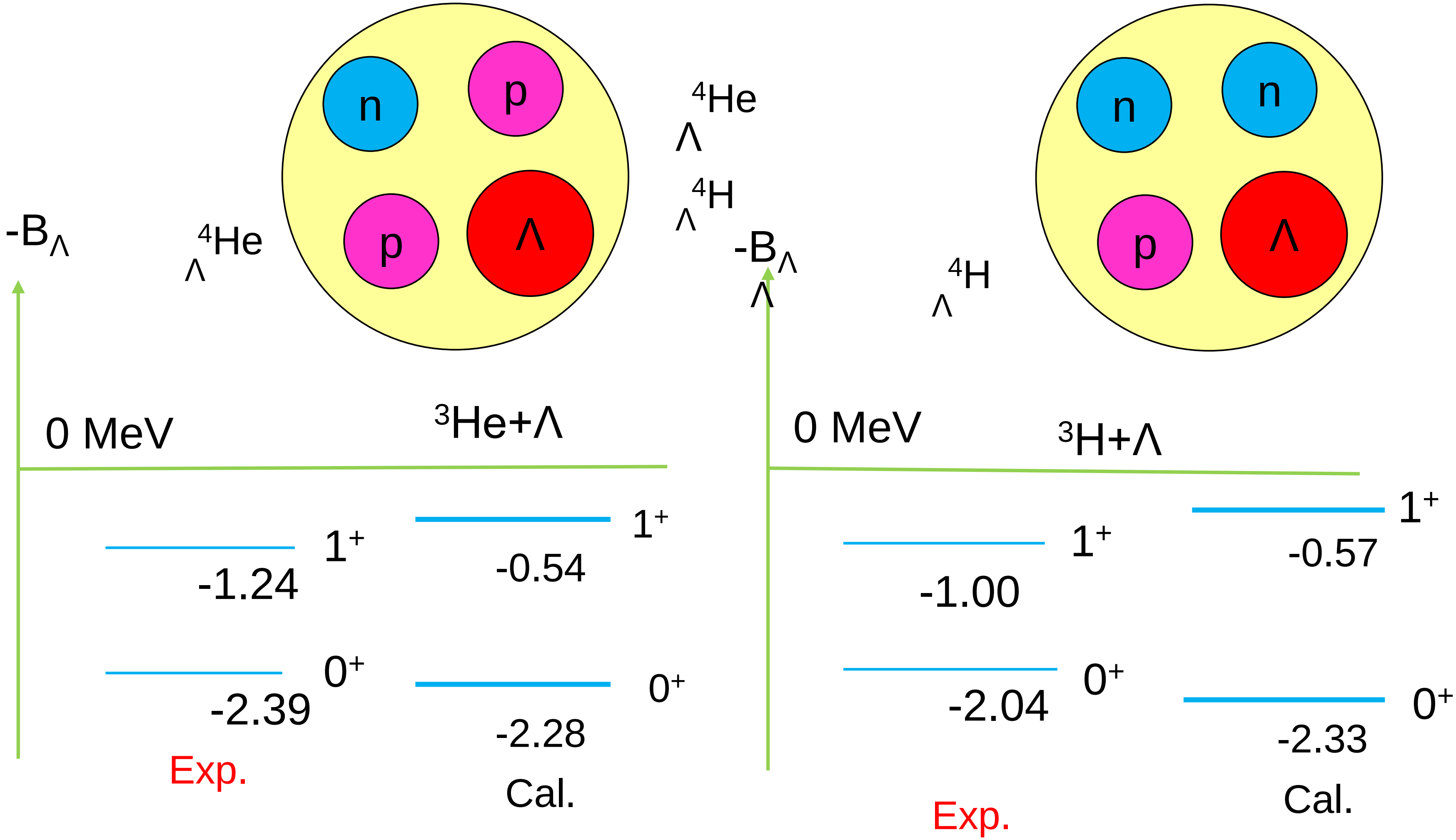
- A variational method using Gaussian basis functions
- Take all the sets of Jacobi coordinates

Developed by Kyushu Univ. Group,
Kamimura and his collaborators.
Review article :
E. Hiyama, M. Kamimura and Y. Kino,
Prog. Part. Nucl. Phys. 51 (2003), 223.

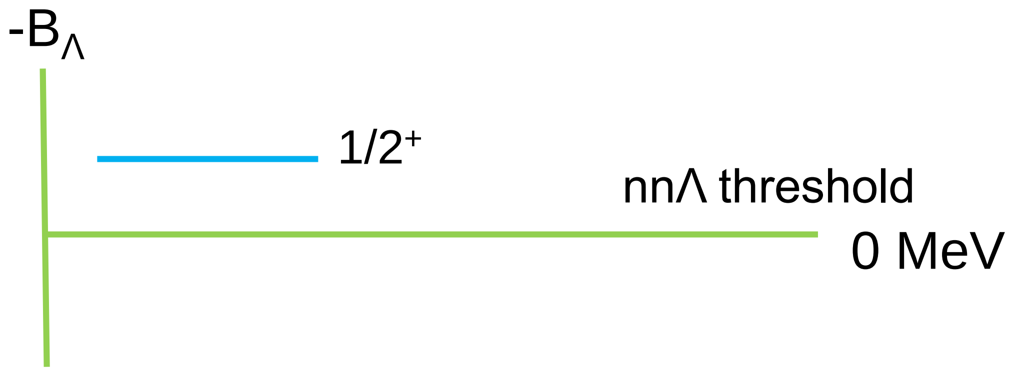
High-precision calculations of various 3- and 4-body systems:

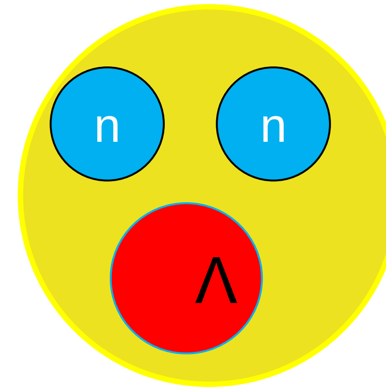
Exotic atoms / molecules ,	Light hypernuclei,
3- and 4-nucleon systems,	3-quark systems,
multi-cluster structure of light nuclei,	^{4}He-atom tetramer


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



What is binding energy of nnΛ?





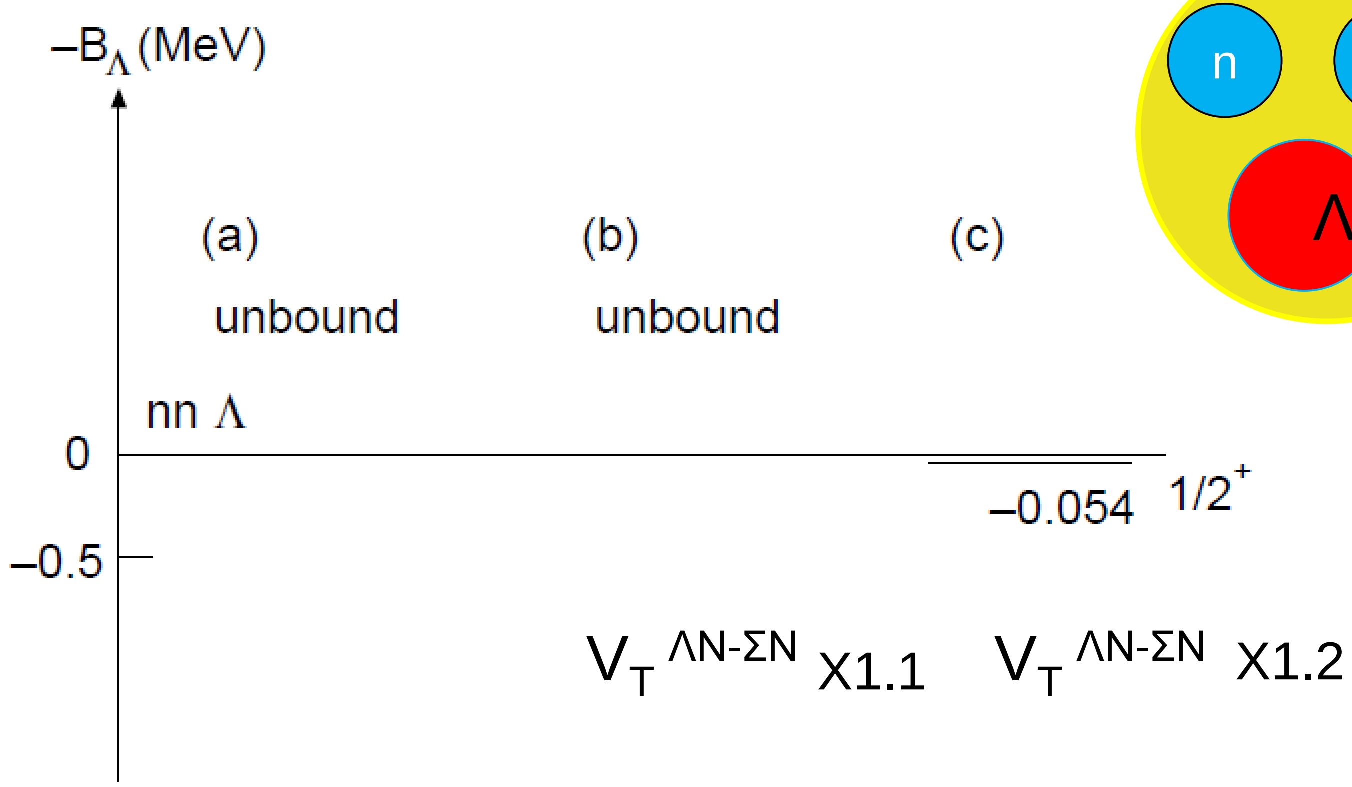
We have no bound state in nnΛ system.
This is inconsistent with the data.

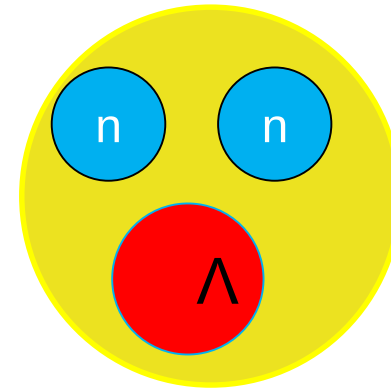
Now, we have a question.

