Recent progress of hypernuclear physics

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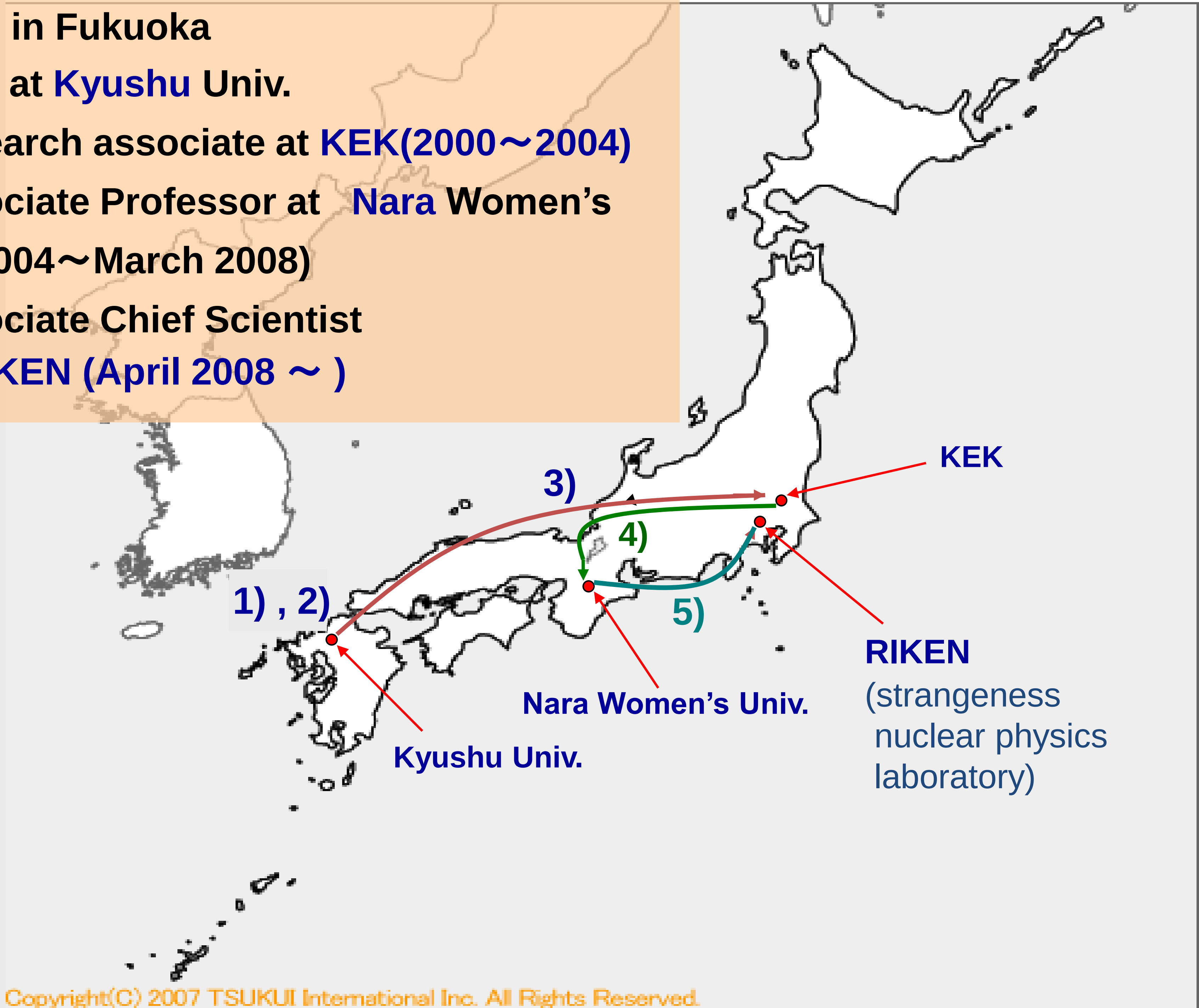

I shall explain about my laboratory.

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▲仁科記念棟

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6 PDs	4 Graduate students
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H. Togashi	C.Schmickler (Gemany)
M. Isaka	K.Sallmen(Sweden)
N. Yamanaka	
T. Sun	


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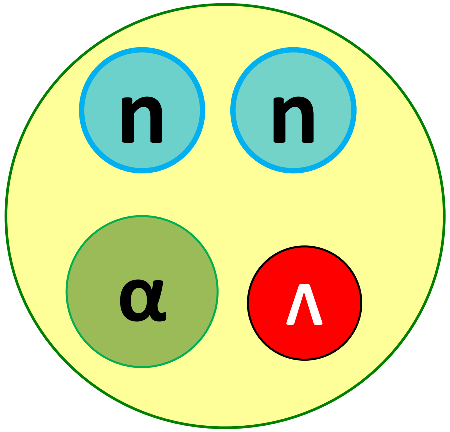
i-Wipe

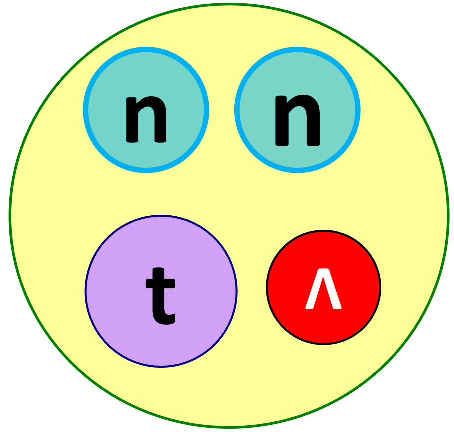
Recently, we had three epoch-making data from the view point of few-body problems.

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

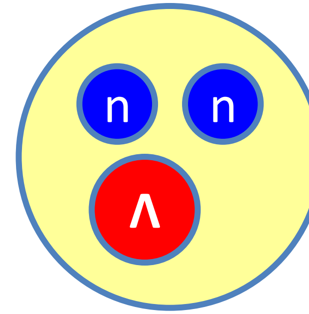


JLAB experiment-E011, Phys. Rev. Lett. **110**, 12502 (2013).

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



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



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

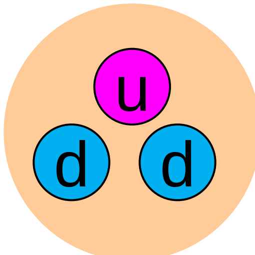
C. Rappold et al., HypHI collaboration Phys. Rev. C 88, 041001 (R) (2013)

Observation of Neutron-rich **Λ-**hypernuclei

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

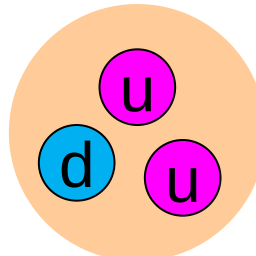
What is Λ particle?

neutron



No charge

proton: 3 quarks

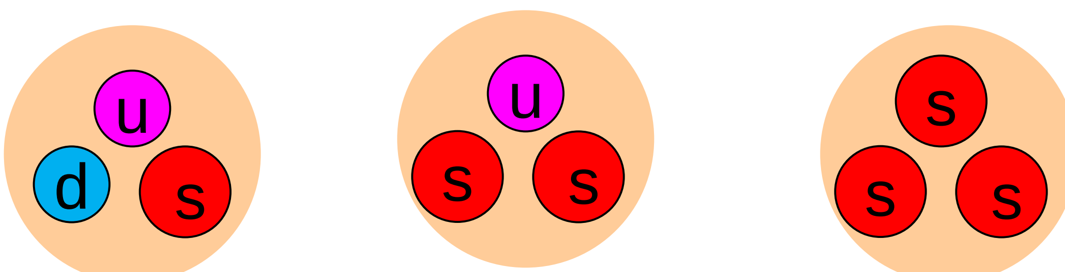


+charge

spin:1/2 isospin:1/2

Mass: 938 MeV

hyperon: including strangeness quark

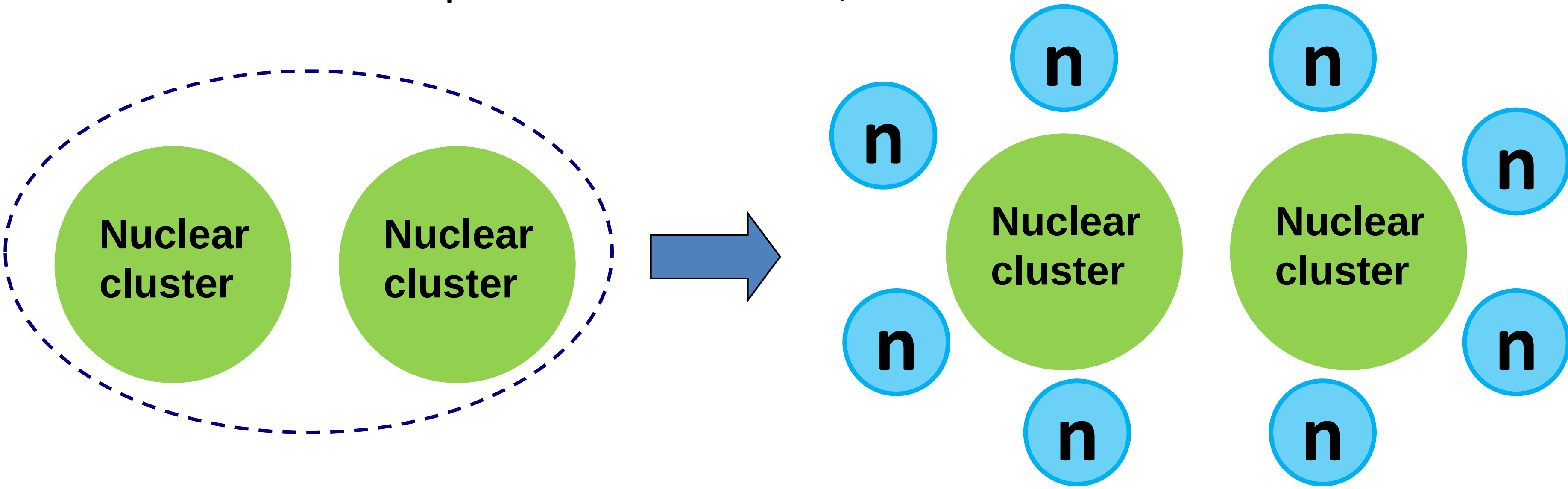


Λ、Σ Ξ Ω

I focus on Λ particle. The mass of Λ is similar with neutron
And no charge. Life time ∼ 10^{-10} sec

Sec.1 Introduction

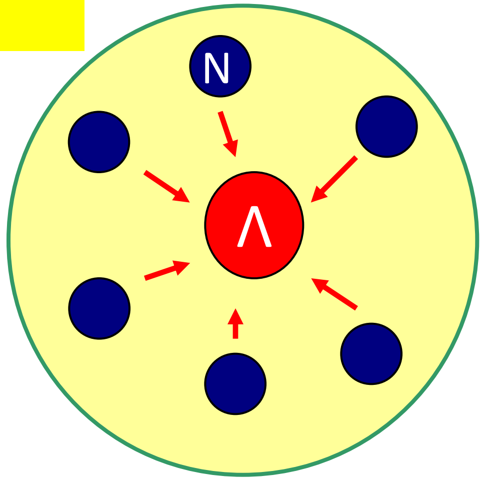
In neutron-rich and proton-rich nuclei,



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.

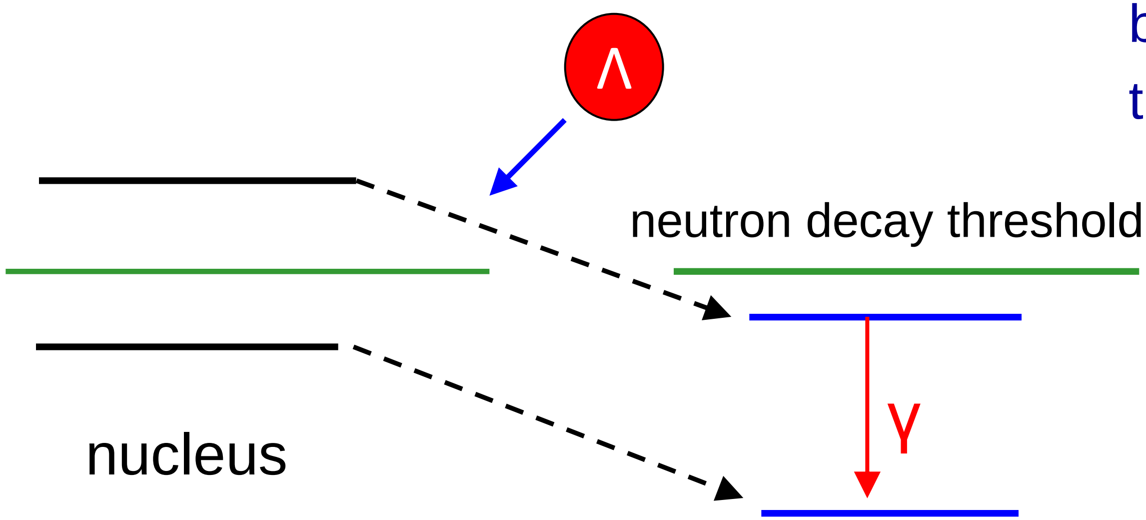
No Pauli principle
Between N and Λ



Hypernucleus

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

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

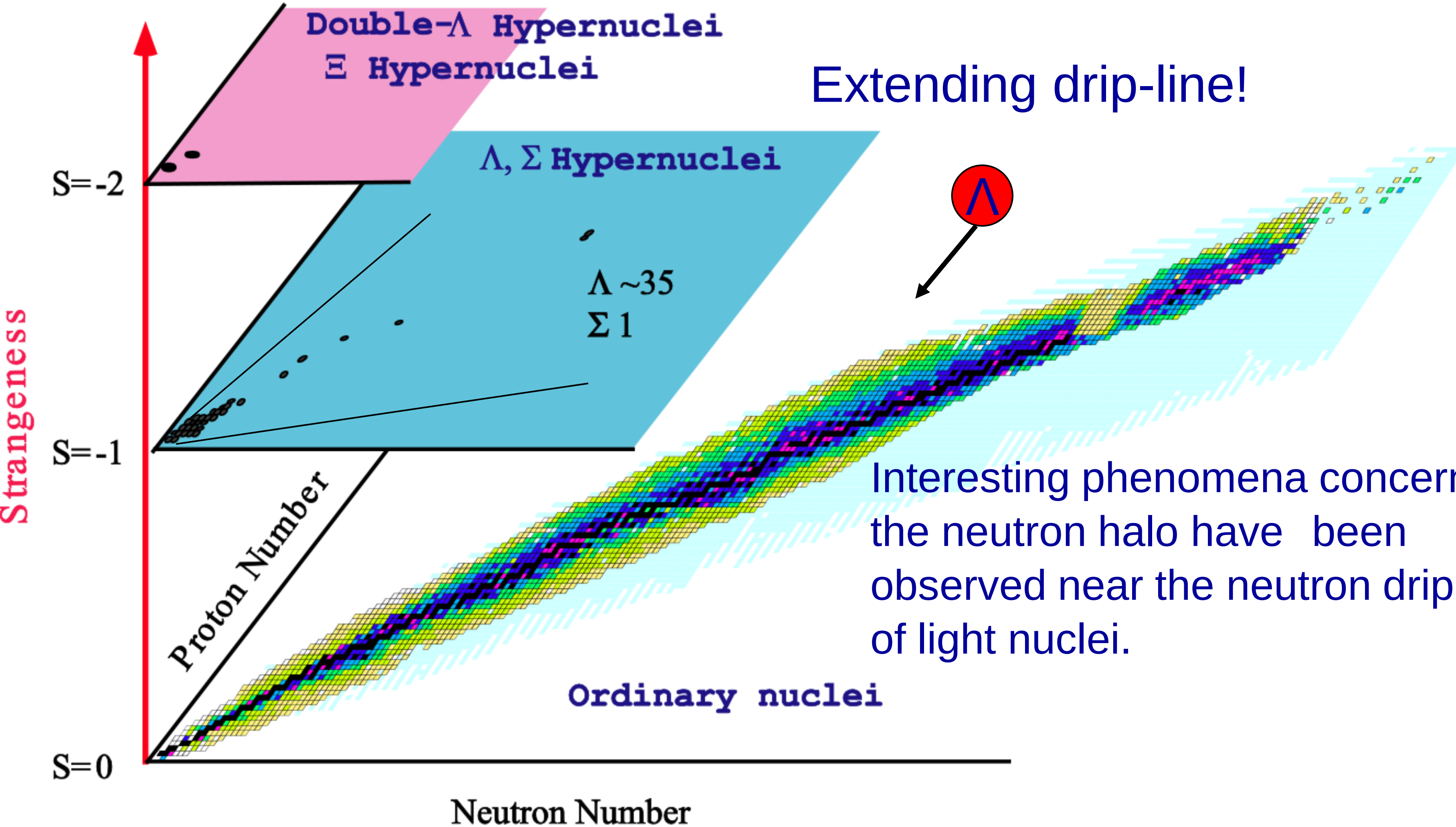


hypernucleus

Nuclear chart with strangeness

Multi-strangeness system
such as Neutron star

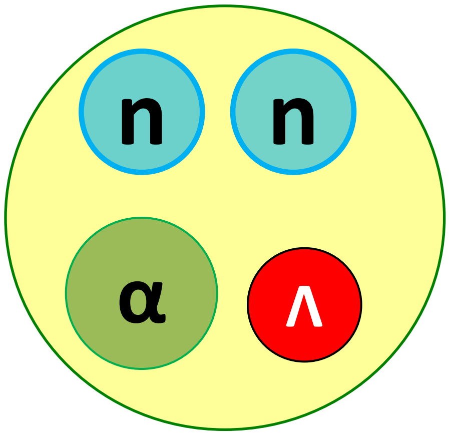
Extending drip-line!