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

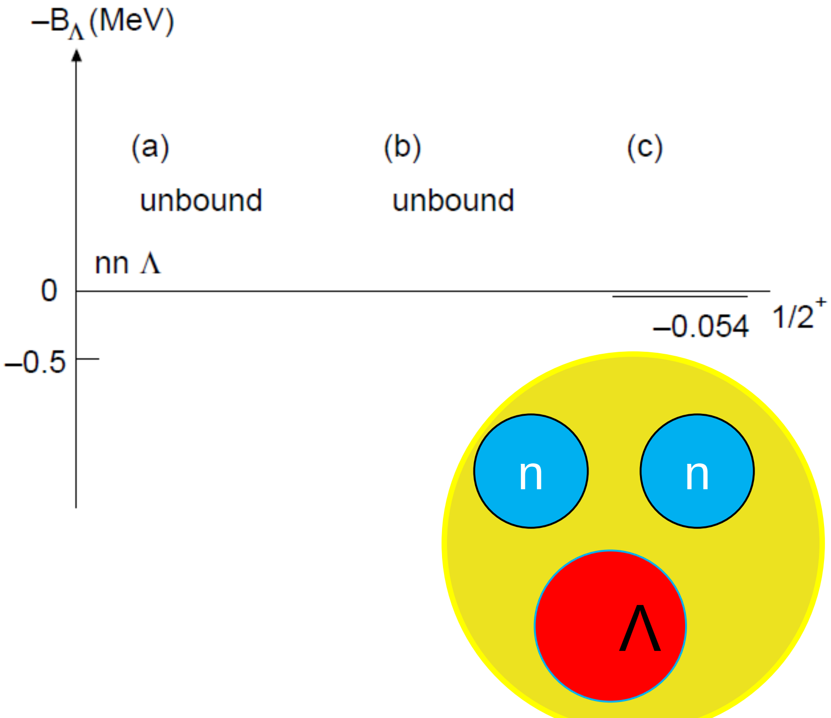
It should be noted to maintain consistency with the binding energies of ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ and ${}^{4}_{\Lambda}He$.

$V_T^{\Lambda N\text{-}\Sigma N}$ 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?



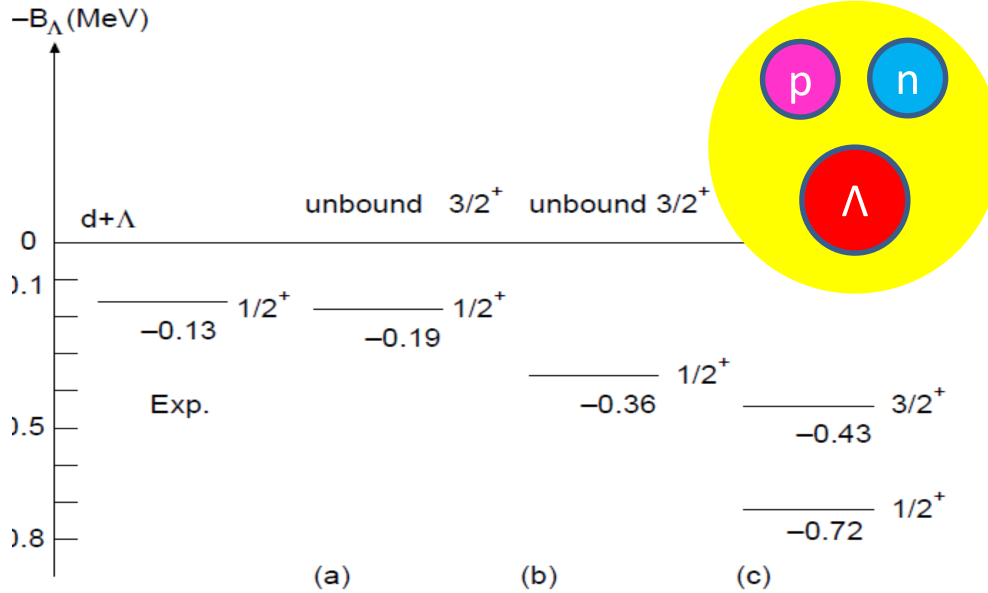
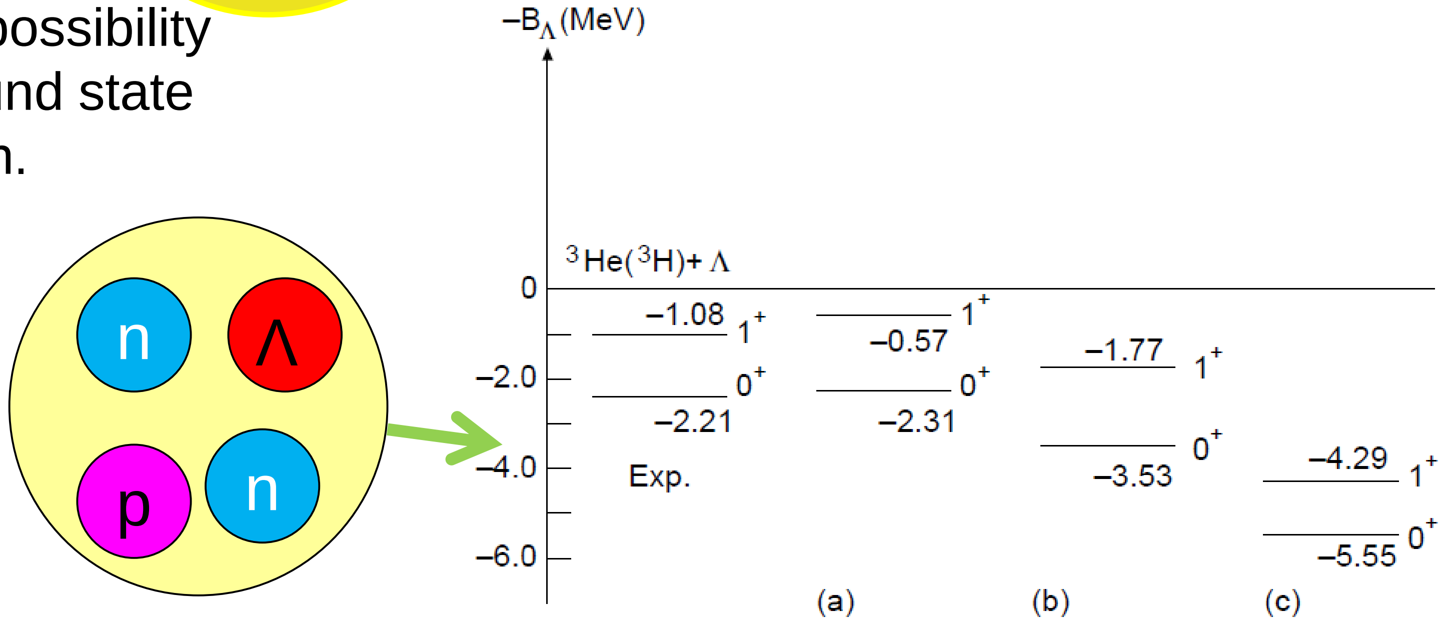


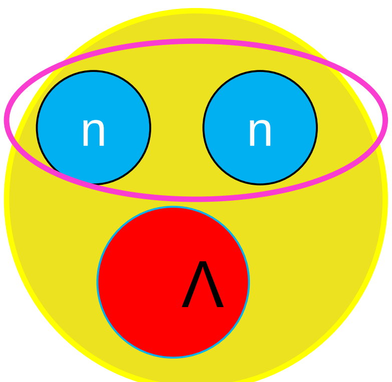
FIG. 3: Calculated Λ-separation energy for $^3_\Lambda$H with (a) $^3V^T_{N\Lambda-N\Sigma}$ × 1.00, (b) $^3V^T_{N\Lambda-N\Sigma}$ × 1.10, and (c) $^3V^T_{N\Lambda-N\Sigma}$ ×

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



Question: If we tune $^{1}S_{0}$ 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, $^{1}S_{0}$ state
I multiply component of $^{1}S_{0}$ 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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M. Smoluchowski Institute of Physics, Jagiellonian University, PL-30059 Kraków, Poland

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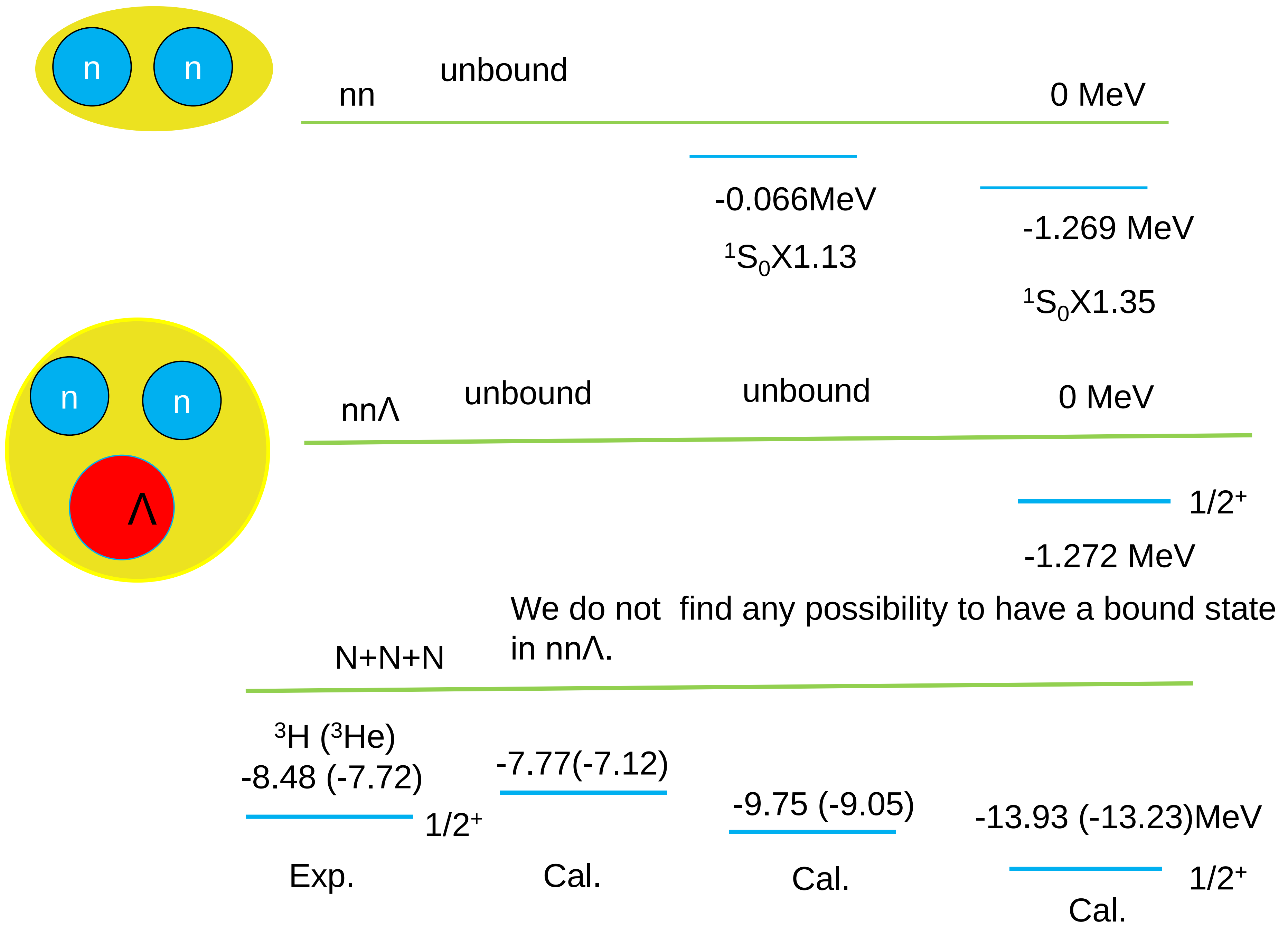
(Received 24 April 2012; published 25 June 2012)

We investigate how strongly a hypothetical $^{1}S_{0}$ 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 $^{1}S_{0}$ 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 $^{1}S_{0}$ 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.

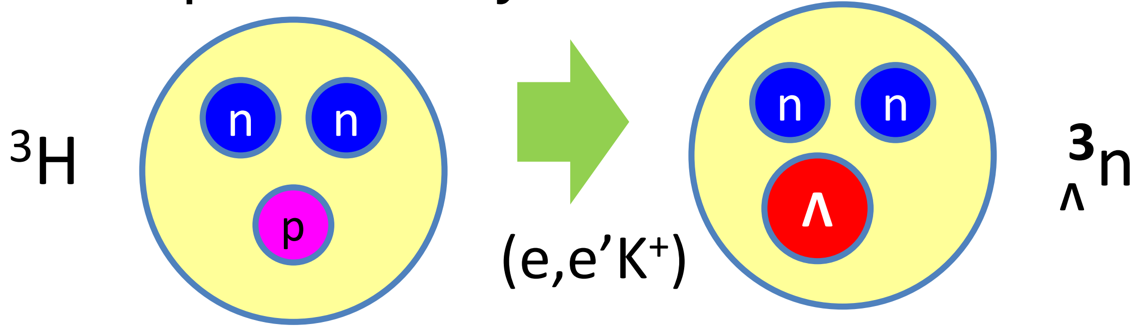


n
n
unbound
nn
0 MeV
-0.066MeV
-1.269 MeV
1S0X1.13
1S0X1.35
n
n
Λ
nnΛ
unbound
unbound
0 MeV
1/2+
-1.272 MeV
We do not find any possibility to have a bound state in nnΛ.
N+N+N
3H (3He)
-8.48 (-7.72)
-7.77(-7.12)
-9.75 (-9.05)
-13.93 (-13.23)MeV
1/2+
1/2+
Exp.
Cal.
Cal.
Cal.

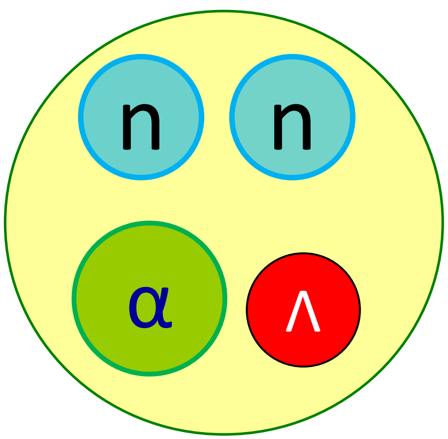
Summary of nnΛ system:

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. 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.
Unfortunately, they did not report binding energy.

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.



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



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

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.