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

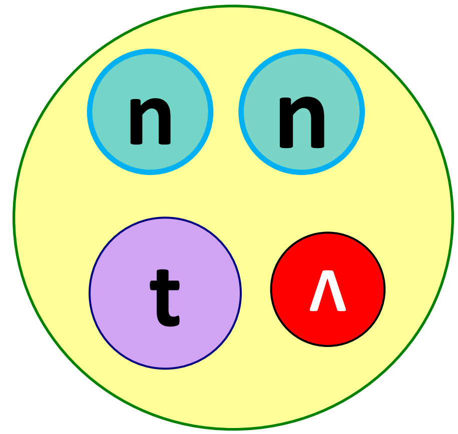
Question : How is structure change when a Λ particle is injected into neutron-rich nuclei?

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

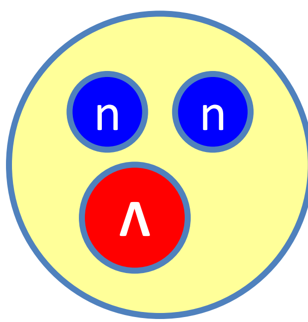


Observed at JLAB, Phys. Rev. Lett. **110**, 12502 (2013).

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



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



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

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

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 ,

3- and 4-nucleon systems,

multi-cluster structure of light nuclei,

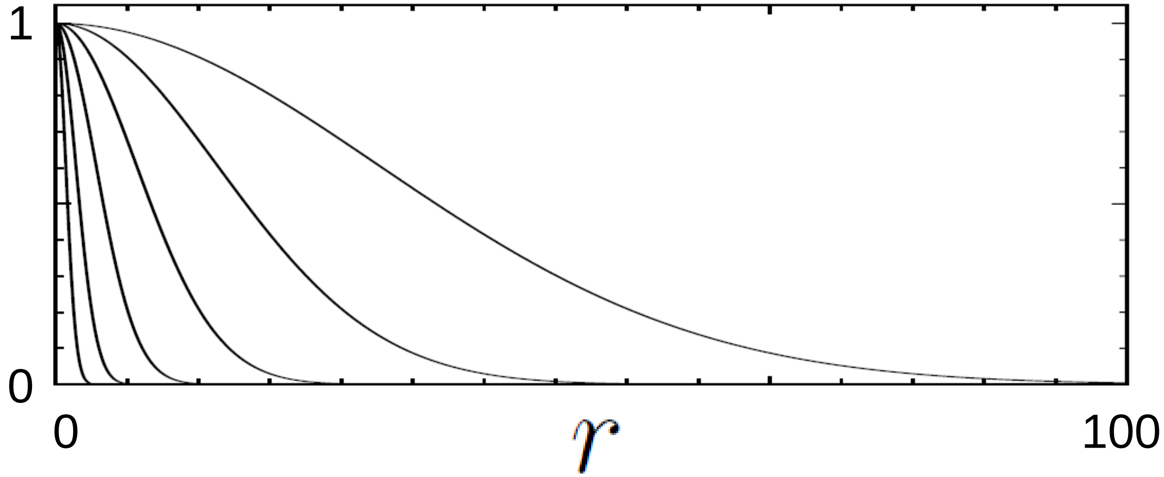
Light hypernuclei,

3-quark systems,

^{4}He-atom tetramer

Section 2

Gaussian Expansion Method (GEM) for Few-Body Systems



In order to solve the **Schrödinger equation, we use Rayleigh-Ritz variational method and we obtain eigen value E and eigen function Ψ.**

$$(\mathbf{H} - \mathbf{E})\,\boldsymbol{\Psi} = \mathbf{0}$$

Here, we expand the total wavefunction in terms of a set of L^2-integrable basis function $\{\Phi_n$:n=1,….,N)}

$$\boldsymbol{\Psi} = \sum_{\mathbf{n}=1}^{\mathbf{N}} \mathbf{C_n}\,\boldsymbol{\Phi}_\mathbf{n}$$

The Rayleigh-Ritz variational principle leads to a generalized matrix eigenvalue problem.

$$\langle\, \boldsymbol{\Phi}_\mathbf{i} \,|\, \mathbf{H} - \mathbf{E} \,|\, \underbrace{\sum_{\mathbf{n}=1}^{\mathbf{N}} \mathbf{C_n}\,\boldsymbol{\Phi}_\mathbf{n}}_{=\,\boldsymbol{\Psi}} \,\rangle = \mathbf{0}\,, \qquad (\mathbf{i} = \mathbf{1}, \ldots, \mathbf{N})$$

Where the energy and overlap matrix elements are given by

$$H_{in} = \langle \Phi_i \mid H \mid \Phi_n \rangle$$

$$N_{in} = \langle \Phi_i \mid 1 \mid \Phi_n \rangle$$

Next, by solving eigenstate problem, we get eigenenergy E and unknown coefficients C_n .

$$\left[(H_{in}) - E\,(N_{in}) \right] \left[\mathbf{C_n} \right] = 0$$

An important issue of the variational method is how to select a good set of basis functions.

What is good set of basis functions?

(1) To describe short-ranged correlation and long-range tail behaviour, highly oscillatory character of few-body wave functions, etc.

(2) Easily to calculate the matrix elements of Hamiltonian

$$H_{in} = \langle \Phi_i \mid H \mid \Phi_n \rangle, \quad N_{in} = \langle \Phi_i \mid 1 \mid \Phi_n \rangle$$

For this purpose, we use the following basis function:

$$\Phi_{lmn}(r) = r^{\ell} e^{-\nu_n r^2} Y_{\ell m}(\hat{\mathbf{r}})$$

$$v_n = (1/r_n)^2$$

$$r_n = r_1 a^{n-1} \quad (n = 1 - n_{max})$$

The Gaussian basis function is suitable not only for the calculation of the matrix elements but also for describing short-ranged correlations, long-ranged tail behaviour.

The merit of this method:

(1)To calculate the energy of bound state
very accurately

(2) To calculate the wavefunction very precisely

one successful examples

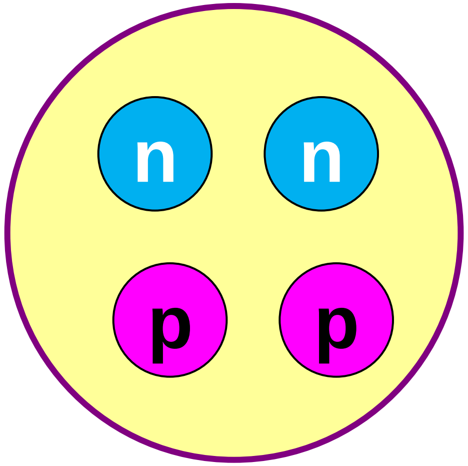
PRC **64**, 044001(2001)

Benchmark-test calculation to solve the 4-nucleon bound state

7 different groups (18 co-authors)

1. Faddeev-Yakubovski (Kamada et al.)
2. Gaussian Expansion Method
   (Kamimura and Hiyama)
3. Stochastic varitional (Varga et al.)
4. Hyperspherical variational (Viviani et al.)
5. Green Function Variational Monte Carlo
   (Carlson at al.)
6. Non-Core shell model (Navratil et al.)
7. Effective Interaction Hypershperical
   HarmonicsEIHH (Barnea et al.)

^{4}He



4-nucleon
bound state
NN**:** AV8’

Benchmark-test calculation of the 4-nucleon bound state

Good agreement among 7different methods

In the binding energy, r.m.s. radius and wavefunction density

TABLE I. The expectation values $\langle T \rangle$ and $\langle V \rangle$ of kinetic and potential energies, the binding energies E_b in MeV, and the radius in fm.

Method	$\langle T \rangle$	$\langle V \rangle$	E_b	$\sqrt{\langle r^2 \rangle}$
FY	102.39(5)	−128.33(10)	−25.94(5)	1.485(3)
GEM	102.30	−128.20	−25.90	1.482
SVM	102.35	−128.27	−25.92	1.486
HH	102.44	−128.34	−25.90(1)	1.483
GFMC	102.3(1.0)	−128.25(1.0)	−25.93(2)	1.490(5)
NCSM	103.35	−129.45	−25.80(20)	1.485
EIHH	100.8(9)	−126.7(9)	−25.944(10)	1.486

ours

very different techniques and the complexity of the nuclear force chosen. Except for NCSM and EIHH, the expectation values of T and V also agree within three digits. The NCSM results are, however, still within 1% and EIHH within 1.5% of the others, but note that the EIHH results for T and V are

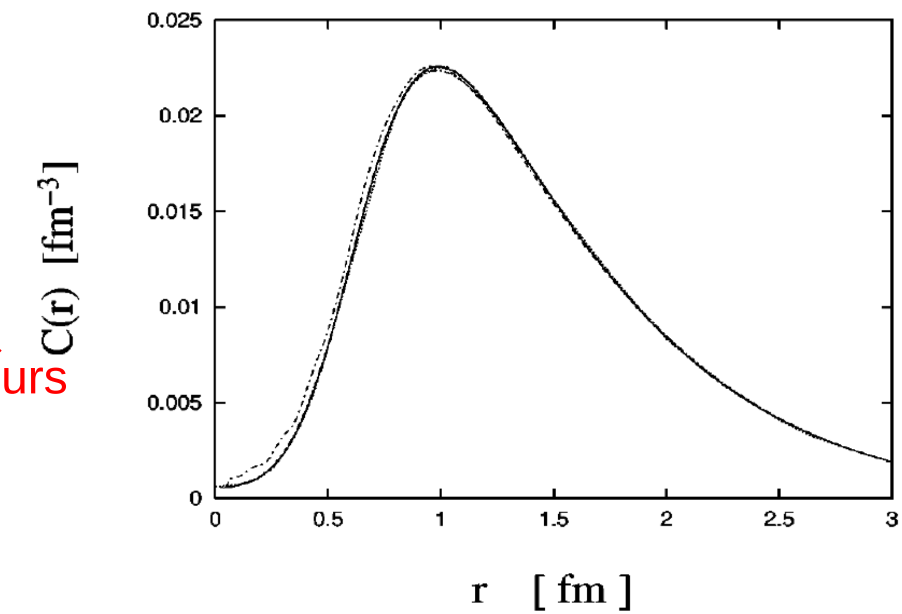
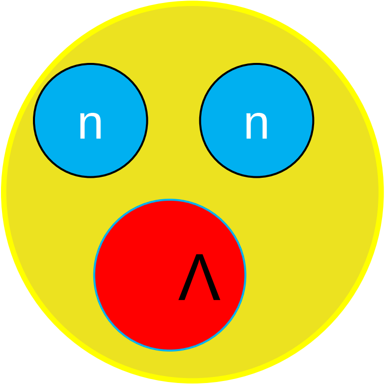


FIG. 1. Correlation functions in the different calculational schemes: EIHH (dashed-dotted curves), FY, CRCGV, SVM, HH, and NCSM (overlapping curves).

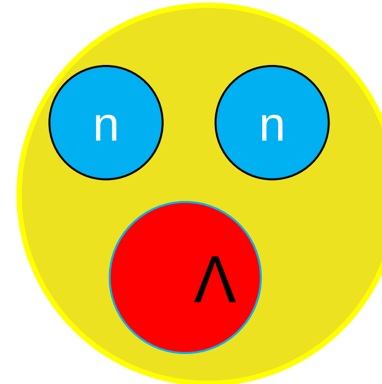
Section 3

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



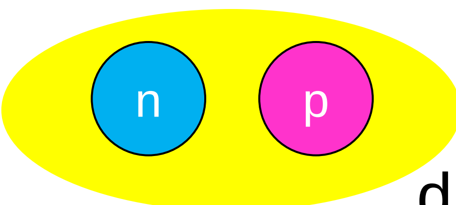
E. Hiyama, S. Ohnishi, B.F. Gibson, and T. A. Rijken, PRC89, 061302(R) (2014).

What is interesting to study nnΛ system?



S=0

The lightest nucleus to have a bound state is deuteron.



d

n+p threshold

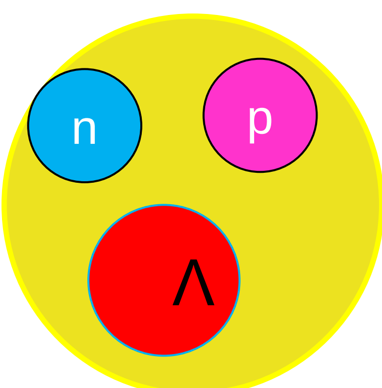
J=1^+

-2.22 MeV

Exp.

S=-1 (Λ hypernucear sector)

n+p+Λ



Lightest hypernucleus to have a bound state

d+Λ

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

0.13 MeV

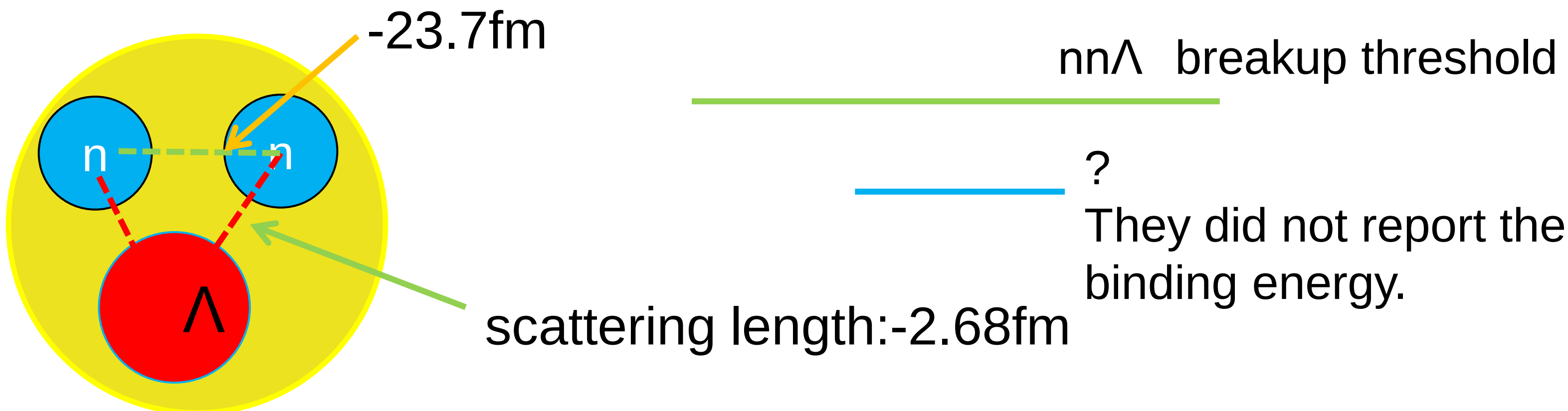
J=$1/2^+$

Exp.

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

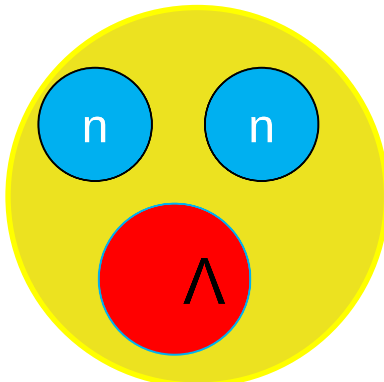
Search for evidence of ${}^{3}_{\Lambda}n$ by observing $d+\pi^-$ and $t+\pi^-$ final states in the reaction of ${}^{6}\mathrm{Li}+{}^{12}\mathrm{C}$ at $2A$ GeV

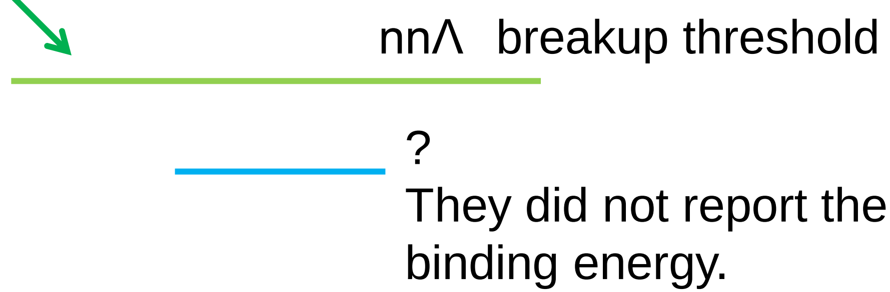
C. Rappold,[1,2,*] E. Kim,[1,3] T. R. Saito,[1,4,5,†] O. Bertini,[1,4] S. Bianchin,[1] V. Bozkurt,[1,6] M. Kavatsyuk,[7] Y. Ma,[1,4] F. Maas,[1,4,5] S. Minami,[1] D. Nakajima,[1,8] B. Özel-Tashenov,[1] K. Yoshida,[1,5,9] P. Achenbach,[4] S. Ajimura,[10] T. Aumann,[1,11] C. Ayerbe Gayoso,[4] H. C. Bhang,[3] 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)



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?



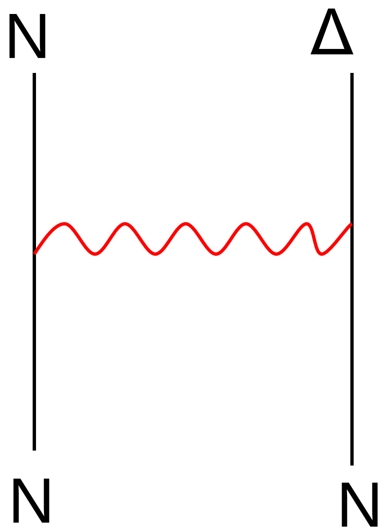


NN interaction : to reproduce the observed binding energies of ^{3}H and ^{3}He

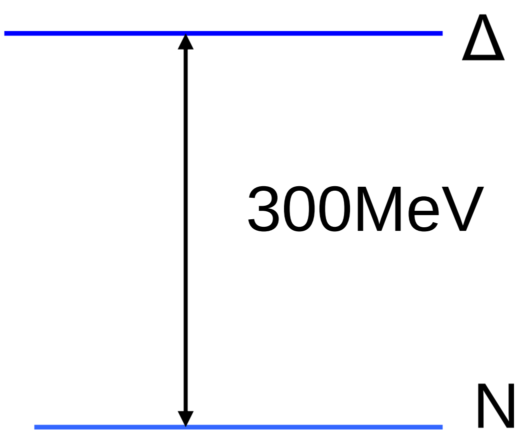
NN: AV8 potential
We do not include 3-body force for nuclear sector.

How about YN interaction?

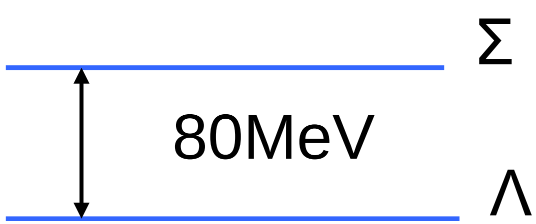
Non-strangeness nuclei

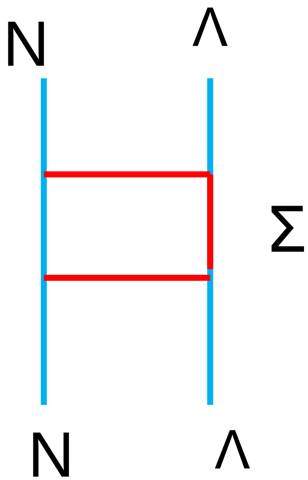


Nucleon can be converted into Δ.
However, since mass difference between nucleon and Δ is large, then probability of Δ in nucleus is not large.

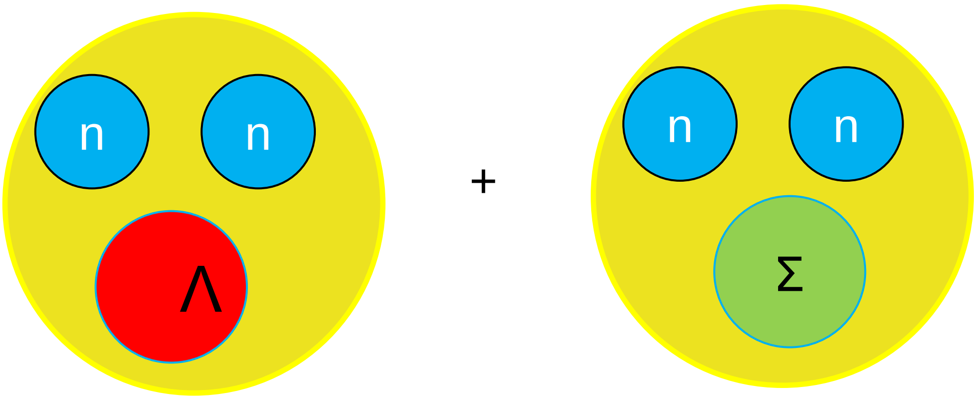


On the other hand, the mass difference between Λ and Σ is much smaller, then Λ can be converted into Σ particle easily.



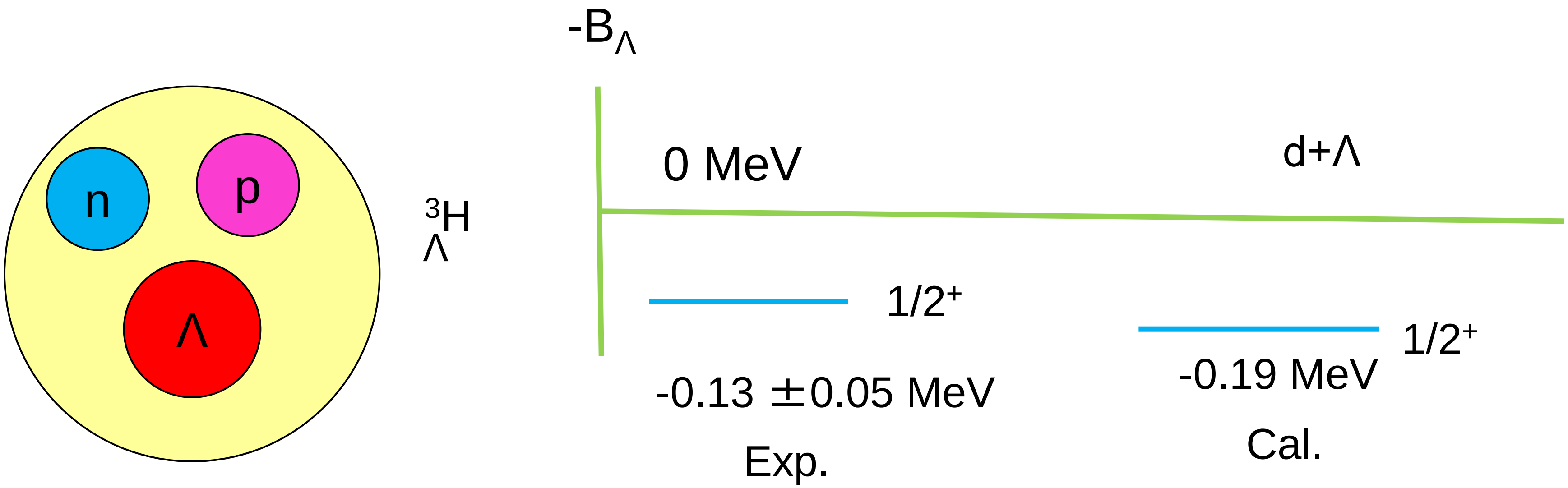


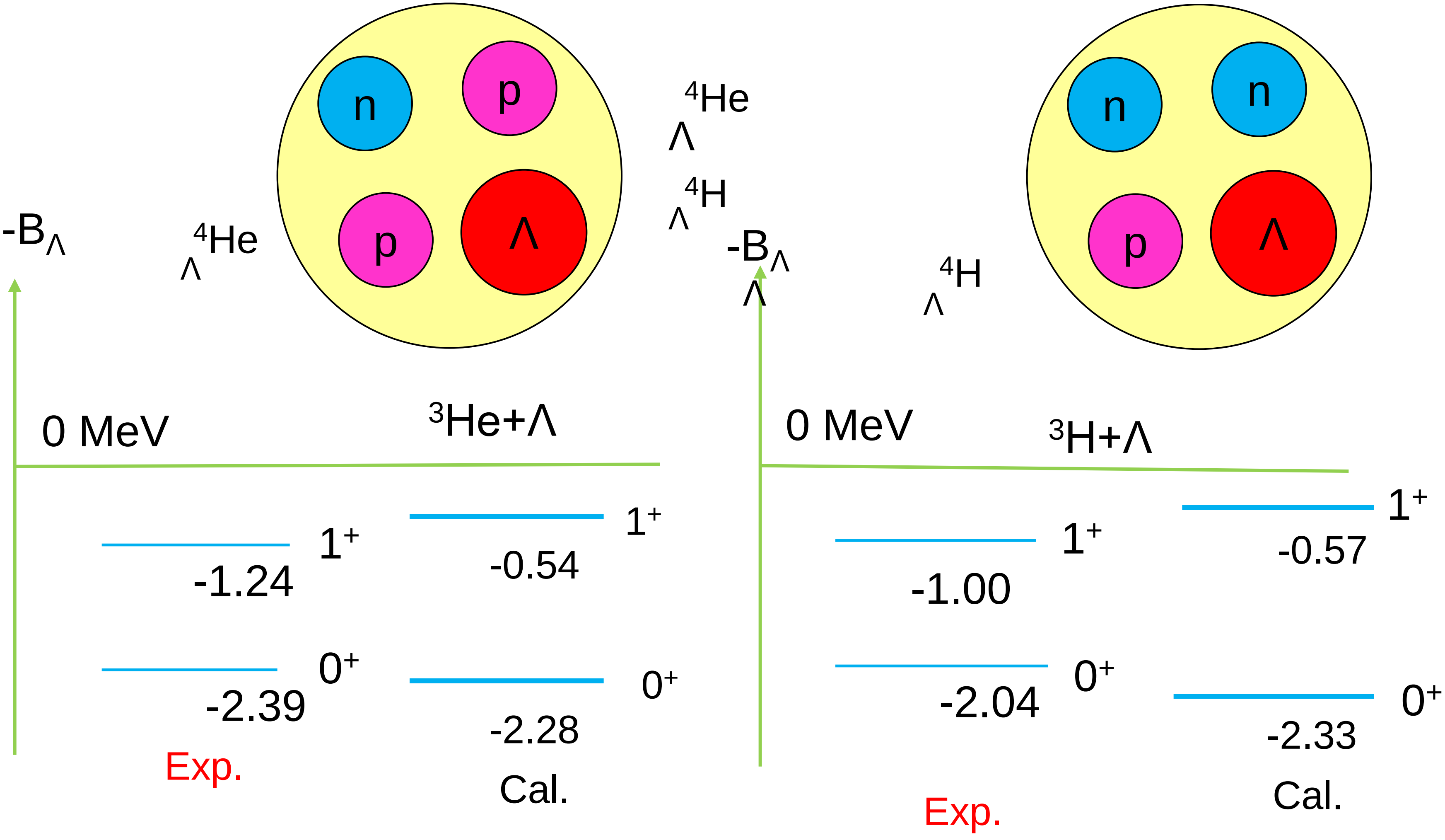
To take into account of Λ particle to be converted into Σ particle, we should perform below calculation using realistic hyperon(Y)-nucleon(N) interaction.



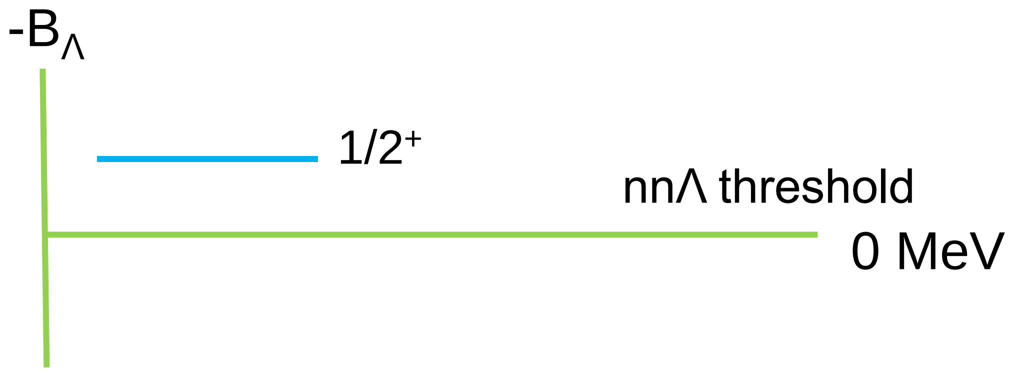
YN interaction: Nijmegen soft core '97f potential (NSC97f) proposed by Nijmegen group

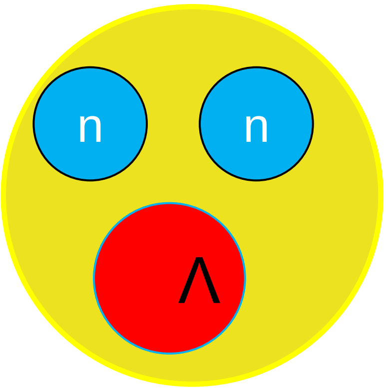
reproduce the observed binding energies of ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$ and ${}^{4}_{\Lambda}He$


n
p
Λ
³ΛH
-BΛ
0 MeV
d+Λ
1/2+
1/2+
-0.13 ±0.05 MeV
-0.19 MeV
Exp.
Cal.



What is binding energy of nnΛ?





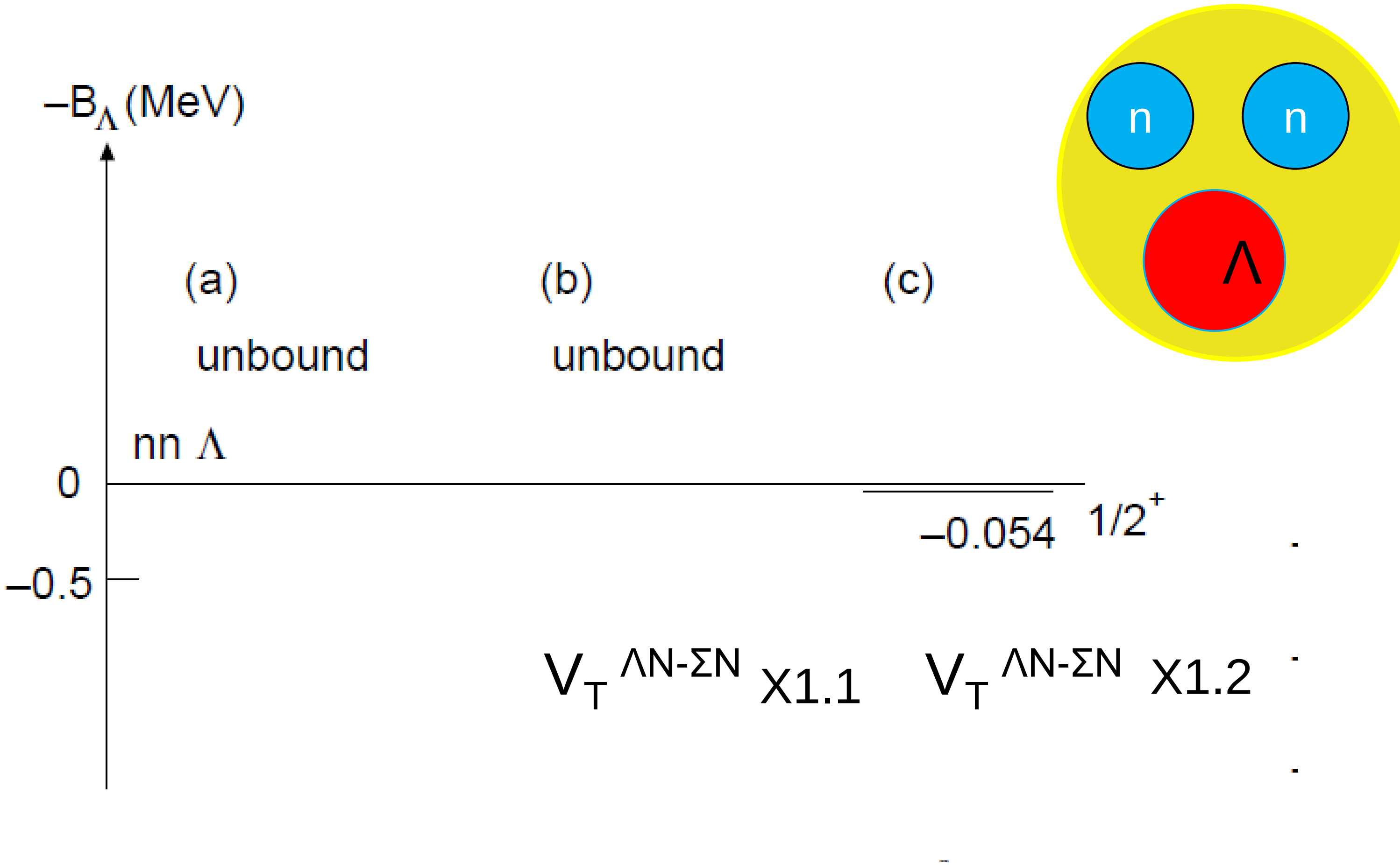
We have no bound state in nnΛ system.
This is inconsistent with the data.

Now, we have a question.