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

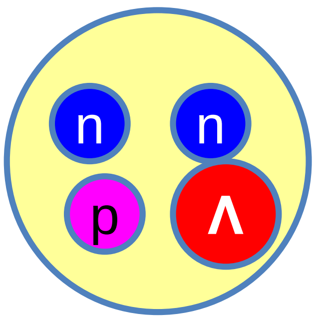
(1) Charge symmetry breaking

(2) ΛN－ΣN coupling

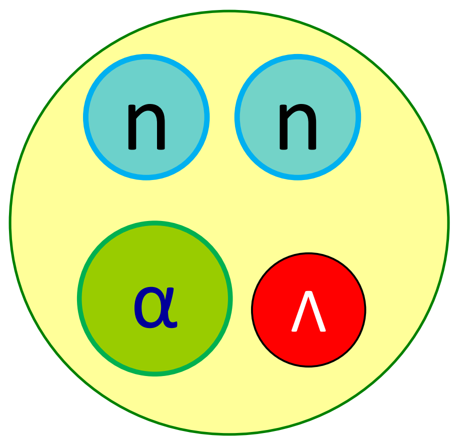
J-PARC : Day-1 experiment
E13

Jlab E05-115,

Mainz



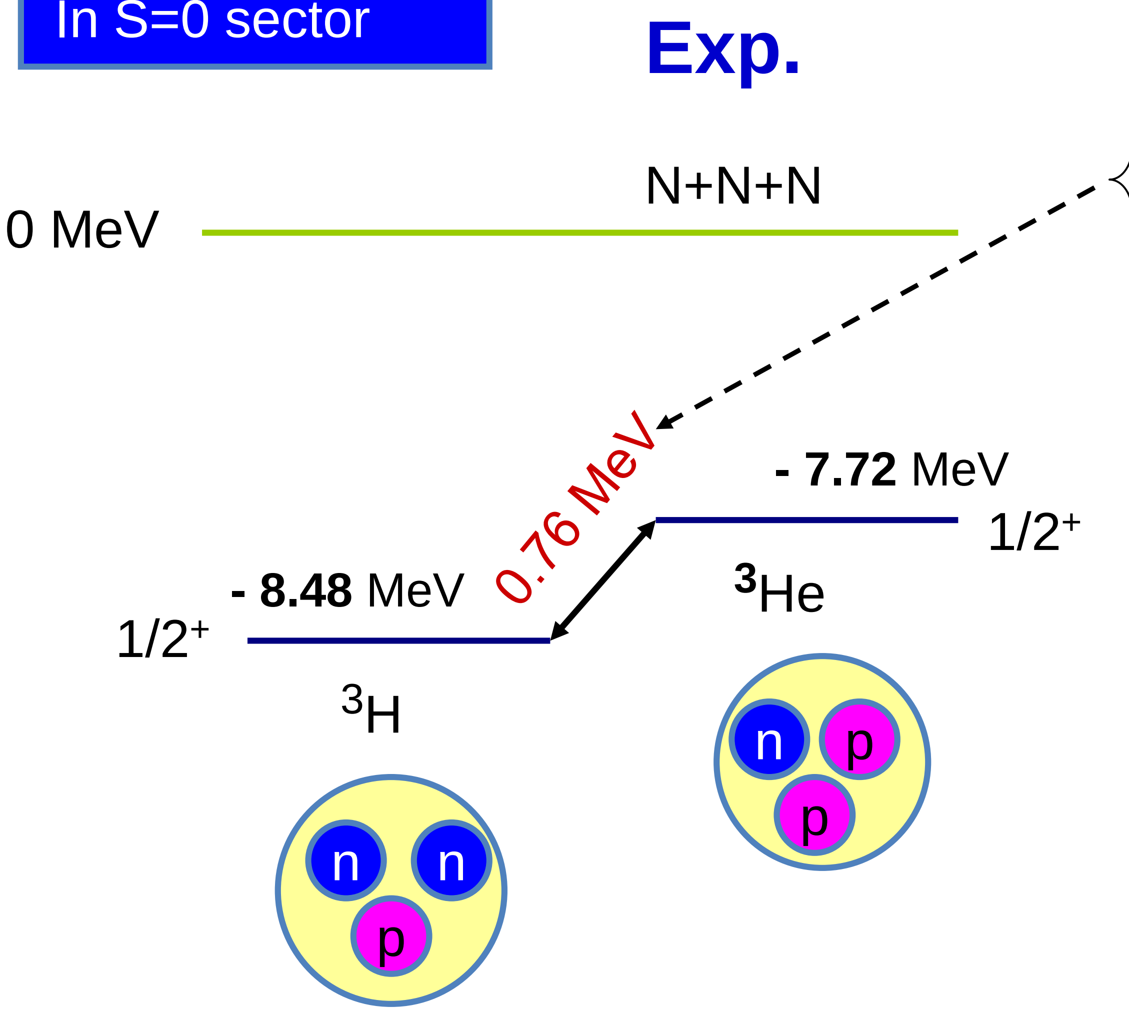
$^{4}_{\Lambda}$H



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

(1) Charge Symmetry breaking

In S=0 sector

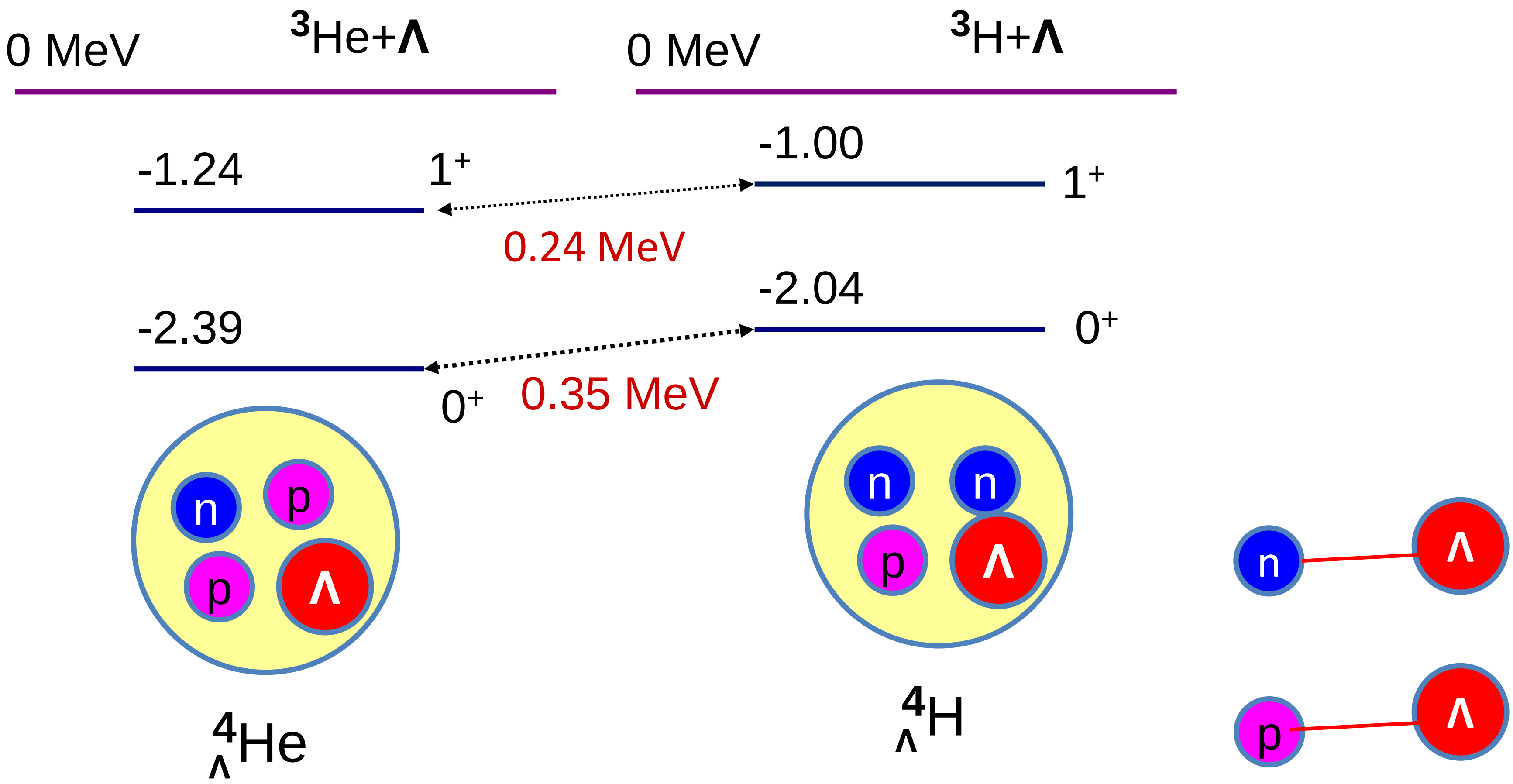


Energy difference comes from dominantly Coulomb force between 2 protons.

Charge symmetry breaking effect is small.

In S= -1 sector

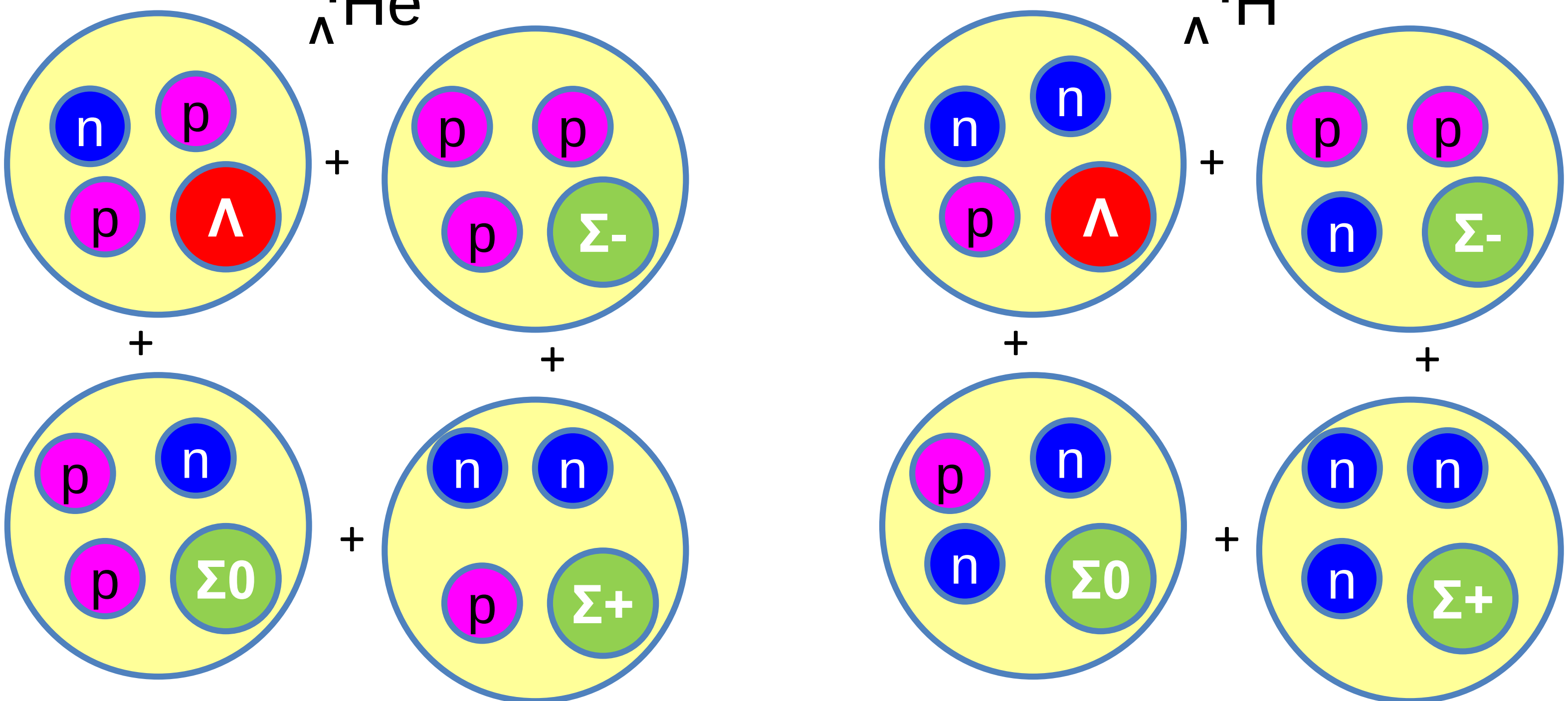
Exp.



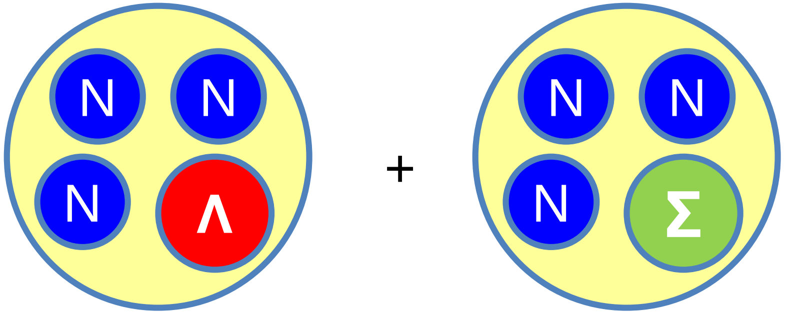
$^{4}_{\Lambda}He$ $^{4}_{\Lambda}H$

However, Λ particle has no charge.

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



In order to explain the energy difference, 0.35 MeV,



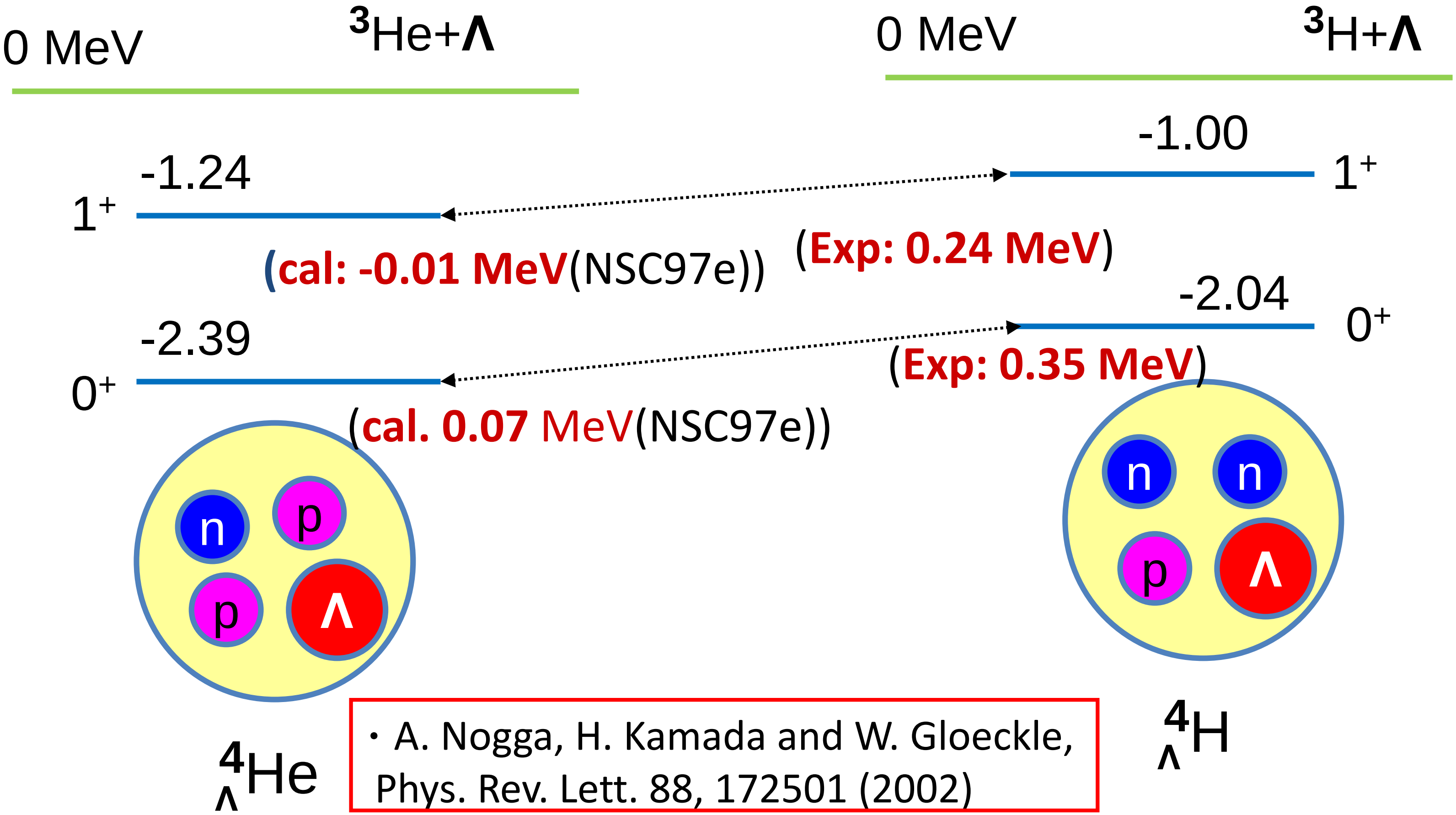
(3N+**Λ**)   (3N+**Σ**)

・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)

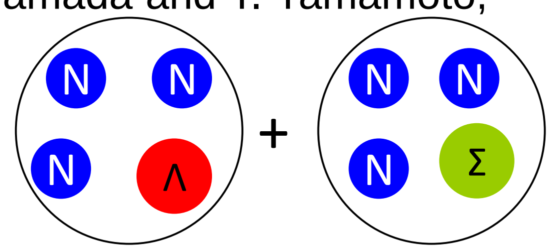
・H. Nemura. Y. Akaishi and Y. Suzuki,
Phys. Rev. Lett.89, 142504 (2002).