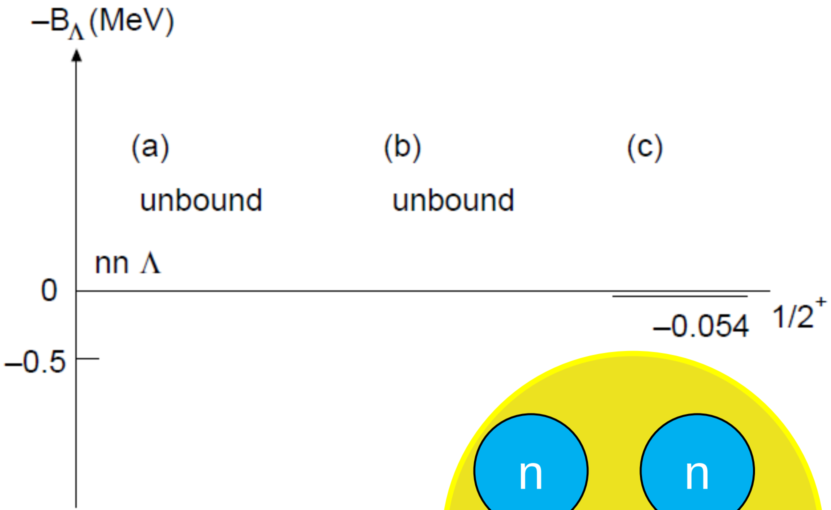
Do we have a possibility to have a bound state in nnΛ system tuning strength of YN potential ?

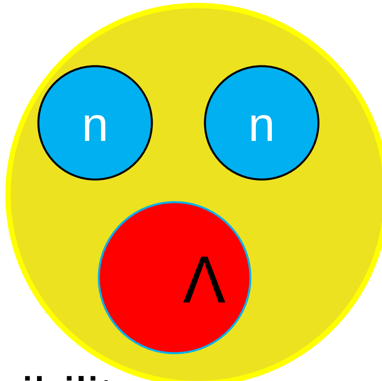
It should be noted to maintain consistency with the binding energies of ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He.

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





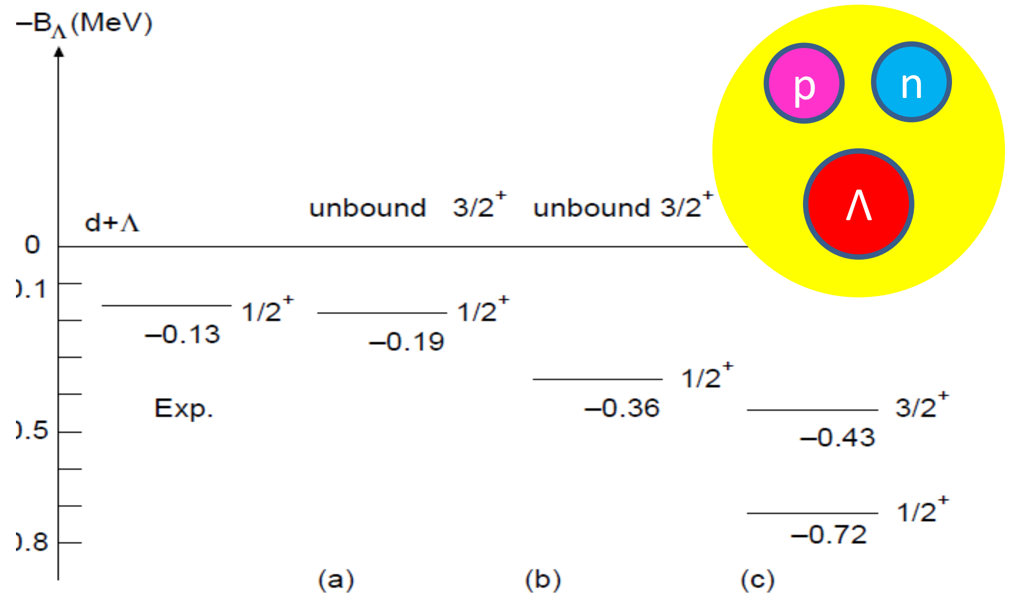
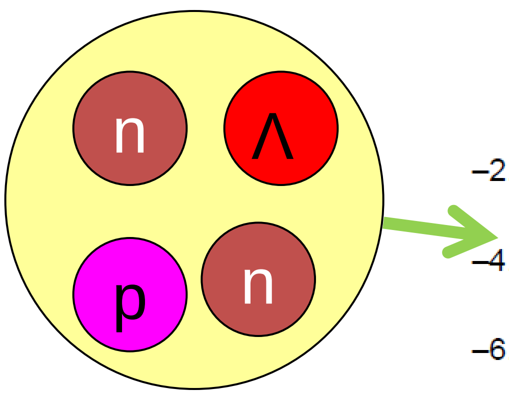
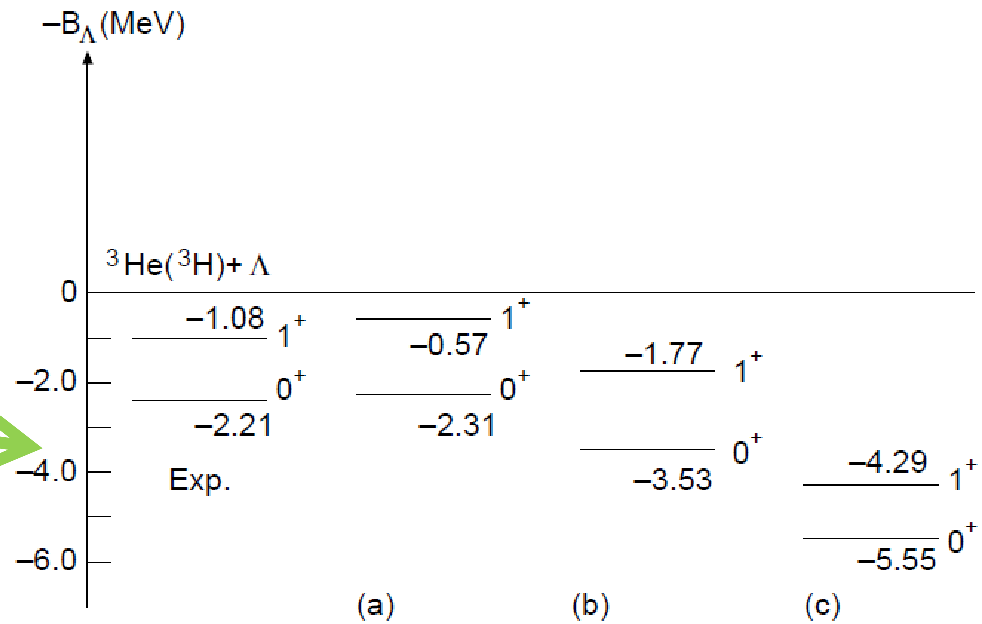


FIG. 3: Calculated Λ-separation energy for $^3_\Lambda$H with (a) $^3V^T_{N\Lambda-N\Sigma}$ × 1.00, (b) $^3V^T_{N\Lambda-N\Sigma}$ × 1.10, and (c) $^3V^T_{N\Lambda-N\Sigma}$ ×

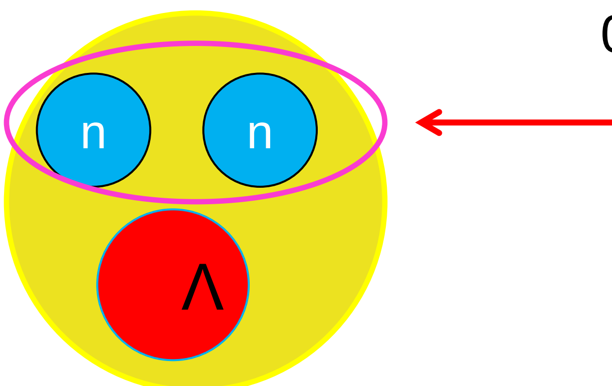
We have no possibility to have a bound state in nnΛ system.





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 ^3H and ^3He 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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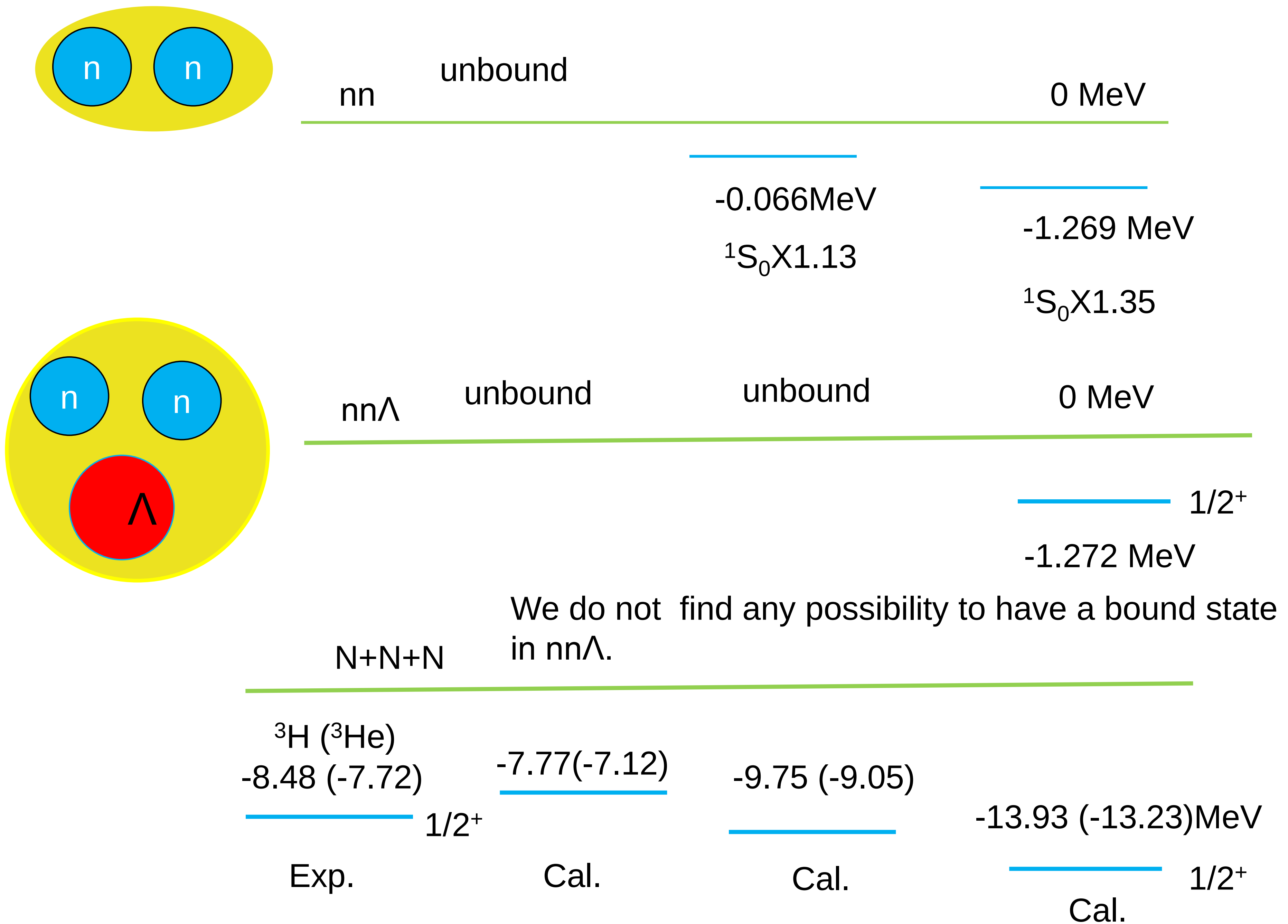
(Received 24 April 2012; published 25 June 2012)

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)
$1/2^+$
Exp.
-7.77(-7.12)
Cal.
-9.75 (-9.05)
Cal.
-13.93 (-13.23)MeV
$1/2^+$
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.

H. Garcilazo and A. Valcarce, PRC89, 057001(2014).

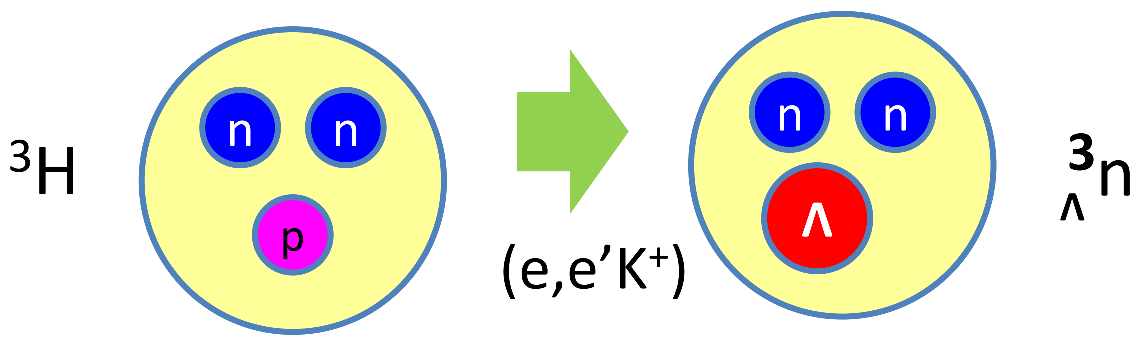
A. Gal and H. Garcilazo, PLB736, 93 (2014).

They concluded to have no bound state in nnΛ system.

It is planned to perform an improved experiment of nnΛ system at HypHI collaboration+Super FRS in 2018.

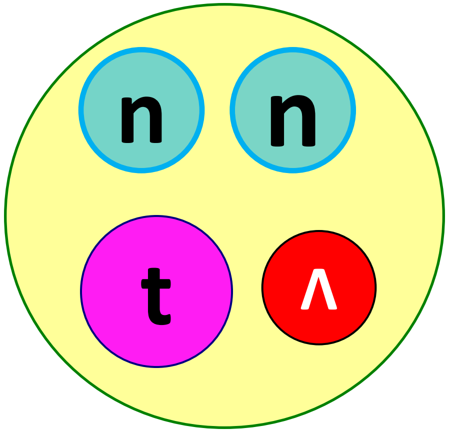
Furthermore, it should be noted that a direct measurement of nnΛ by the (e,e'K+) reaction can be possible at JLab.
If we have a bound state for this system, it is important to get information on ΛN-ΣN coupling.

For this purpose, it is a quite important measurement theoretically as well as experimentally.



Section 4

Four-body calculation of ${}^{6}_{\Lambda}H$



E. H, S. Ohnishi, M. Kamimura, Y. Yamamoto, NPA **908** (2013) 29.

PRL 108, 042501 (2012) PHYSICAL REVIEW LETTERS week ending 27 JANUARY 2012

Evidence for Heavy Hyperhydrogen $^{6}_{\Lambda}H$

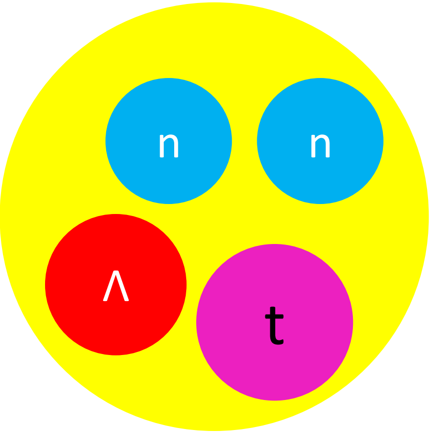
M. Agnello,[1,2] L. Benussi,[3] M. Bertani,[3] H. C. Bhang,[4] G. Bonomi,[5,6] E. Botta,[7,2,*] M. Bregant,[8] T. Bressani,[7,2] S. Bufalino,[2] L. Busso,[9,2] D. Calvo,[2] P. Camerini,[10,11] B. Dalena,[12] F. De Mori,[7,2] G. D'Erasmo,[13,14] F. L. Fabbri,[3] A. Feliciello,[2] A. Filippi,[2] E. M. Fiore,[13,14] A. Fontana,[6] H. Fujioka,[15] P. Genova,[6] P. Gianotti,[3] N. Grion,[10] V. Lucherini,[3] S. Marcello,[7,2] N. Mirfakhrai,[16] F. Moia,[5,6] O. Morra,[17,2] T. Nagae,[15] H. Outa,[18] A. Pantaleo,[14,†] V. Paticchio,[14] S. Piano,[10] R. Rui,[10,11] G. Simonetti,[13,14] R. Wheadon,[2] and A. Zenoni[5,6]

(FINUDA Collaboration)

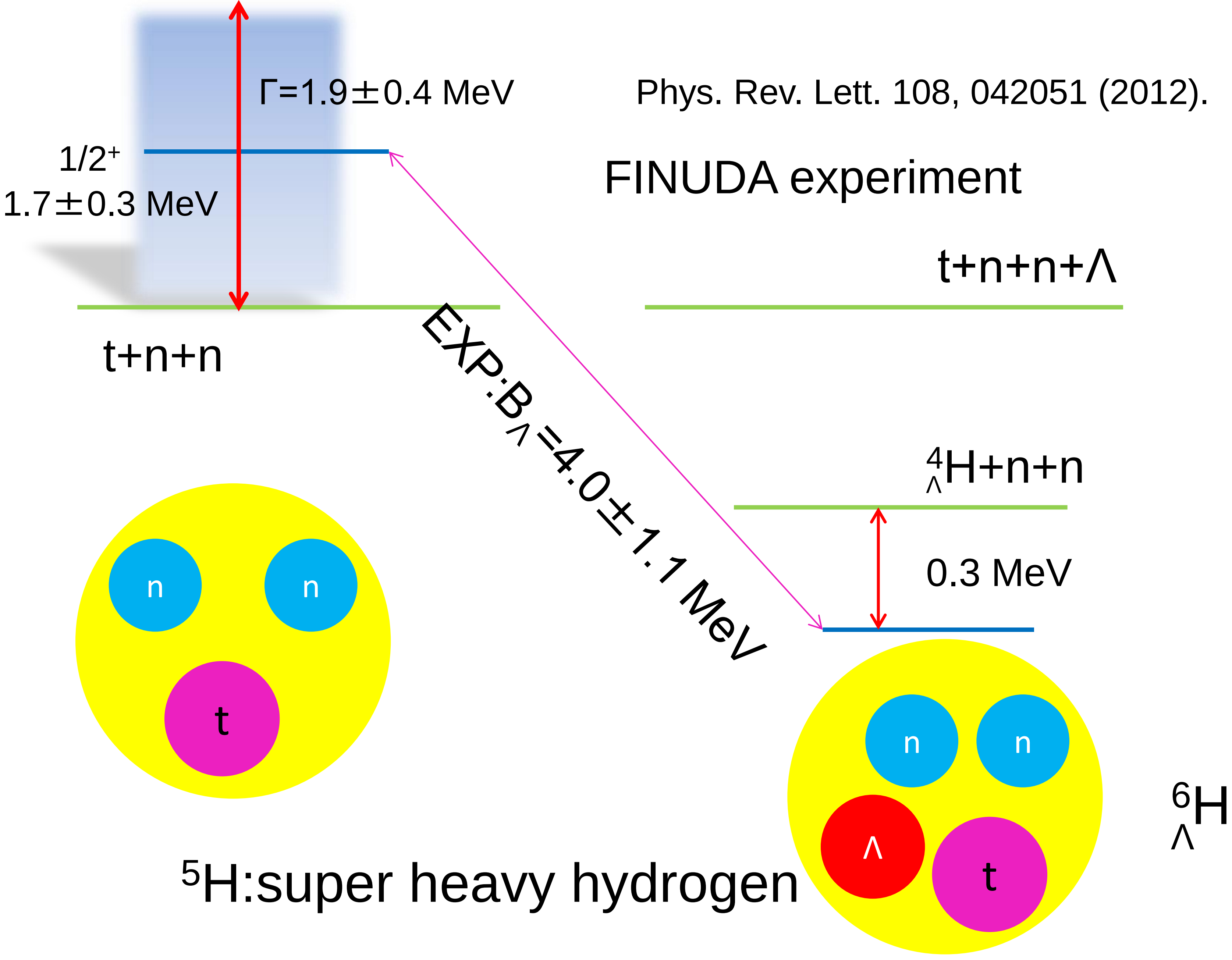
A. Gal

Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel

(Received 2 November 2011; published 24 January 2012)



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


Γ=1.9±0.4 MeV
Phys. Rev. Lett. 108, 042051 (2012).
1/2+
1.7±0.3 MeV
FINUDA experiment
t+n+n+Λ
t+n+n
EXP:BΛ =4.0±1.1 MeV
4ΛH+n+n
0.3 MeV
n
n
t
n
n
Λ
t
6ΛH
5H:super heavy hydrogen

Before experiment, the following authors calculated the binding energies by shell model picture and G-matrix theory.

(1) R. H. Dalitz and R. Kevi-Setti, Nuovo Cimento 30, 489 (1963).

(2) L. Majling, Nucl. Phys. A585, 211c (1995).

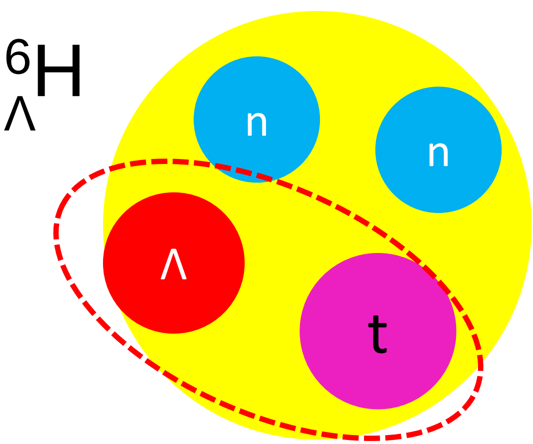
(3) Y. Akaishi and T. Yamazaki, Frascati Physics Series Vol. 16 (1999).

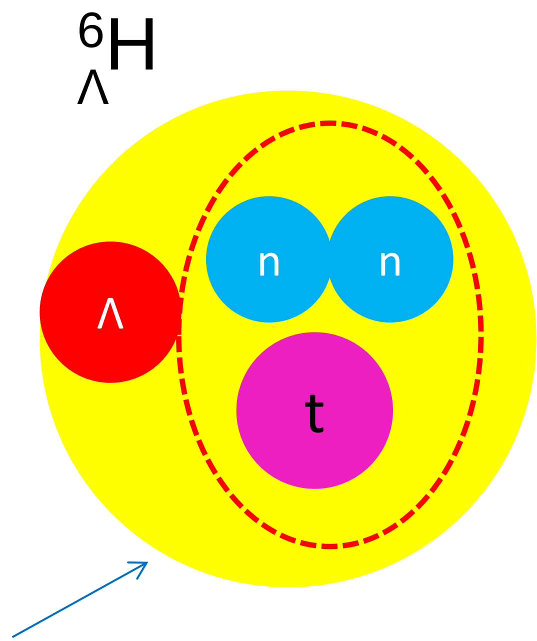
Motivating the experimental data, I calculated the binding energy of ${}^{6}_{\Lambda}H$ and I shall show you my result.

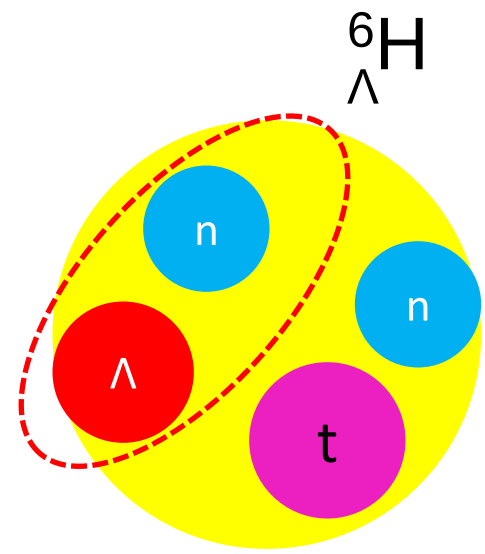
Before doing full 4-body calculation,

it is important and necessary to reproduce the observed binding energies of all the sets of subsystems in $^{6}_{\Lambda}\mathrm{H}$.

Namely, All the potential parameters are needed to
adjust in the 2- and 3-body subsystems.



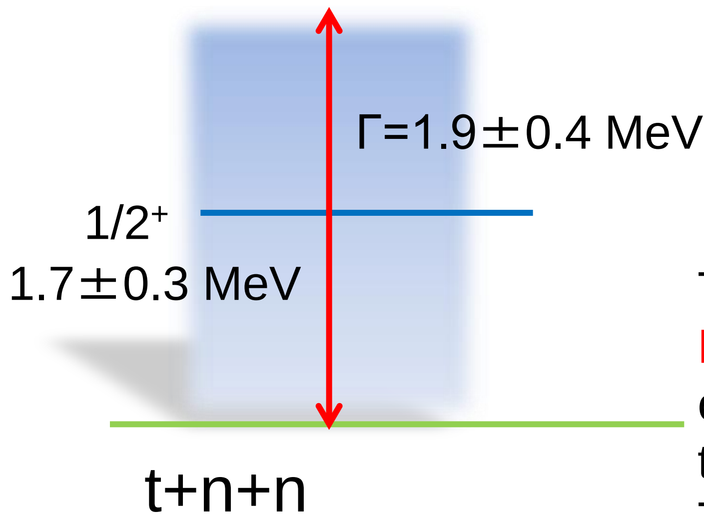




Among the subsystems, it is extremely important to adjust the energy of $^{5}\mathrm{H}$ core nucleus.

Framework:

To calculate the binding energy of $_{\Lambda}{}^{6}H$, it is very important to reproduce the binding energy of the core nucleus ^5H.



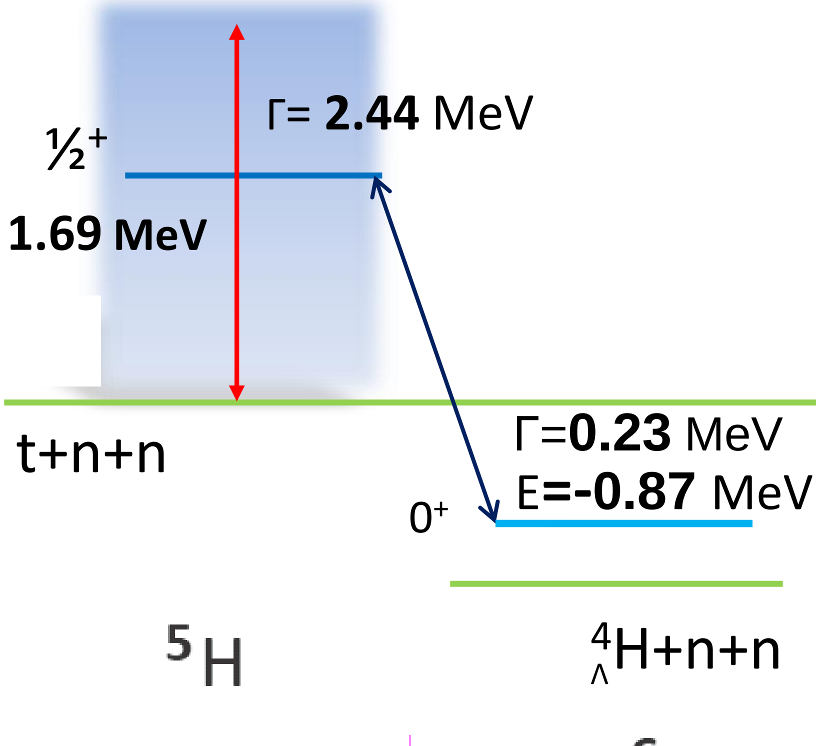
transfer reaction p(^{6}He, ^{2}He)^{5}H

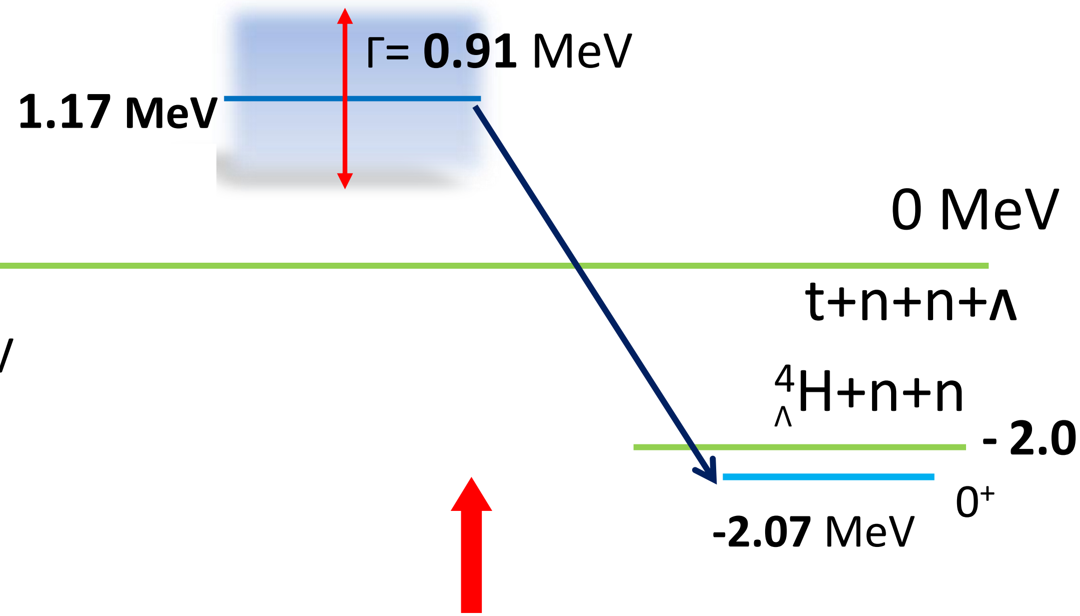
A. A. Korcheninnikov, et al. Phys. Rev. Lett. 87 (2001) 092501.

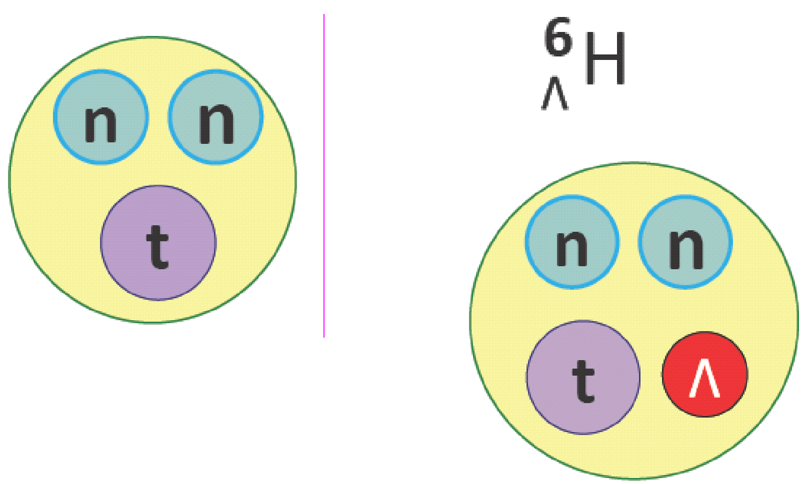
To reproduce the data, for example,
R. De Diego et al, Nucl. Phys. A786 (2007), 71.
calculated the energy and width of ^{5}H with t+n+n three-body model using complex scaling method. The calculated binding energy for the ground state of ^{5}H is 1.6 MeV with respect to t+n+n threshold and width has 1.5 MeV.

Exp: 1.7 ±0.3 MeV
Γ=1.9 ±0.4 MeV

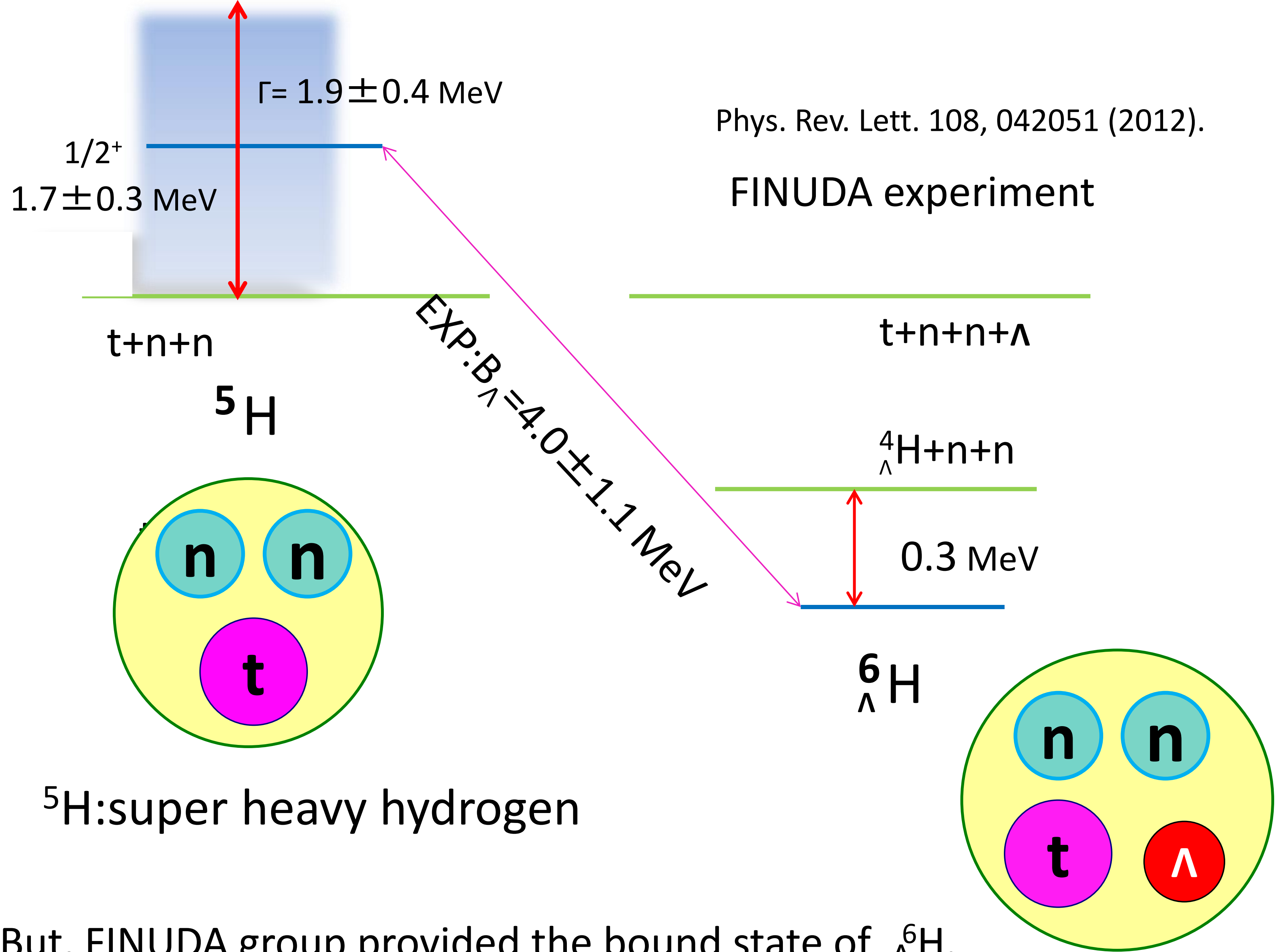
Even if the potential parameters were tuned so as to reproduce the lowest value of the Exp. , E=1.4 MeV, Γ=1.5 MeV, we do not obtain any bound state of $^{6}_{\Lambda}H$.