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

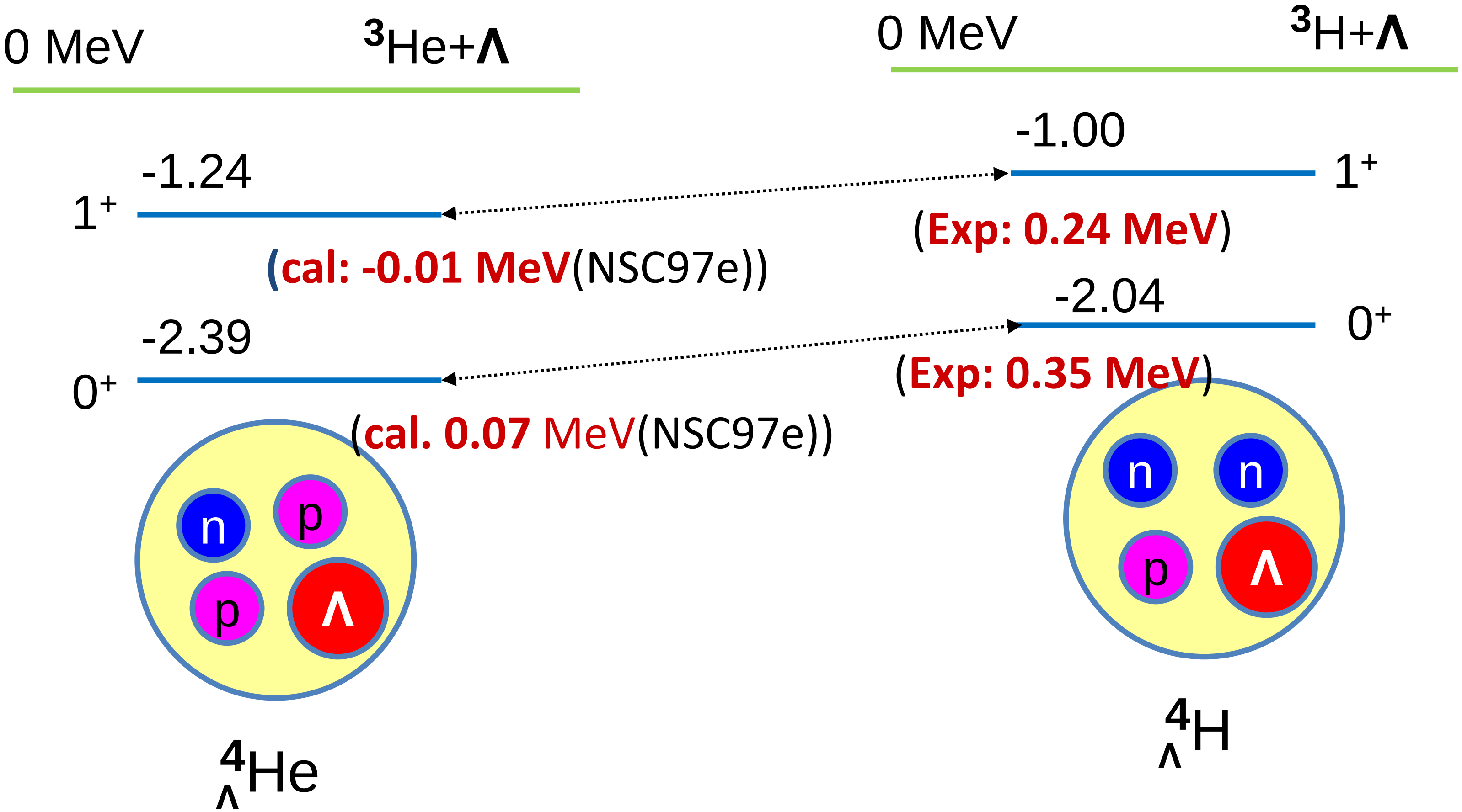


- A. Nogga, H. Kamada and W. Gloeckle, Phys. Rev. Lett. 88, 172501 (2002)

- 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).



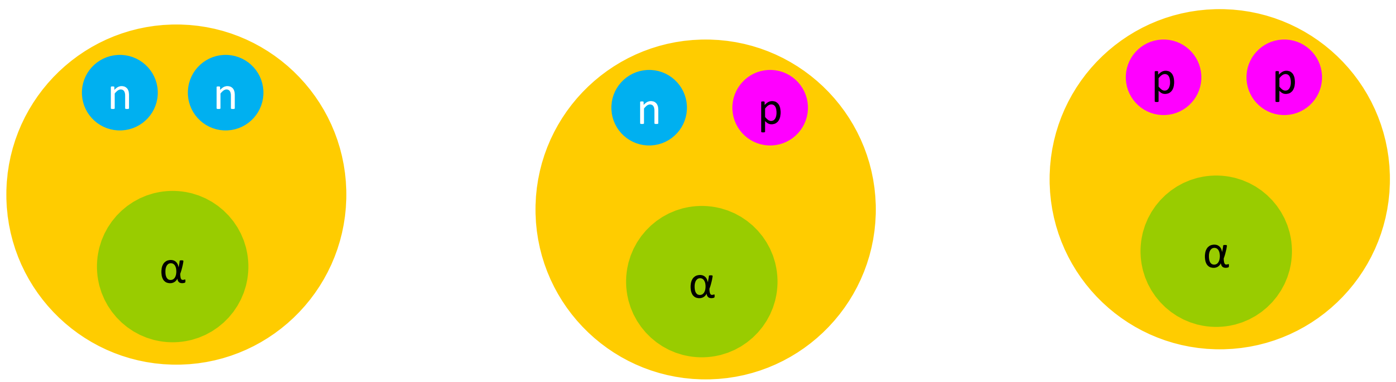
There exist NO YN interaction to reproduce the data.

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

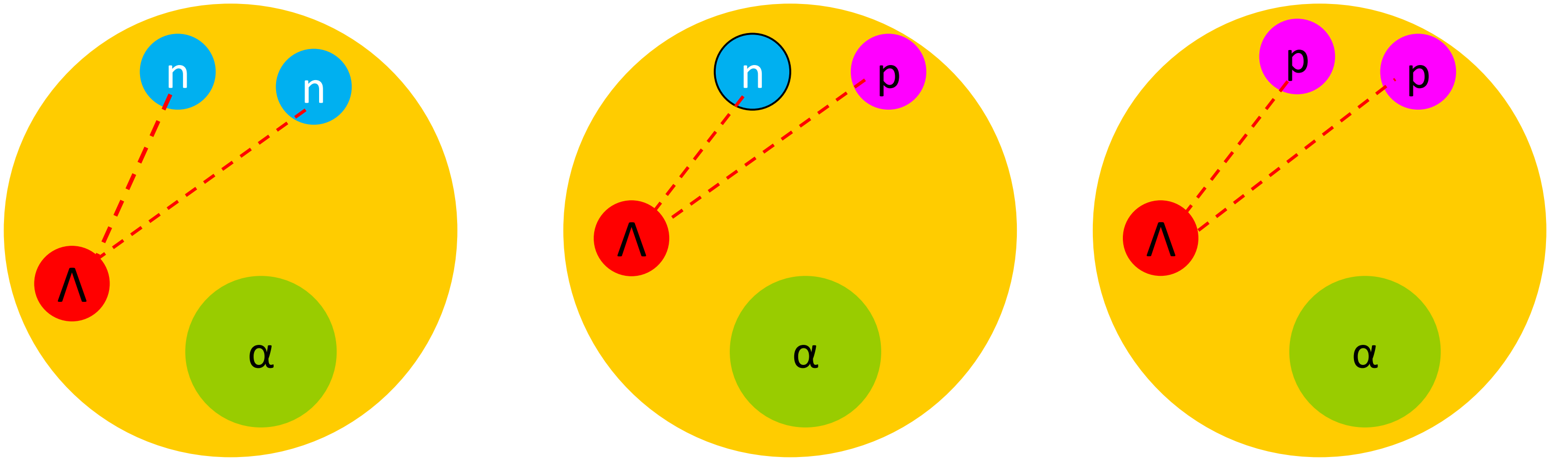
It is interesting to investigate the charge symmetry breaking effect in p-shell Λ hypernuclei as well as s-shell Λ hypernuclei.

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

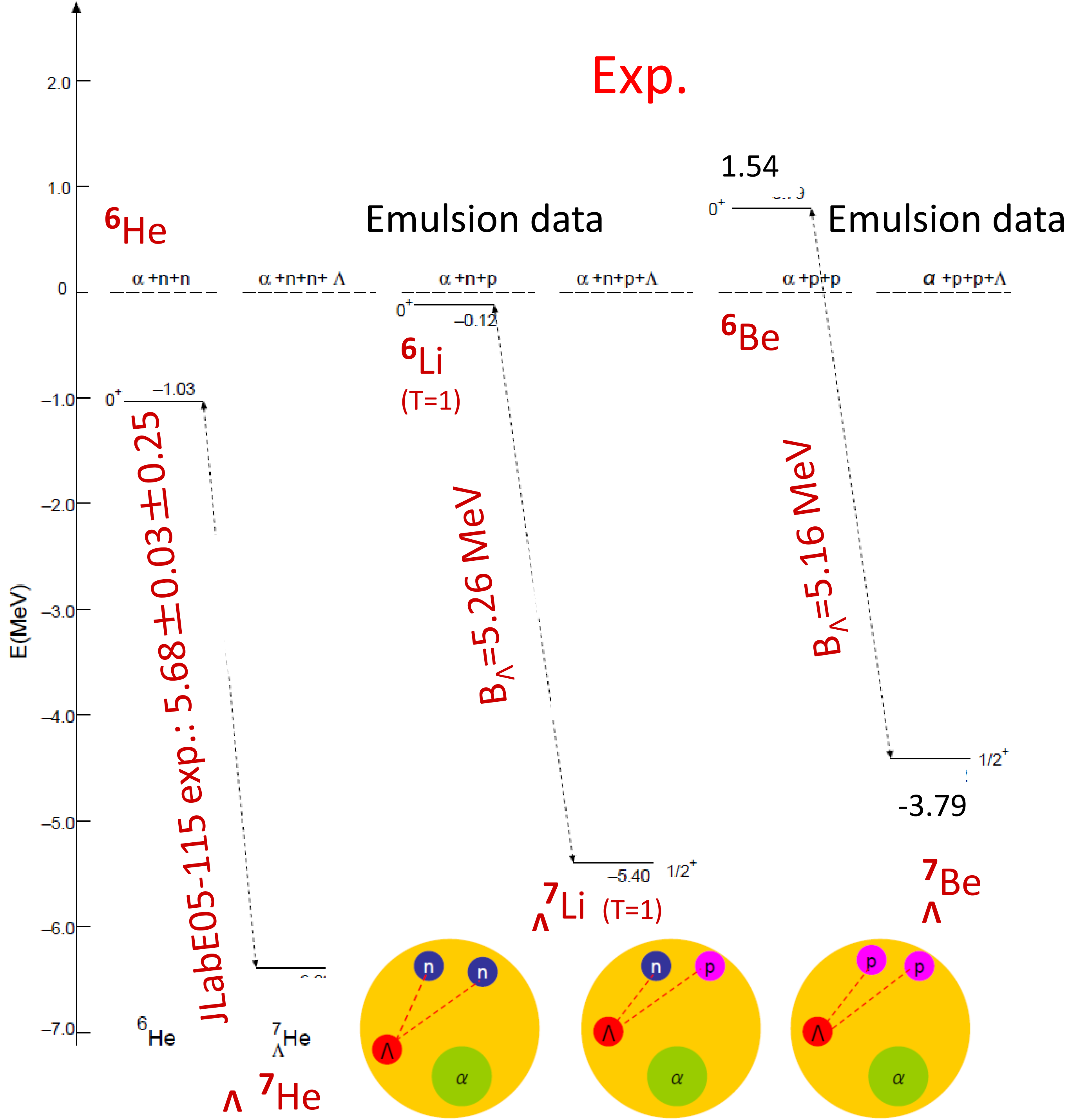


${}^{7}_{\Lambda}\mathrm{He}$ ${}^{7}_{\Lambda}\mathrm{Li}(T=1)$ ${}^{7}_{\Lambda}\mathrm{Be}$

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.

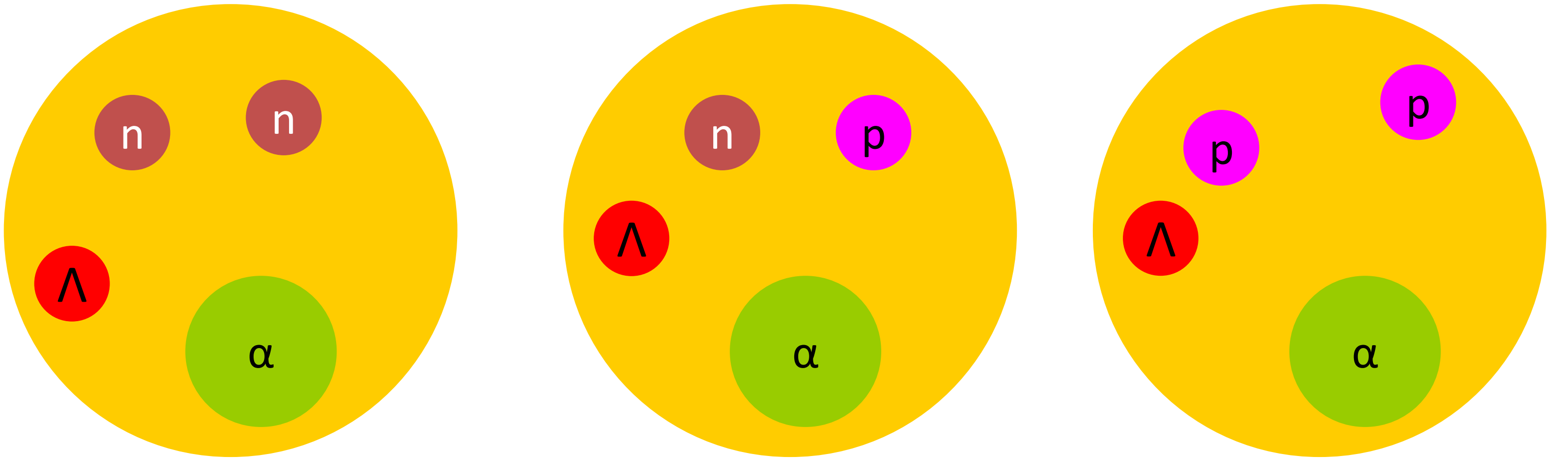


E(MeV)
2.0
1.0
0
–1.0
–2.0
–3.0
–4.0
–5.0
–6.0
–7.0
6He
Emulsion data
Emulsion data
1.54
α +n+n
α +n+n+ Λ
α +n+p
α +n+p+Λ
α +p+p
α +p+p+Λ
0+
–0.12
6Li
(T=1)
6Be
0+
–1.03
JLabE05-115 exp.: 5.68±0.03±0.25
BΛ=5.26 MeV
BΛ=5.16 MeV
1/2+
-3.79
–5.40
1/2+
7Li (T=1)
Λ
7Be
Λ
6He
7He
Λ
Λ 7He
n
n
Λ
α
n
p
Λ
α
p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



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

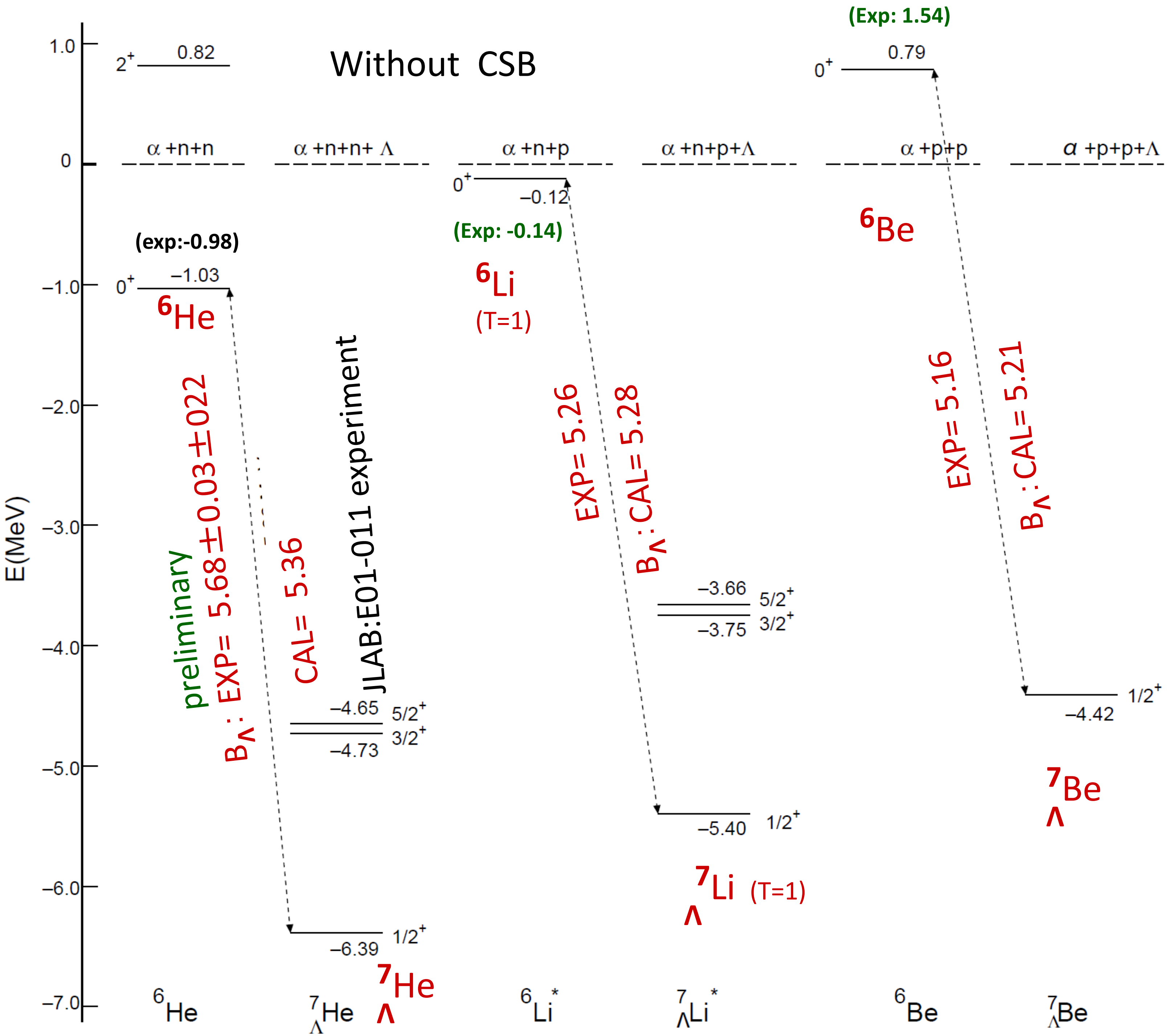
For this purpose, we study structure of A=7 hypernuclei within the framework of α+Λ+N+N 4-body model.

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

Now, it is interesting to see as follows:

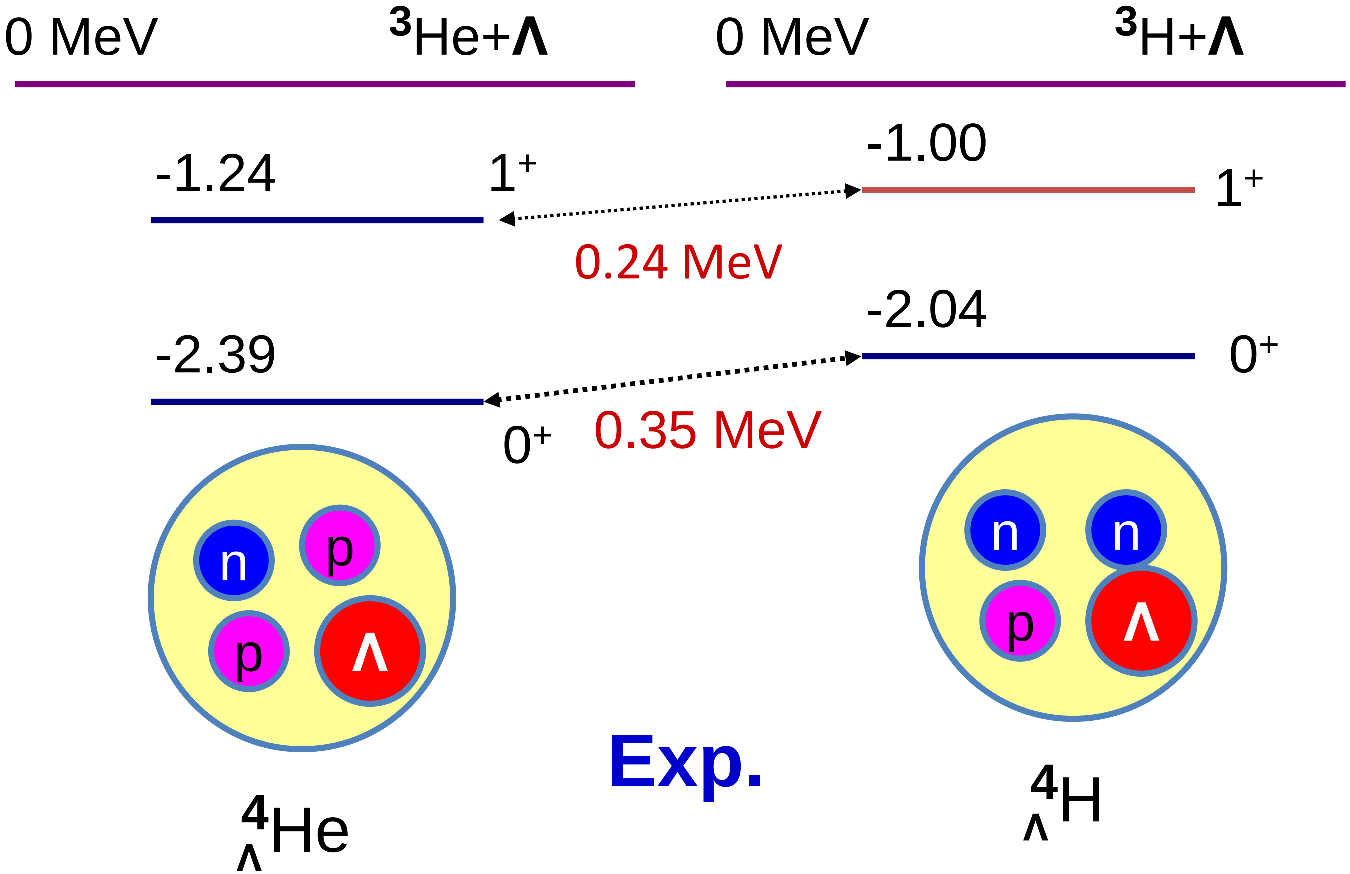
(1)What is the level structure of A=7 hypernuclei without CSB interaction?

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

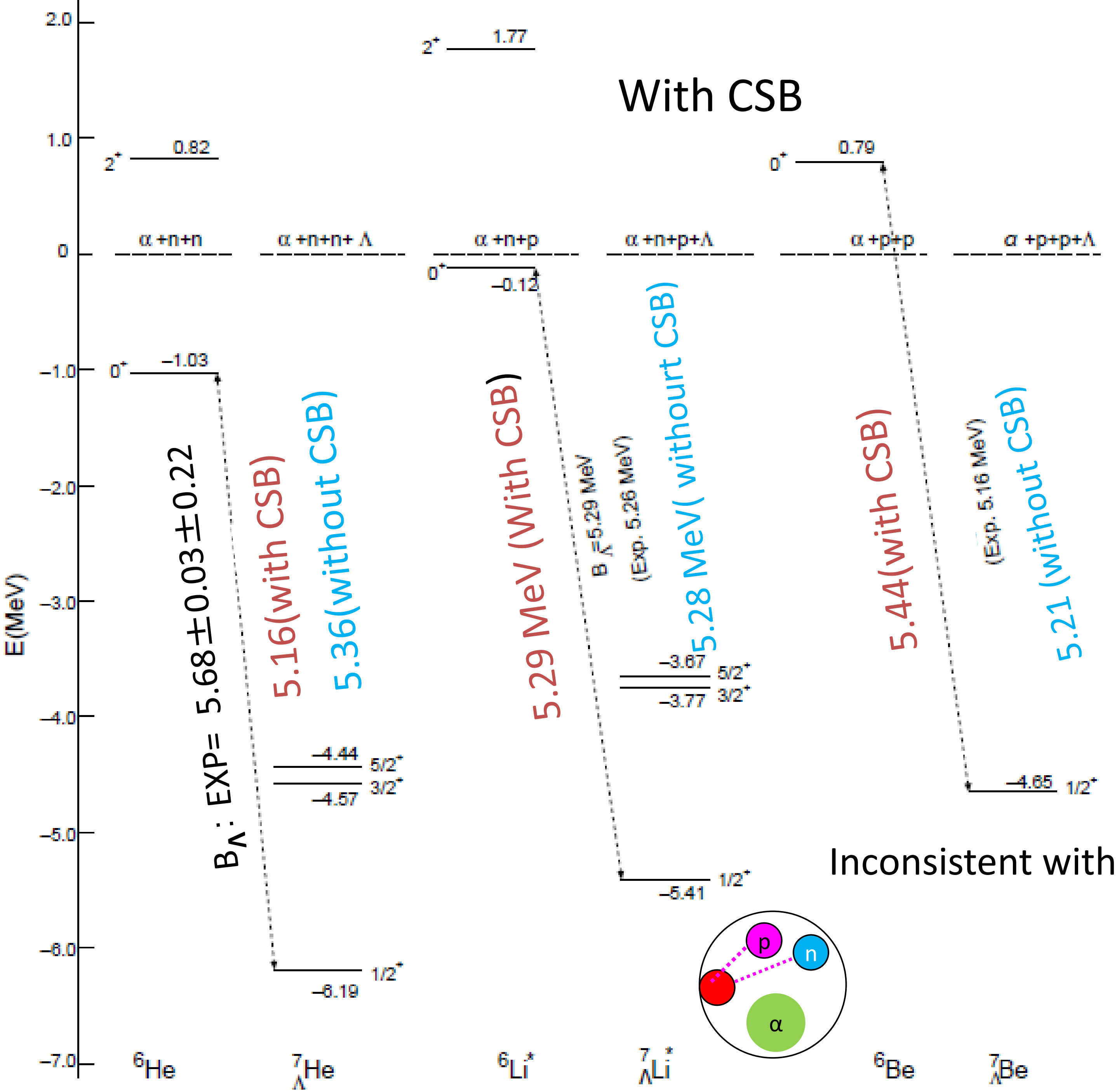
Next we introduce a phenomenological CSB potential with the central force component only.

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

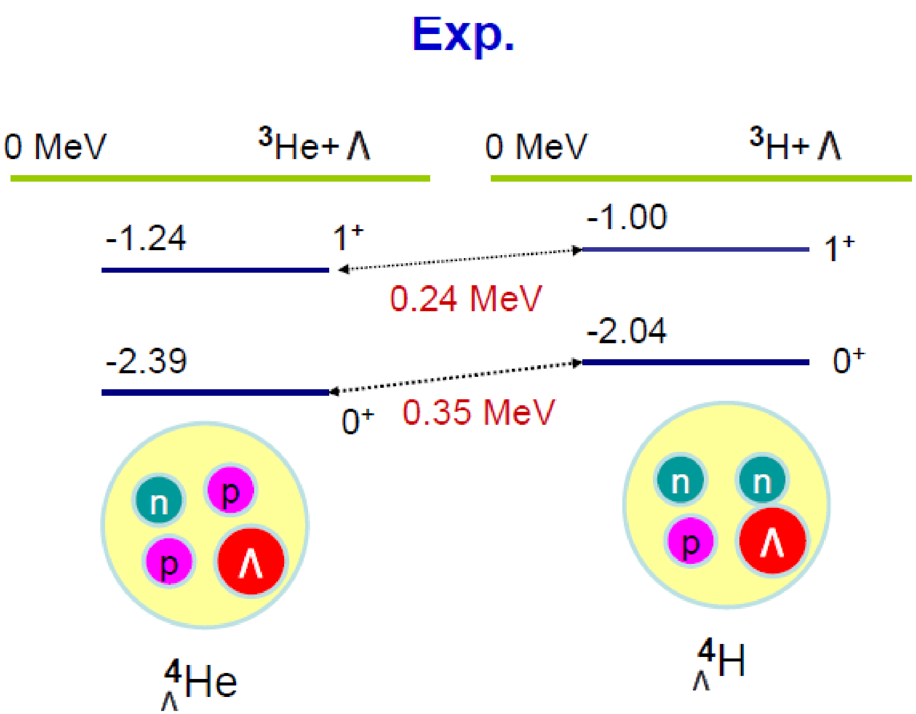
Strength, range are determined so as to reproduce the data.

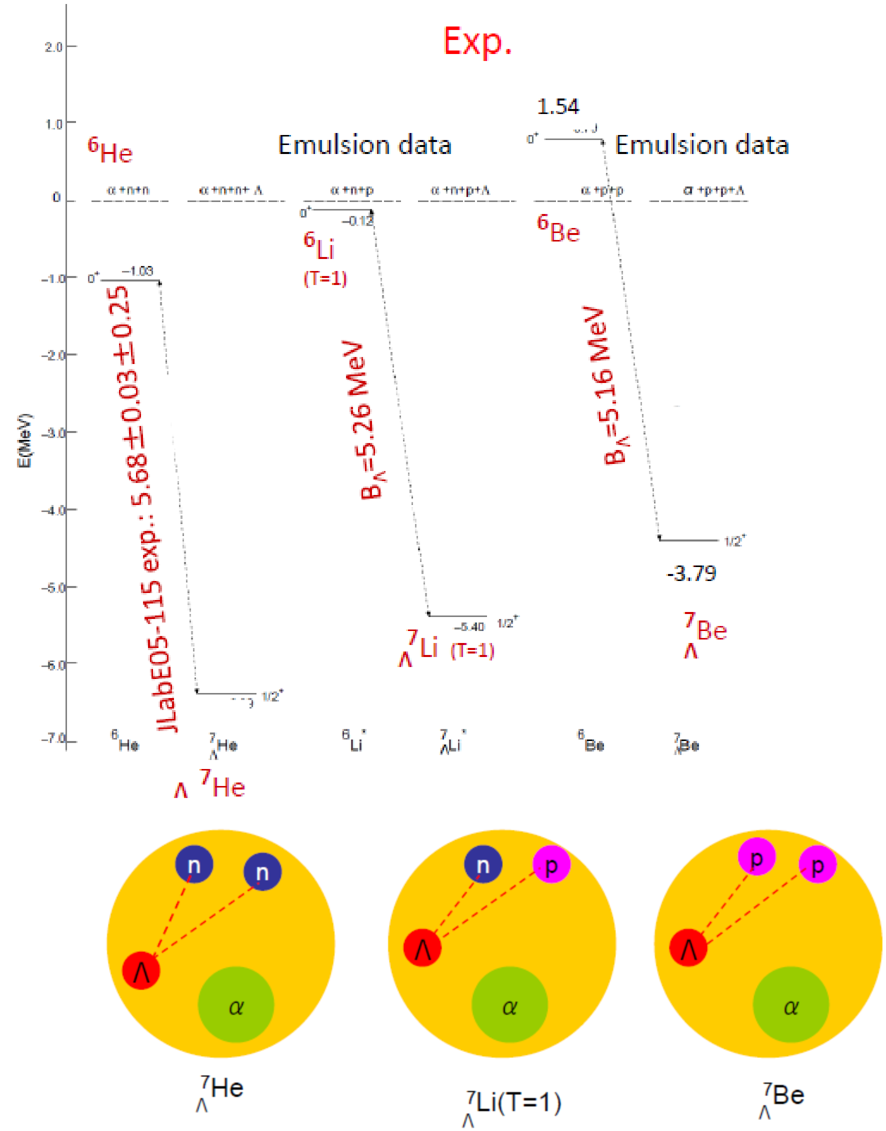


With CSB



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.