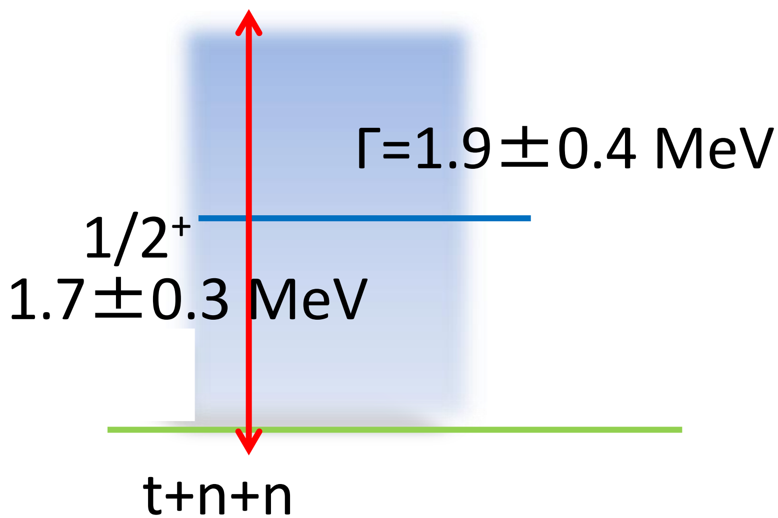
On the contrary, if we tune the potentials to have a bound state in $^{6}_{\Lambda}H$, then what is the energy and width of ^{5}H?



But, FINUDA group provided the bound state of ${}^{6}_{\Lambda}H$.

How should I understand the inconsistency between our results and the observed data?

We need more precise data of ^{5}H.



A. Korcheninnikov, et al. Phys. Rev. Lett. 87 (2001) 092501.

To get bound state of $^{6}_{\Lambda}\mathbf{H}$, the energy should be lower than the present data.

It is planned to measure the energy and width of ^{5}H more precisely at RCNP in December in 2014 . We should wait for new data at RCNP.

(E_R, Γ_R) (MeV)	
J^π	$1/2^+$
^{5}H (full)	(1.57, 1.53)
^{5}H ($d = 0$)	(1.55, 1.35)
Theor. [16]	(2.26, 2.93)
Theor. [12]	(2.5–3.0, 3–4)
Theor. [13]	(3.0–3.2, 1–4)
Theor. [15]	(1.59, 2.48)
Exp. [3]	(1.7 ± 0.3, 1.9 ± 0.4) ←
Exp. [8]	(1.8 ± 0.1, < 0.5)
Exp. [4]	(1.8, 1.3)
Exp. [5]	(2, 2.5)
Exp. [6]	(3, 6)
Exp. [9]	(5.5 ± 0.2, 5.4 ± 0.6)

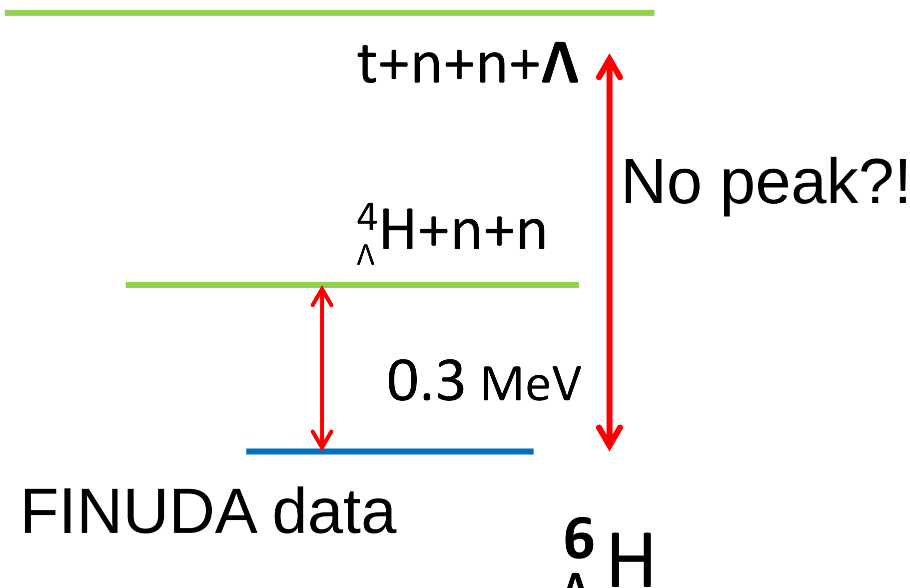
We cited this experiment. However, you have many different decay widths. width is strongly related to the size of wavefunction.

[3] A.A. Korosheninnikov et al., PRL87 (2001) 092501
[8] S.I. Sidorchuk et al., NPA719 (2003) 13
[4] M.S. Golovkov et al. PRC 72 (2005) 064612
[5] G. M. Ter-Akopian et al., Eur. Phys. J A25 (2005) 315.

Search for $^{6}_{\Lambda}$H hypernucleus by the ^{6}Li(π^-, K^+) reaction at p_{π^-} = 1.2 GeV/c

H. Sugimura[a,b,*], M. Agnello[c,d], J.K. Ahn[e], S. Ajimura[f], Y. Akazawa[g], N. Amano[a], K. Aoki[h], H.C. Bhang[i], N. Chiga[g], M. Endo[j],
P. Evtoukhovitch[k], A. Feliciello[d], H. Fujioka[a], T. Fukuda[l], S. Hasegawa[b], S. Hayakawa[j], R. Honda[g], K. Hosomi[g], S.H. Hwang[b],
Y. Ichikawa[a,b], Y. Igarashi[h], K. Imai[b], N. Ishibashi[j], R. Iwasaki[h], C.W. Joo[i], R. Kiuchi[i,b], J.K. Lee[e], J.Y. Lee[i], K. Matsuda[j],
Y. Matsumoto[g], K. Matsuoka[j], K. Miwa[g], Y. Mizoi[l], M. Moritsu[f], T. Nagae[a], S. Nagamiya[b], M. Nakagawa[j], M. Naruki[a],
H. Noumi[f], R. Ota[j], B.J. Roy[m], P.K. Saha[b], A. Sakaguchi[j], H. Sako[b], C. Samanta[n], V. Samoilov[k], Y. Sasaki[g], S. Sato[b],
M. Sekimoto[h], Y. Shimizu[l], T. Shiozaki[g], K. Shirotori[f], T. Soyama[j], T. Takahashi[h], T.N. Takahashi[o], H. Tamura[g], K. Tanabe[g],
T. Tanaka[j], K. Tanida[i], A.O. Tokiyasu[f], Z. Tsamalaidze[k], M. Ukai[g], T.O. Yamamoto[g], Y. Yamamoto[g], S.B. Yang[i], K. Yoshida[j],
(J-PARC E10 Collaboration)

arXiv:1310.6104v1 [nucl-ex] 23 Oct 2013



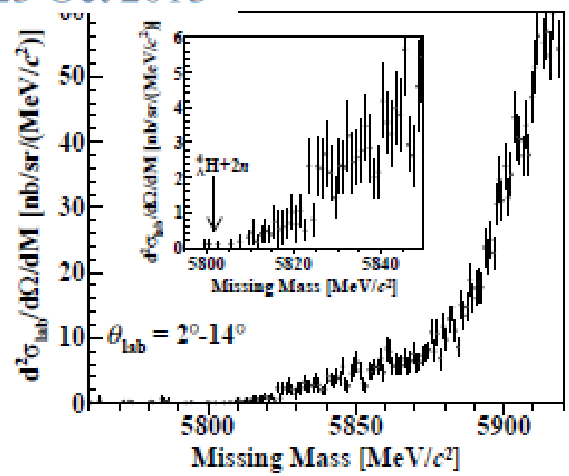
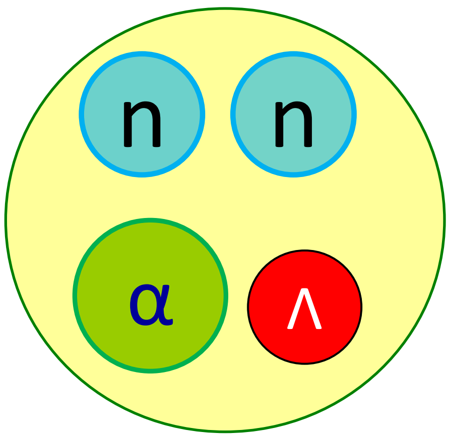


Figure 5: Missing-mass spectrum of the ^{6}Li(π^-, K^+) reaction at 1.2 GeV/c. A magnified view around the Λ bound region is shown in the inset. The arrow labeled as $^{4}_{\Lambda}$H+2n shows the particle decay threshold (5801.7 MeV/c^2).

Theoretically, we might understand by the following reason.
If the state is resonant state, the reaction cross section would be much smaller than that we expect. => I should calculate reaction cross section ^{6}Li (π,K) $^{6}_{\Lambda}$H.

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



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

PHYSICAL REVIEW C **91**, 054316 (2015)

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

E. Hiyama and M. Isaka

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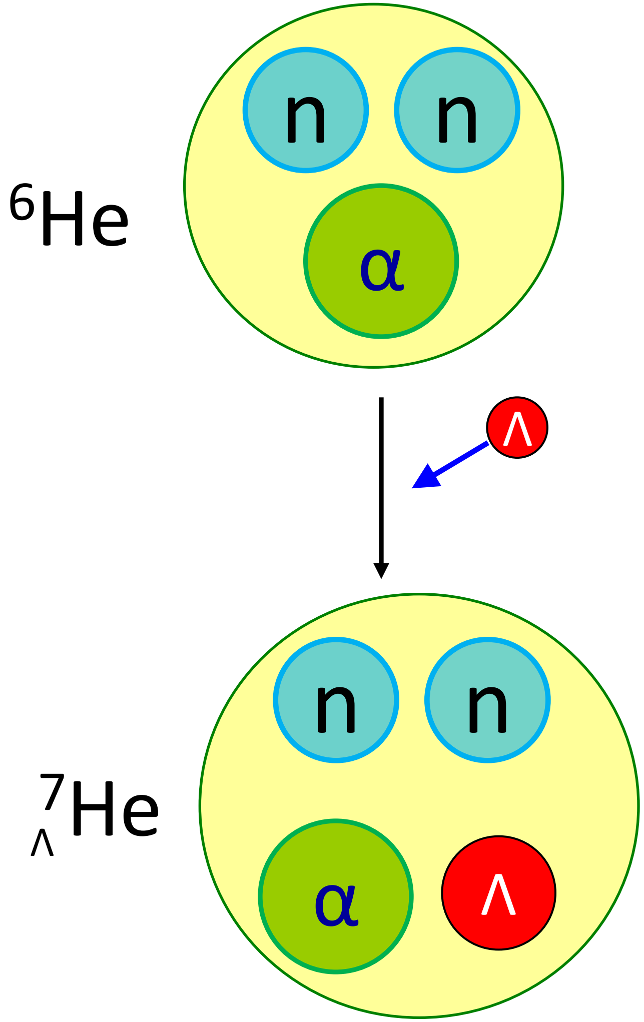
(Received 27 October 2014; revised manuscript received 20 April 2015; published 18 May 2015)