${}^{4}_{\Lambda}He$ →(decay) $\pi^- + {}^1H + {}^3He$ → 2.42 ± 0.05 MeV

${}^{4}_{\Lambda}He$ → $\pi^- + {}^1H + {}^1H + {}^2H$ → 2.44 ± 0.09 MeV

Total: 2.42 ± 0.04 MeV

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

${}^{4}_{\Lambda}H$ →(decay) $\pi^- + {}^1H + {}^3H$ → 2.14 ± 0.07 MeV

${}^{4}_{\Lambda}H$ → $\pi^- + {}^2H + {}^2H$ → 1.92 ± 0.12 MeV

Two different modes give 0.22 MeV

↓

This value is so large to discuss CSB effect.

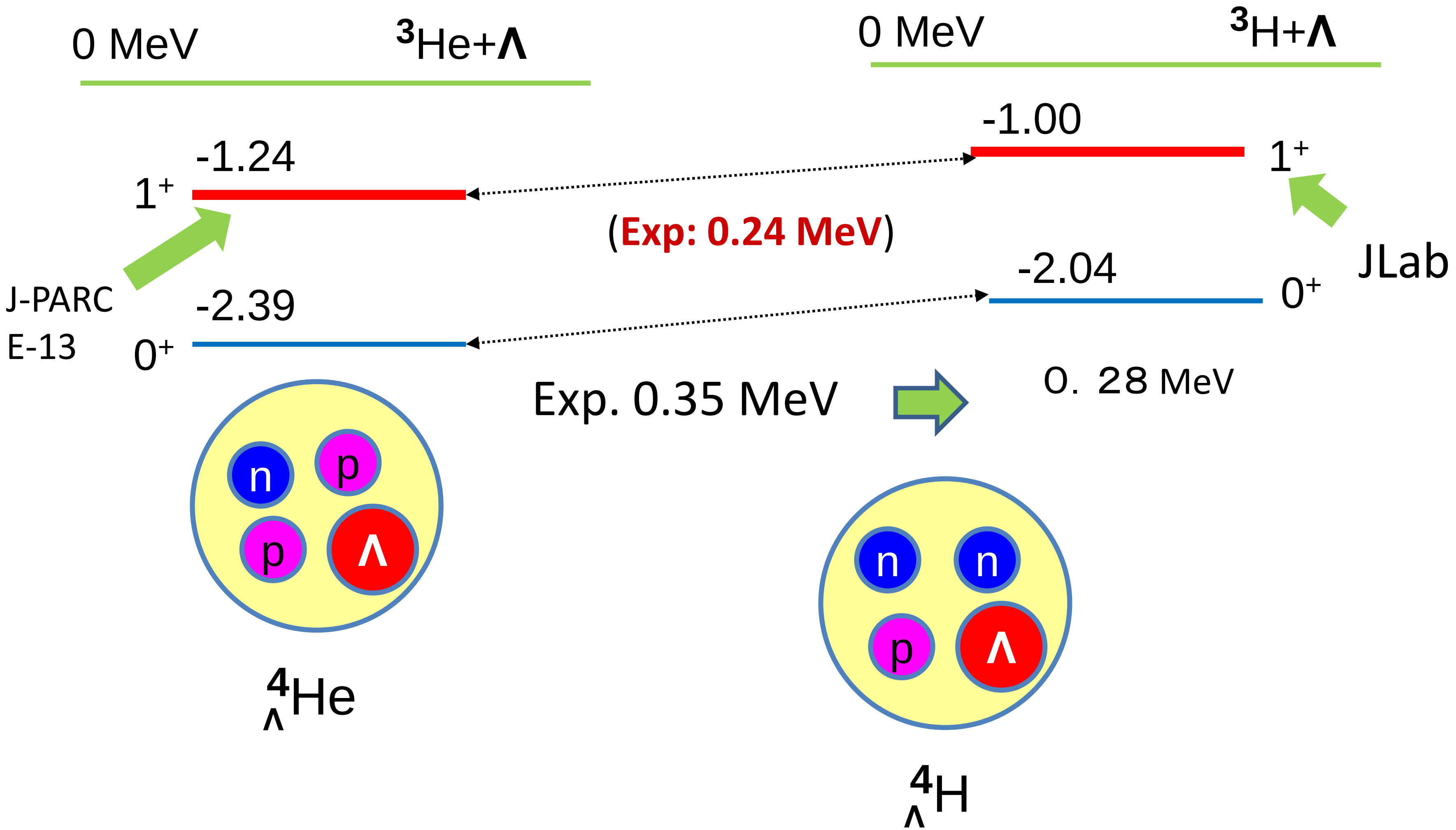
Total: 2.08 ± 0.06 MeV

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

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

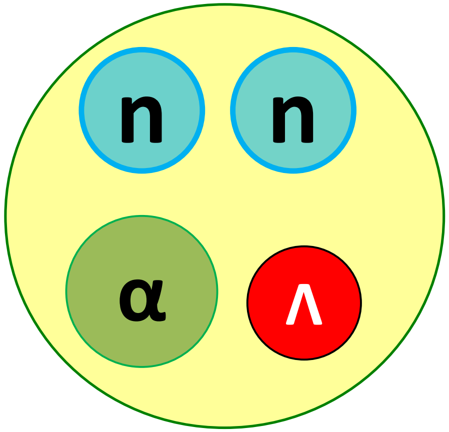
${}^4He\,(e, e'K^+)\,{}^{4}_{\Lambda}H$ ⇒ Key experiment to get information about CSB.

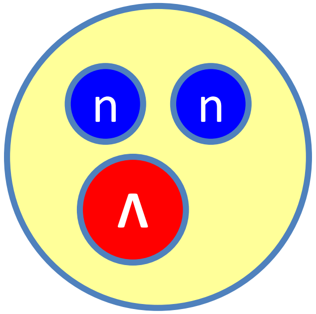
Future experimental plan



Conclusion

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





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

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

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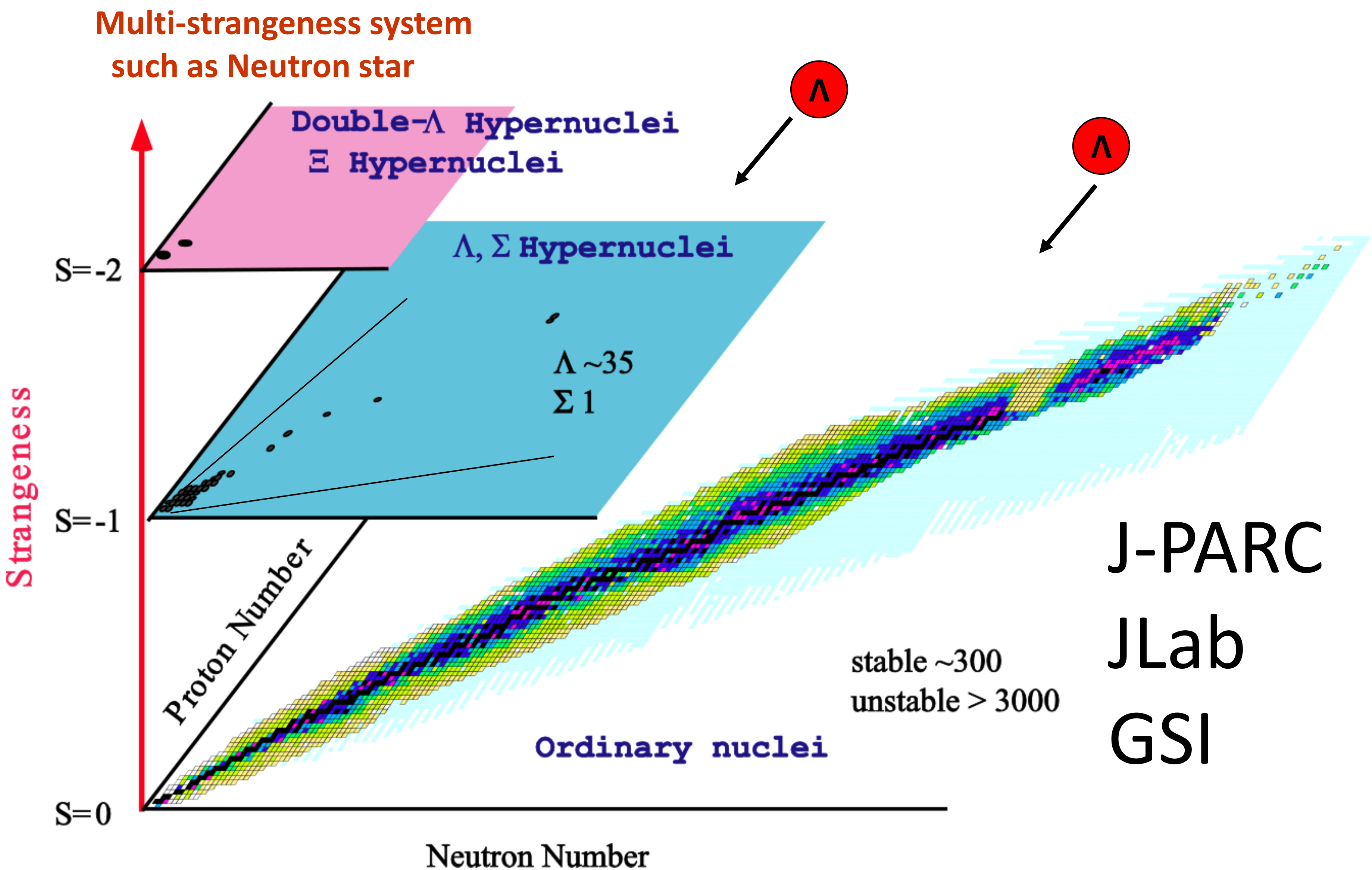
041001 (R) (2013)

Nuclear chart with strangeness



Thank you!