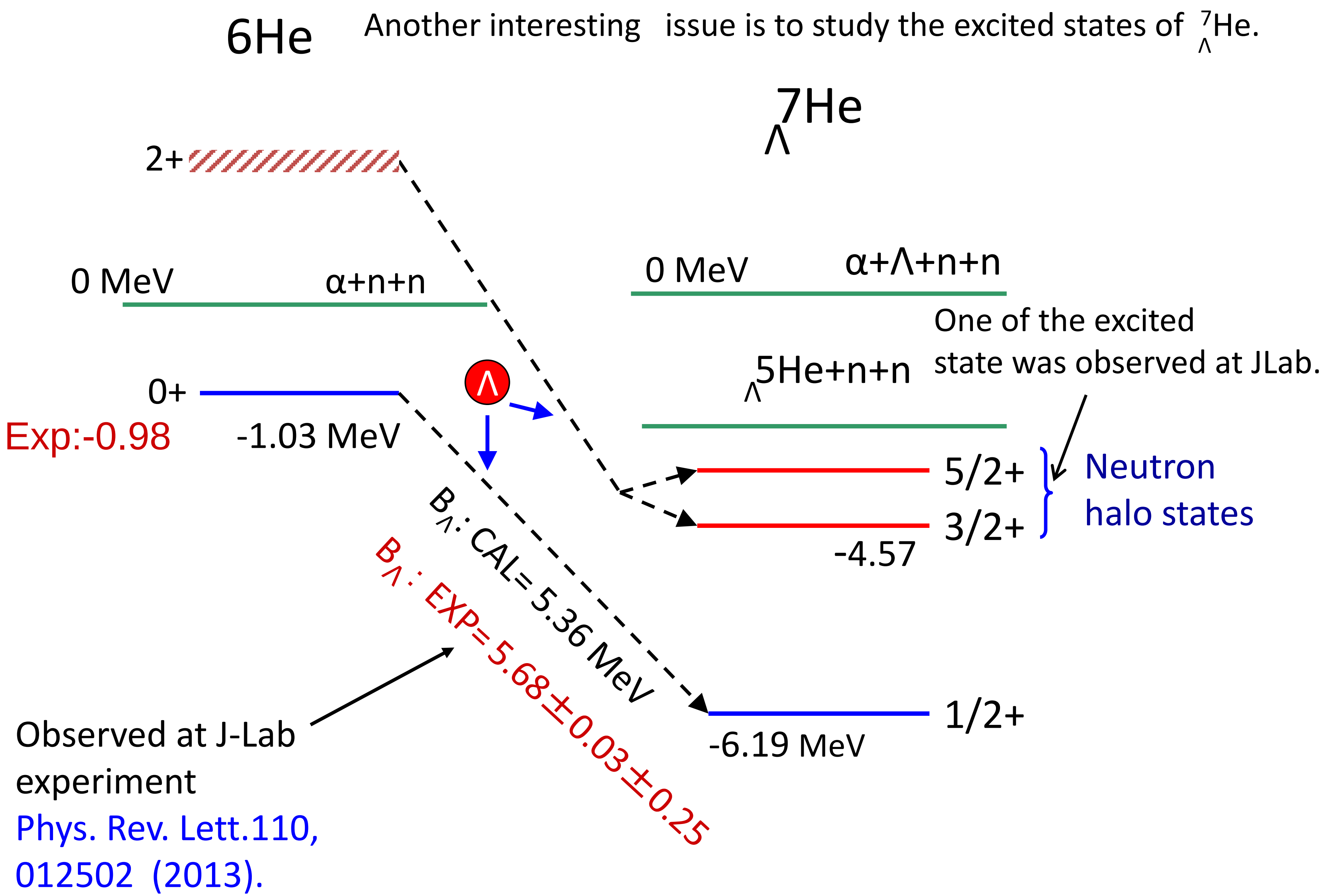


^{6}He : One of the lightest n-rich nuclei

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

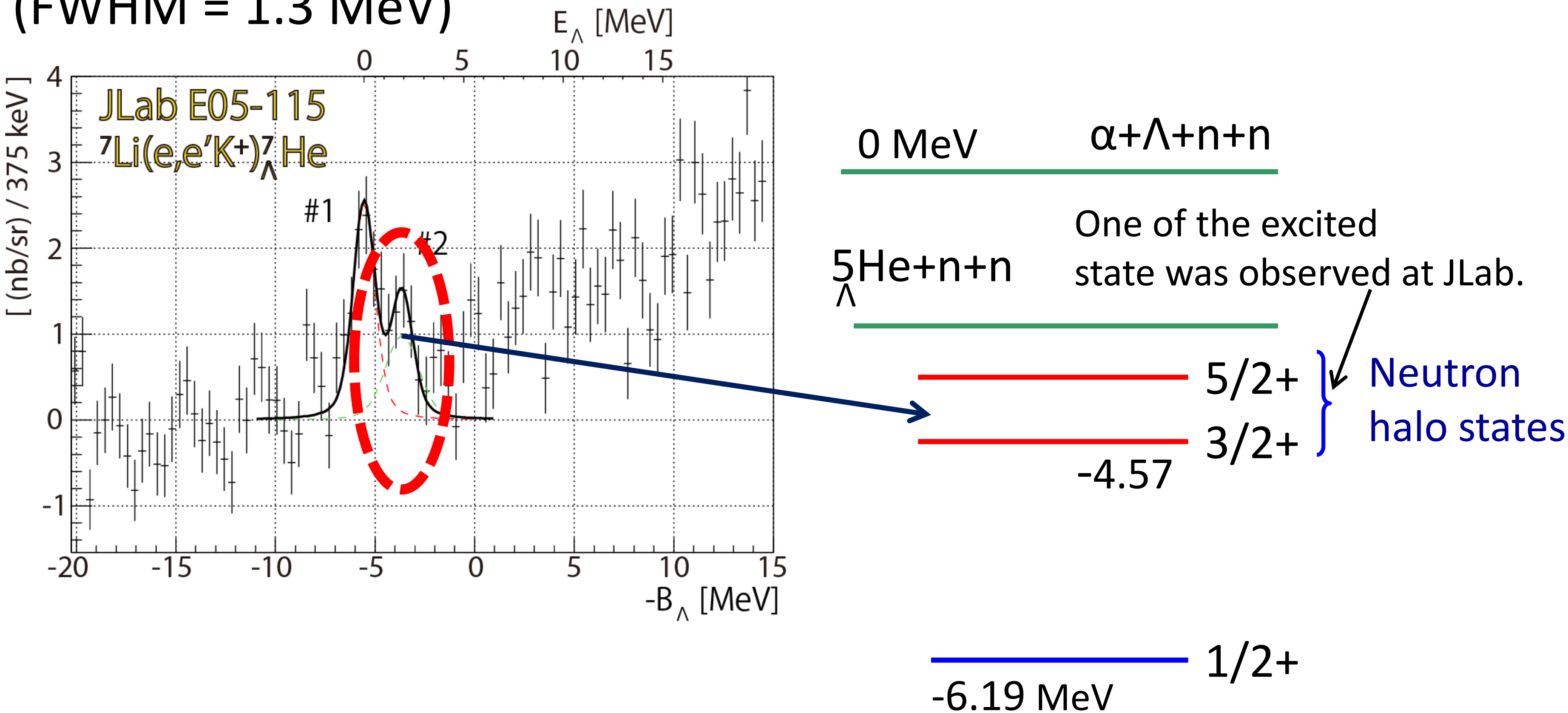
Observed at JLAB,
Phys. Rev. Lett. 110, 12502 (2013).

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



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

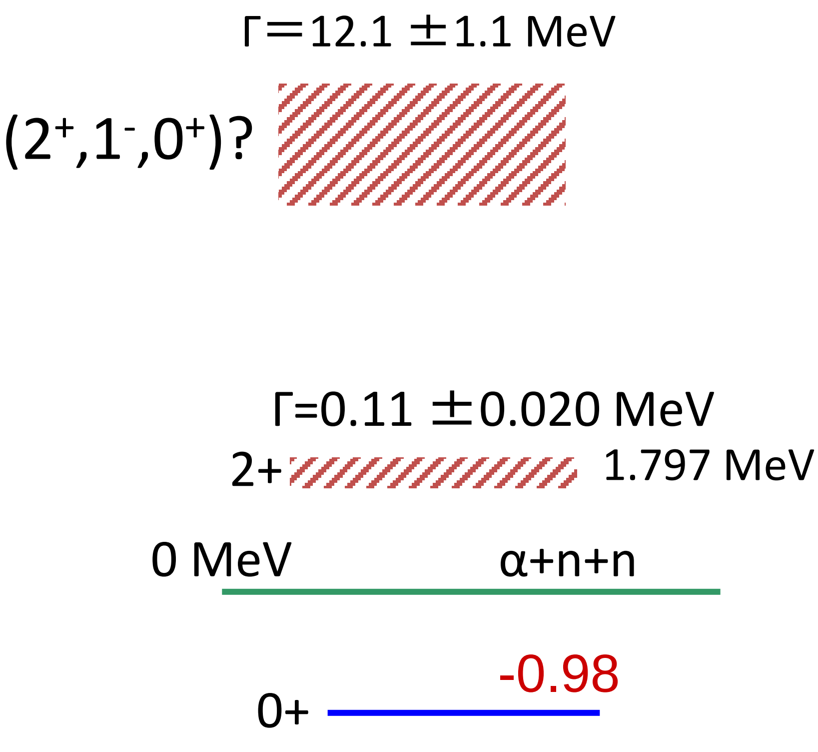
(FWHM = 1.3 MeV)



The calculated energy of the excited state is in good agreement with the data.

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

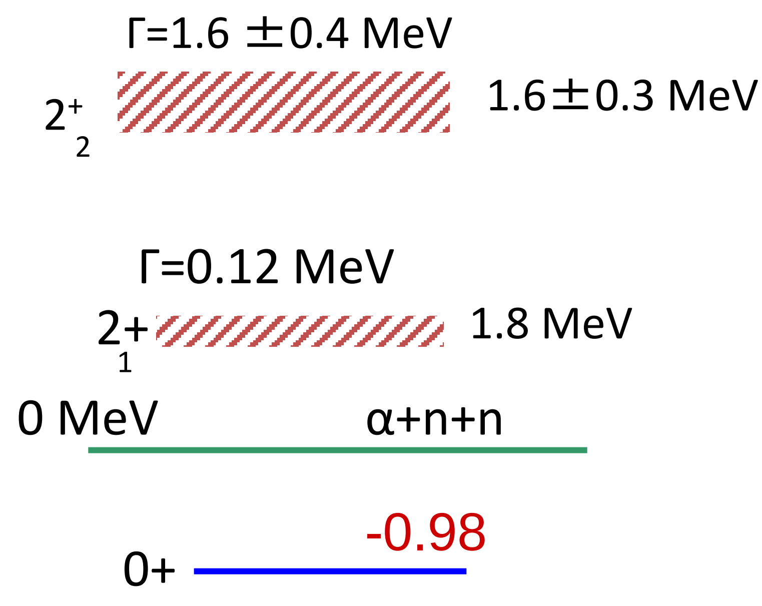
First, let us discuss about energy spectra of ^{6}He core nucleus.



^{6}He

Exp.

Data in 2002



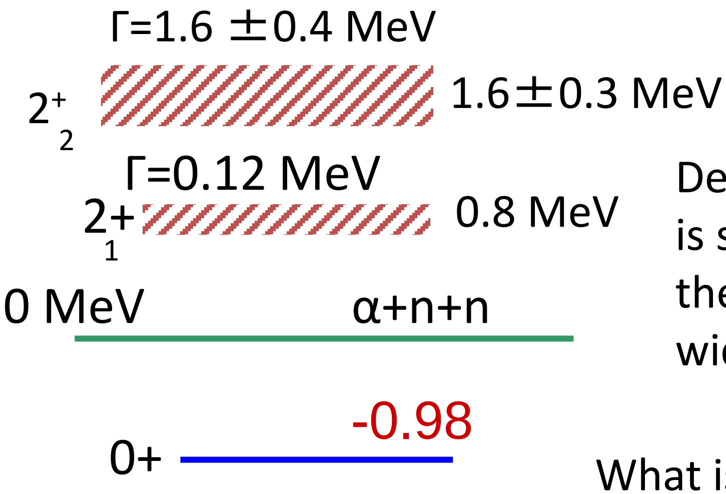
^{6}He

Exp.

Core nucleus

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

How about theoretical result?



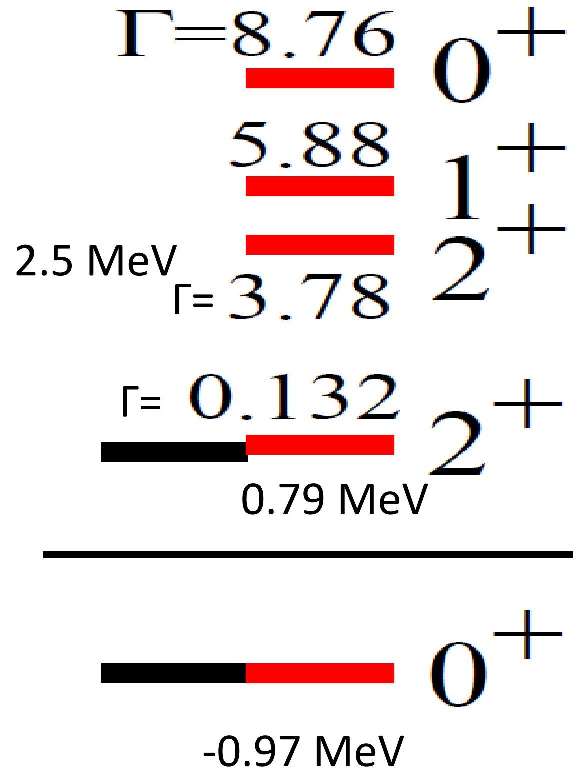
^{6}He

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 the calculated width.

What is my result?

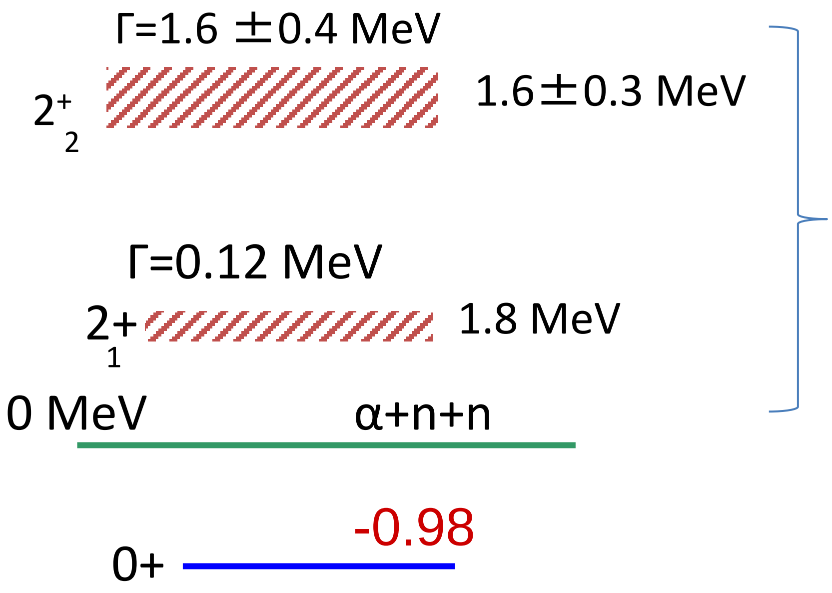


theory

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

^{6}He

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

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.
I will not explain about this method.

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.

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

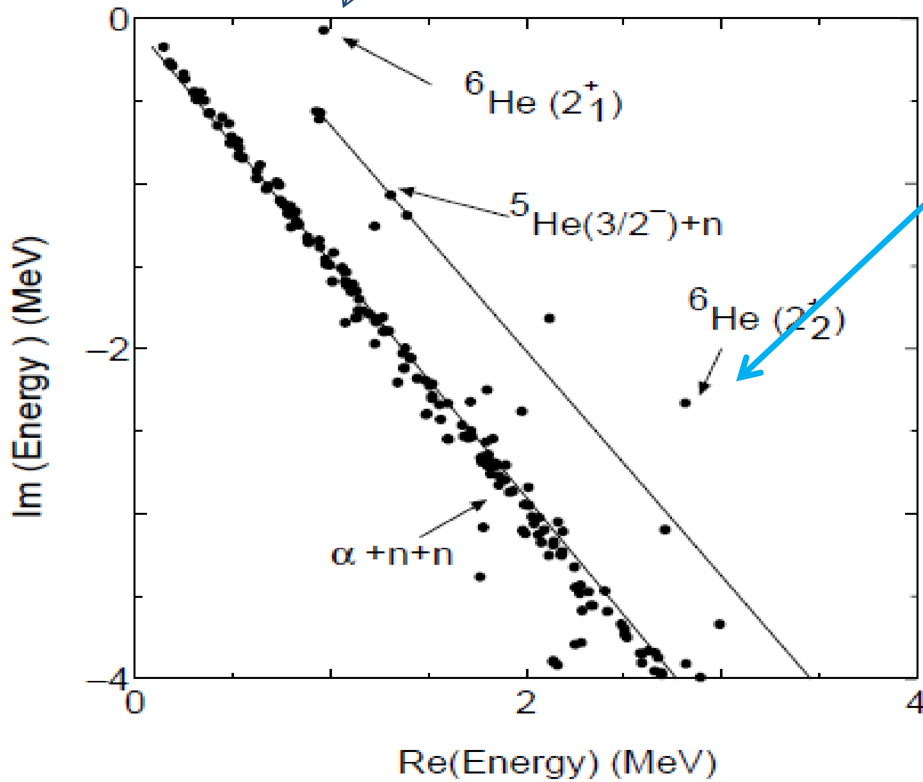
$E = E_r + i\Gamma/2$

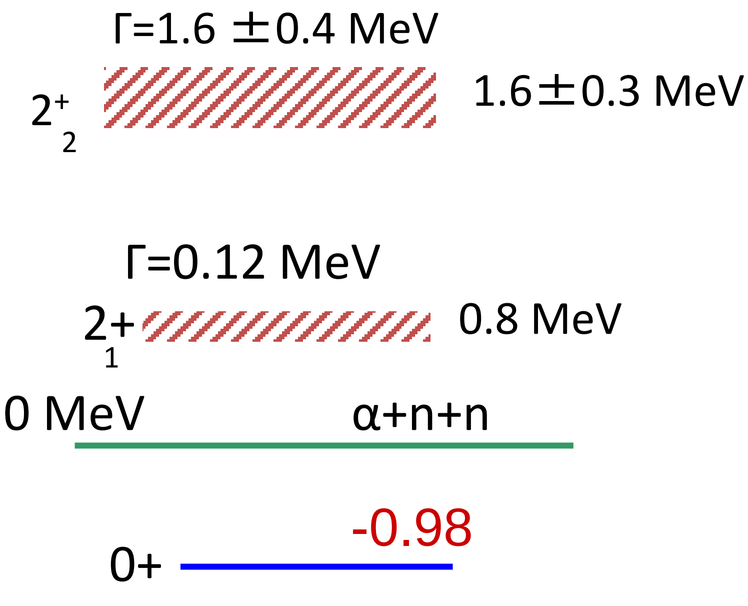
My result

E=0.96 + 0.14 MeV

θ=28° ～33°
The pole is stable.

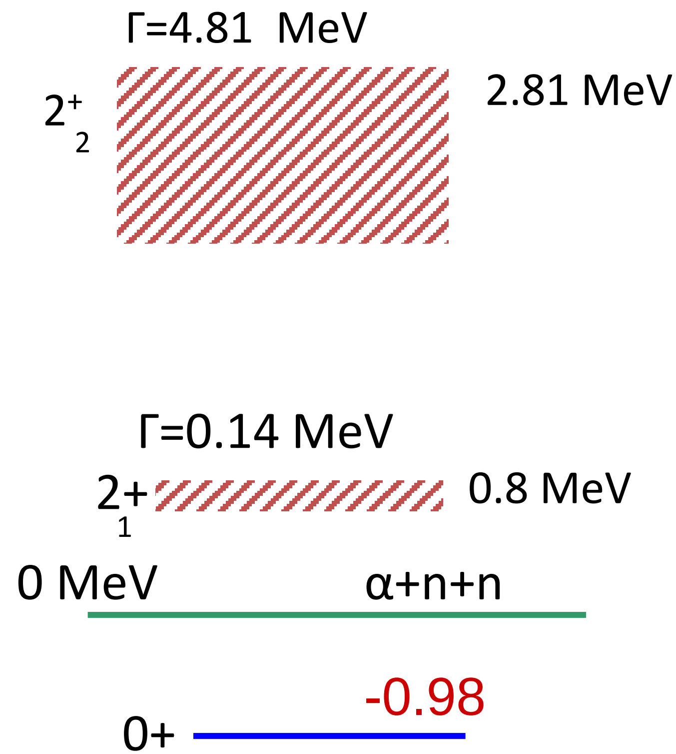
E=2.81 +4.81 MeV





^{6}He

Exp.



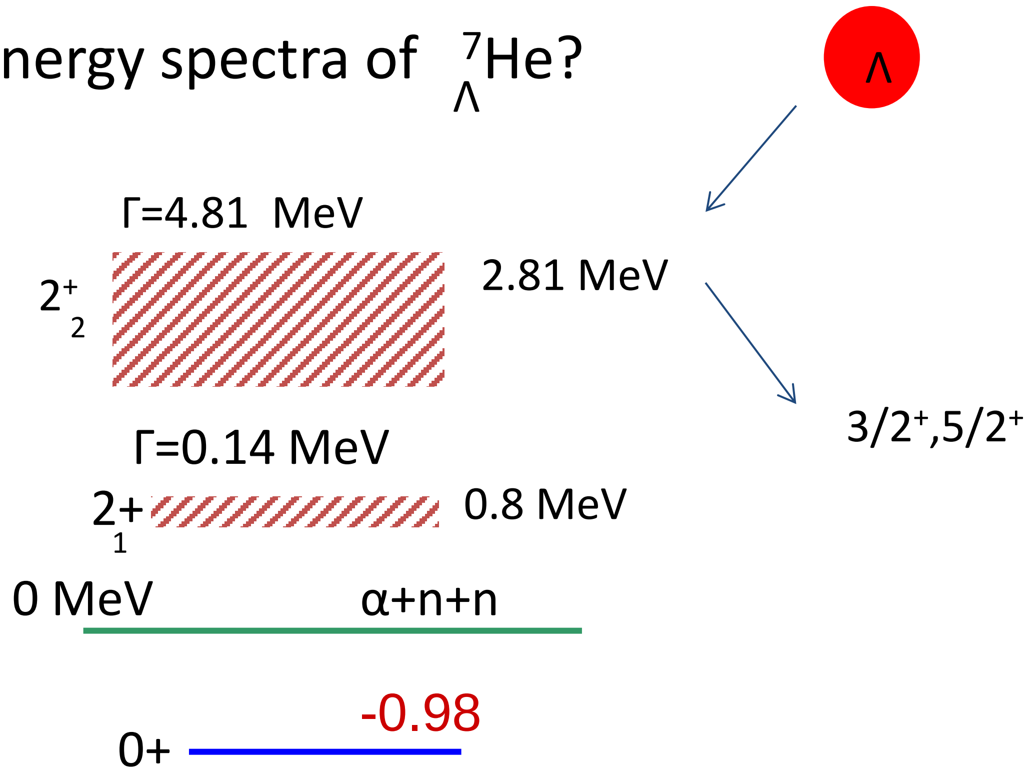
^{6}He

Cal.

Data in 2012

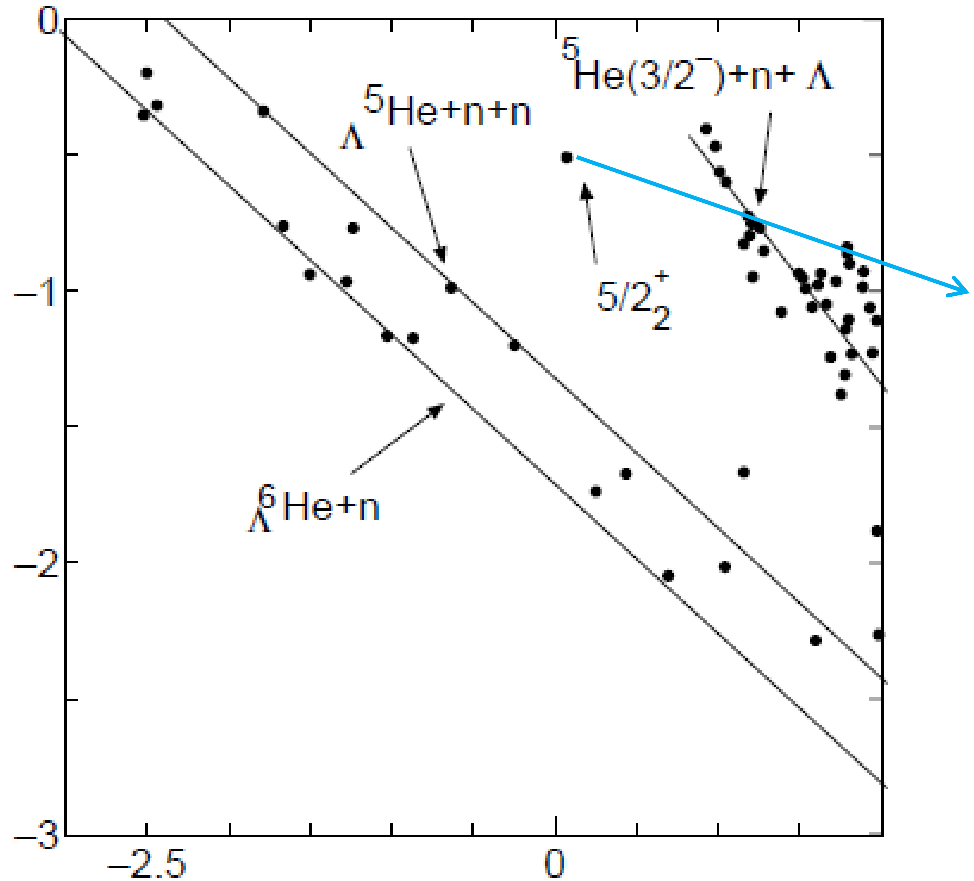
X. Mougeot et al., Phys. Lett. B 718 (2012) 441. p(^{8}He, t)^{6}He

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

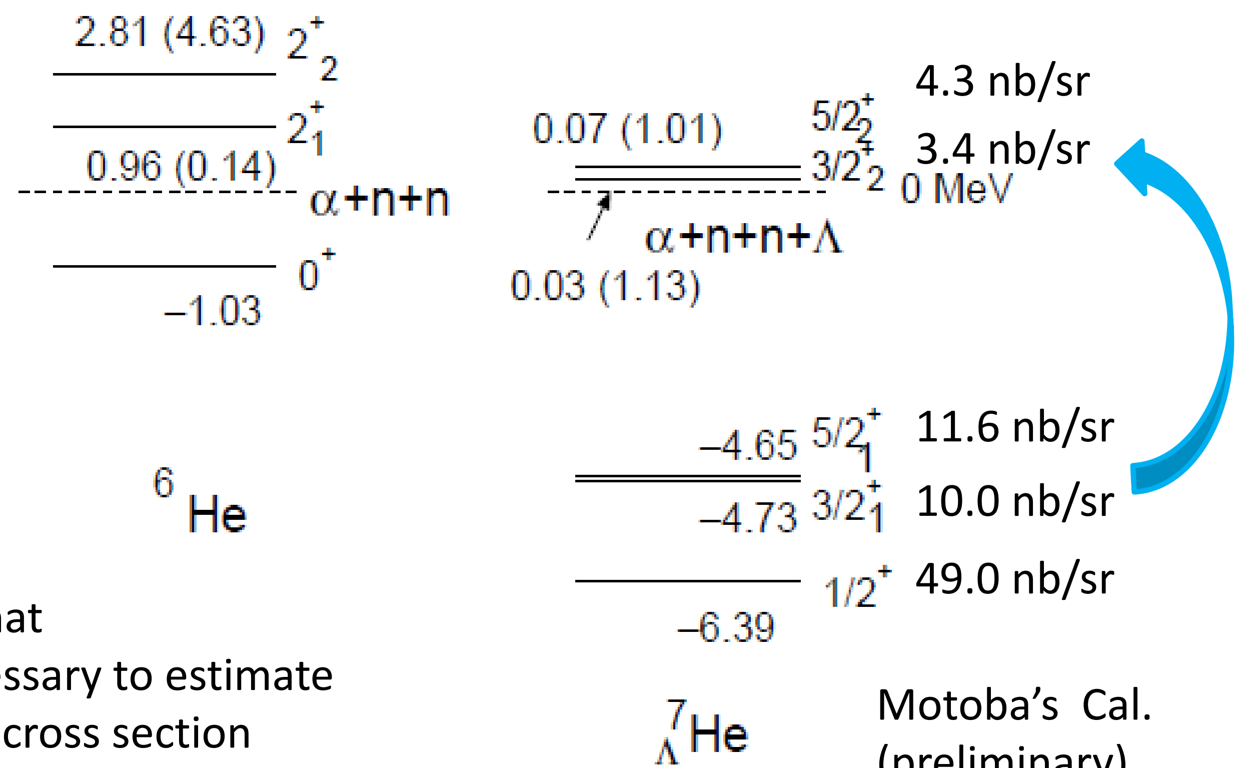


^{6}He

Cal.



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



I propose to experimentalists to observe these states.

40% reduction

Motoba's Cal.
(preliminary)

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

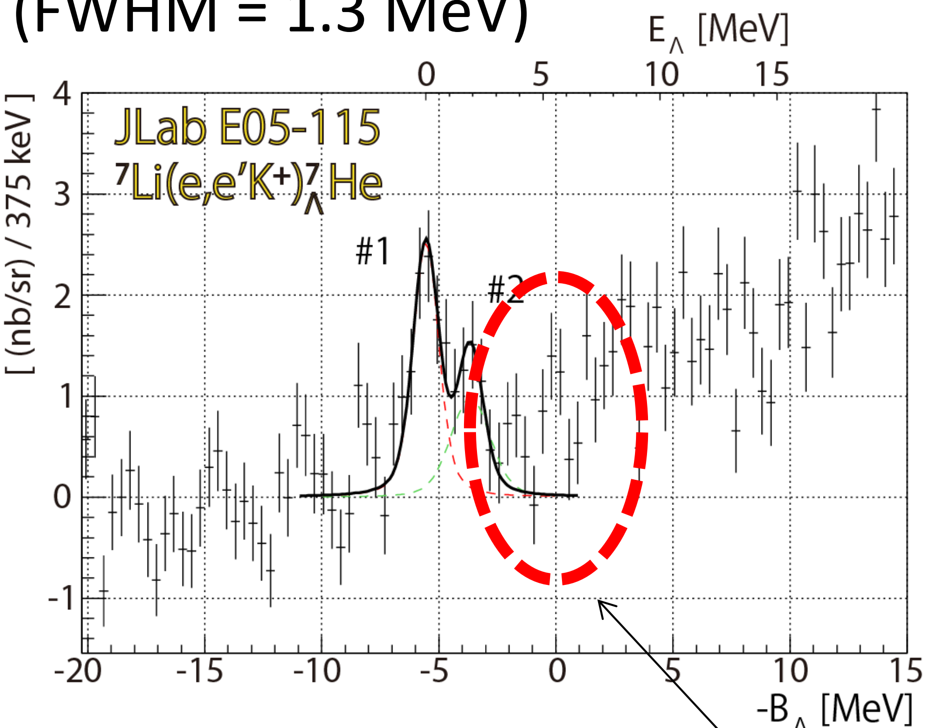
Motoba san recently estimated differential cross sections for each state.

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

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

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.

(FWHM = 1.3 MeV)



Fitting results

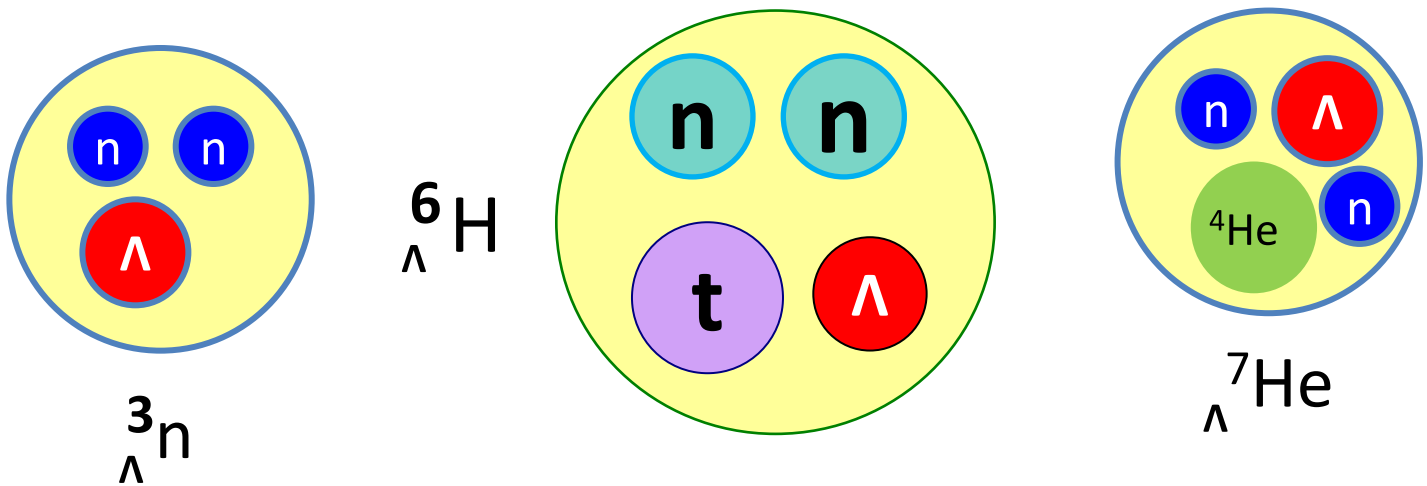
Peak number	State $^6\mathrm{He}[J_C] \otimes j^\Lambda$	Number of events	$-B_\Lambda$ [MeV] (E_Λ)	$\left(\frac{d\sigma}{d\Omega_K}\right)\Big\vert_{1°-13°}$ [nb/sr]
1	$1/2^+$ $[0^+;\ \mathrm{g.s.}] \otimes s^\Lambda_{1/2}$	413±20	-5.55±0.10±0.11 (0.0)	10.7±0.5±1.7
2	$3/2^+,\ 5/2^+$ $[2^+;\ 1.80] \otimes s^\Lambda_{1/2}$	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

Third peak???

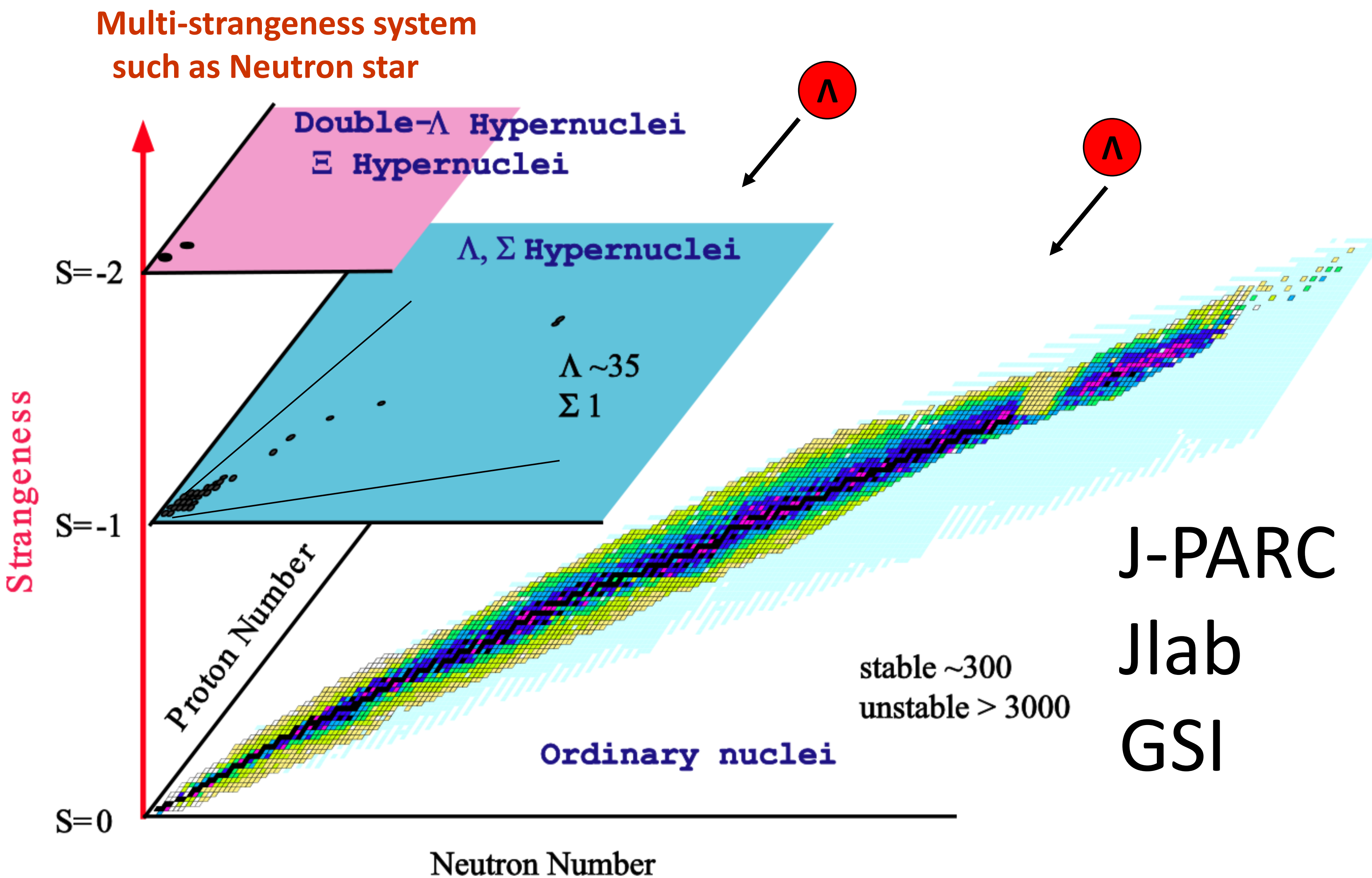
They plan to submit their proposal for $^7_\Lambda$He to JLab next June.

Summary



Neutron-rich Λ hypernuclei

Nuclear chart with strangeness



J-PARC
Jlab
GSI

Thank you!